# Capturing New Forms of Video Footage in Remote Locations through the Design, Development and Deployment of an Autonomous, Open Source, Unmanned Aerial System: A Case Study of South African Enduro Motorcycle Racers


**by**

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## ABSTRACT

This study explores the use of an autonomous Unmanned Aerial System (UAS), in the capturing of video footage of sporting events, specifically enduro motorcycle racing, in remote areas of southern Africa. Remote areas are defined as those that are far removed from urban centres, are inaccessible by motor vehicle and that have no internet or cell phone coverage. Autonomous UAS refers to drones which are pre-programmed to fly a specific path and thus fly automatically once launched.

Conditions of remoteness place unique constraints on the objective of capturing video footage of sporting events in such areas. Traditional means of video coverage, such as those from ground-based camera operators, Go-Pro cameras mounted on the riders, or helicopter-based camera operators, results in video footage which is either limited in range and consists of numerous shots of shorter duration, or otherwise prohibitively expensive. A newer form of video coverage would be the type obtained by a manually flown drone, but even this coverage is limited as it typically consists of the footage acquired solely from a position behind the riders. In contrast, video footage captured from an automated UAS allows for a greater range and an expanded duration of shots. The defining characteristic of video footage captured by an automated UAS is the lengthy, lingering wide shot, which includes multiple camera angles, height changes, and camera movements, all within the duration of a single shot. This constitutes a new form of video coverage of remote sporting events.

This research is practice-based and includes three related parts:

Firstly, the design, construction and programming of a UAS for use in remote areas with the objective of capturing video footage of enduro motorcycle racing events. An ‘open source’ approach to all the software with which the UAS is programmed is utilised;

Secondly, the capturing and editing of video footage which has been gathered from the UAS;

And thirdly, a dissertation and practice-based reflection on the process.

# DECLARATIONS

I, Peter Gregory Burnett, declare that

1. The research reported in this thesis, except where otherwise indicated, is my original work.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain text, data, pictures, graphs or other information obtained from another person or source, unless specifically acknowledged as being so obtained.
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As the supervisor, I acknowledge that this research dissertation/thesis is ready for examination

Name: ____________________________

Signature: ____________________________ Date: ______________________

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# INTRODUCTION

This is a PhD in Visual and Performing Arts which, unlike traditional doctoral theses, has two parts: (1) a 'substantial body of applied creative work', which is (2) 'supported by a dissertation' that engages intellectually with the creative output.

Accordingly, the PhD will consist of:

*(1) Creative output:*

(a) The construction of an Unmanned Aerial System (UAS) with a range of supporting equipment (radio-controller, batteries, video monitor, laptop, mapping hardware, spares as well as food and drink for the day, all fitting into a portable backpack), guided by Action Research and Practice-based Research methodologies and various design and open-source theories.

(b) A set of videos of motorcycle Enduro events, captured by the UAS.

The camera platform that I will design – the Unmanned Aerial System (UAS) or Unmanned Aerial Vehicle (UAV) – is commonly known as a drone. Note that the abbreviation UAS can be used in a variety of ways, as 'Unmanned Aircraft System', or 'Unmanned Autonomous System', or as I will be using it in this dissertation 'Unmanned Aerial System'. The term, 'Unmanned', refers to the fact that there is no operator aboard the UAS, although there is a pilot controlling it remotely.

Autonomous refers to the ability of the craft to behave according to a pre-programmed set of instructions and carry out its mission according to these. Autonomy refers to the fact that the drone could have limited or no remote pilot input once the flight begins.

*(2) A dissertation*

This will comprise an Action Research-driven critical account of the process of constructing and testing the UAS and an evaluation of the aesthetic components of the resulting aerial video-footage. Distinctions between an aerial view and a ground-based view (‘the traditional way’) are elaborated under ‘Context of the Research’.

**Aims and Scope**

Motorcycle ‘Enduros’ are race events where the competitors traverse large open areas of terrain for long periods of time over the course of the event. The riders ‘race against the clock’, that is they are timed when they individually leave the starting area, and then timed again when they arrive at the finish many hours later. The course is typically in very remote areas, most often where there are not even dirt roads to access the track that the racers are following. The course is set and marked by the organisers beforehand, and the riders race along this course without seeing it beforehand. The race is a test of speed, technical riding skills, and mechanical and physical endurance.

Traditional television coverage of niche sporting events such as Enduros is limited due to prohibitive costs which curtail the use of helicopters for capturing aerial video of the action and rely instead on video footage from ground-based and rider-mounted cameras. Unlike an aerial view, however, ground-based video footage does not have the versatility of perspective to capture the context of the terrain (clearly of major importance in Enduro track racing); the expertise of the riders in relation to the terrain; and, generally, the spirit of the occasion, in which tracking and quick shifts of angle are particularly beneficial.

Given the problems of cost (helicopter hire) and limited versatility of perspective (ground-based footage) my hypothesis is that the video coverage of niche sports events such as Enduros can be facilitated, dramatically improved, and popularised through the design and implementation of cost-effective, unmanned autonomous aerial vehicles – drone systems – which can be designed and built using open-source software.

To apply the hypothesis to Enduro racers, the UAV will be designed to carry a camera in order to capture lingering video footage that is compelling and immersive in shots that engross the viewers so that they 'ride with the rider'. This UAV must be robust, compact, and employ redundancy technologies, so that it is able to survive in the harsh unforgiving environments of very remote uninhabited areas.

My study is governed, therefore, by a humanistic and democratic intent: to open what is currently a prohibitively expensive field (that of filming) to the participation of a wider number of practitioners. The overarching purpose embodies the following two interrelated research questions:

1. How to design a drone that uses cost-effective, open-source software to house the necessary camera facilities while having the portability to film remote, outdoor sporting events.
2. How to measure and assess the advantages and limitations of such 'drone-filming' of remote, outdoor events in comparison with current and expensive applications of 'ground-based' filming techniques.

My subsidiary questions apply the principal questions to the practicalities of a 'case study' (that of a controlled number of Enduro events in the testing terrain of the Southern African Enduro racing calendar):

a. How have niche sports events such as Enduros traditionally been filmed for television?
b. What are the problems and shortfalls of this traditional coverage?
c. How can video coverage of Enduros be improved? What are the gaps and opportunities?
d. What is the best design for an unmanned autonomous aerial vehicle to be used as a video platform for niche sports events such as Enduros?
e. What are the challenges and issues leading to my design solution?

f. What are the roles of online forums and open-source software in the independent design process?

g. How can the television viewing experience of niche sports events such as Enduros be changed using video captured from unmanned autonomous aerial vehicles?

h. How will the craft deal with take-off and landing in less than ideal circumstances, such as areas which are not level, and which are covered in rocks or long grass?

i. What level of redundancy is required from the craft so that should a component fail in flight, it can recover and either continue with its mission, or alternatively return to the launching site?

j. How can assembly in the field be made easier in terms of components which remain attached to the folded version, and components which need to be attached, out in the field? How can it be designed so that a minimum number of tools are needed for this assembly?

k. How can components of the craft be designed in such a way that there are common or modular parts, so that there are a minimum of spare parts needed to be taken to the flying site to avoid having to return to a base which may be many hours away?

l. How can the craft be designed so that components which are likely to break in a crash are easy to replace in the field; and, allied to this, how can the craft be designed so that components which are inherently difficult to replace in the field are unlikely to be damaged in a crash?

m. Most importantly, how can the system be designed so that everything that is needed for a full day in the field is highly compact and portable?

n. What is needed to plan and execute a mission?

o. What equipment would need to be designed and built to map the flying site?

p. How will success be measured? In addition, what constitutes failure of the system?

To confine generality to particular control and evaluation, the drone-filming, to reiterate, will be delimited to a single set of relevant events (namely, that of Enduro motorcycle racing) within a delimited timeframe.

In television sports coverage there are two major delineations regarding how various sports are covered. The first is ‘live’ transmission, where the pictures the viewer is seeing at home are virtually instantaneous with what is happening at the sporting event itself. Typically, the costs involved in live transmission are very high, and so this mode of delivery is limited to those events where the broadcaster can expose their product to the greatest number of viewers, since this can lead to higher advertising revenues.

The second form of sports coverage is where the sport is covered for editing and transmission later. Costs for this type of production are much lower; however, the immediacy of live coverage is lost, and with it, viewership. Typically, more niche types of sport are covered in this way since the viewership for these events are much lower. Off-road and Enduro motorcycling falls into this category.

Another reason that Enduros are not covered in a ‘live multi-camera’ scenario is that the distances covered are so large, and the areas where the competitions take place are very remote and far from urban centres. A multi-camera approach requires that all cameras (and other sources) are available at one central point – the Outside Broadcast van – where the television director can decide which vantage point to select and transmit. These sources (typically cameras) are connected to the OB van by cable, and only in exceptional circumstances, where budget allows, via roving microwave links. Thus, cable length limits the distance a camera can be placed from the OB van, which lends itself to stadium and arena type broadcasts. An exception to this is the Tour De France, which covers huge distances every day, yet is broadcast live in a multi-camera setup. However, as viewership is massive for this event revenue streams from advertising are optimised and thus the expense of OB coverage is offset.

Coverage of Enduros is far more austere and is typically not captured via OB productions. Camera crews are sent to various interesting points along the route, where they capture footage of the competitors and return this to an editor. The footage is edited down and broadcast later. The footage might be supplemented with ‘on board’ cameras taken by the competitors themselves, and in some rare instances by helicopter coverage where budget allows.

For the most part, though, most races rely on individual camera operators working out on the route on foot, trying to find a vantage point where the riding is best shown. This has several disadvantages, not least of which is that the shots they can capture are of limited duration.

My personal experience of both competing in and photographing Enduro motorcycling means that I know first-hand that the sport takes place in terrain that is largely inaccessible, far from roads or even gravel tracks. The courses which the competitors follow cover rivers, valleys, forests, and steep mountainsides. Although at times the course will return to roads or farm tracks, these sections are often not the most interesting, and they are the exception rather than the rule.

I intend, therefore, to get right out to where the toughest, most demanding sections of the course go. The only way to do this is to walk or hike (which is not practical because of the distances involved), or to use a helicopter (not practical because of the costs involved), or to use another off-road motorcycle. I have chosen to go with this last option, and this choice is informed by the fact that I have many years of experience photographing these races by taking all my kit with me on a motorcycle.

This provides the initial parameters which my UAV design must address – compactness and portability. All the equipment I will need must be lightweight, portable, and rugged. It must fit into a backpack which I can carry out into the veld on a motorcycle and be sufficiently rugged to last many hours of being bounced around whilst I ride the motorcycle out to the designated flying area. This is not a simple hurdle to overcome, and it has major implications for my multi-copter design. In addition, the design must be capable of operating in environments that are not conducive to typical multi-copter flying.

What I will need is a multi-copter which folds the arms and legs out of harm's way into a compact size and which can fit inside backpacks. In addition, all the other equipment – transmitter, batteries, FPV monitor, laptop, spares as well as food and drink for the day, must also fit in these backpacks.

I am choosing to use open-source software and hardware for a variety of reasons. Firstly, it has cost implications, and I have hoped to produce a design which is both cost effective and can be replicated with relative ease by someone who has access to a well-equipped home workshop. Secondly, by using open-source code I have been able to recall various forms of data (known as 'logs') after flight and testing, so that I can analyse the performance of various parameters of the craft, and in so doing de-bug and improve on the performance. Thirdly, there is a large network of enthusiasts who provide informal peer review and who are always more than willing to assist in analysing these logs. Fourthly, where open-source hardware is used there are often replicas of the various boards and components available from vendors and which are far cheaper than the originals, so this also has a cost impact.

One of the main reasons, however, for choosing to employ open-source software is the ethos of the open source, which is that anything that is taken and modified should be put back into the creative commons for others' use and benefit. My own outlook on life has always been to help wherever I can with the skills and talents that I have at my disposal. This extends to the work environment as well and is one of the aspects of lecturing, which I enjoy. My intention (with the approval of DUT) is to put all my design work into the public domain once I have finished, so that others can also benefit from my research and designs.

This Introduction is followed by a description of the method that is directing the research project (Chapter 1) and, in Chapter 2, by the context of the research in relation to observation, literature, development, and application. Chapter 3 locates the purpose of the research in an analysis of the principles of flight and unmanned aerial systems, from basic to applied, while Chapters 4 and 6 pursue the design and construction of what is commonly referred to as a 'drone' and unmanned aerial systems. As the design and construction of the drone are to be applied to the specific purpose of an aerial capture of an outdoor sporting event, in this case, Enduro motor-cycle racing, Chapter 5 considers the development of the accompanying requirements of aerial video coverage of an event, and these requirements inform the unmanned aerial system designed and built in Chapter 6 which is specific to this research. With autonomy and video capability having been incorporated into the drone, Chapter 7 explores the research method – Action-based/Practice-based – in the real-time of an aerial tracking of Enduro motor-cycle racers. What 'real-time' application tests is the trial-and-error principle and method central to Action-based and Practice-based research. The writing-up of such a process requires a descriptive and analytical amalgamation of academic objectivity and a more personal, even colloquial, subjective engagement in the experience. Such a 'style' characterises Chapter 7 and leads to a tentative Conclusion about the potential and limitations of the project outcomes up to its current stage of development: this stage that is presented as the culmination of the research project for the purposes of thesis presentation.

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# CHAPTER 1

## Method: Action-based and Practice-based Research

The theoretical and methodological framework for this type of research may be described as 'practice-based research' (Candy: 2006; Scrivener 2002: 2004), where 'a creative artefact is the basis of the contribution to knowledge' (Candy, 1) rather than a single focus on a conceptual argument. She further says that creative outcomes can be '…in the form of designs, music, digital media, performances and exhibitions.' Smith and Dean (2009: 7) refer to the fact that it is not only the work of art which informs the research, but also the creation of such art which generates research insights which are then documented. Scrivener (2004, n.p.) argues that practice-based research has 'the purpose of advancing our capacity for envisioning possible future realities' through 'novel apprehensions', a theoretical orientation peculiar to creative outputs.

Generally, Action Research is understood as a cyclical process, where the researcher reflects on and assesses previous findings (when success is incomplete), which in turn informs the change in the next cycle of experimentation. Cherry (2002: 2) has a comprehensive diagram which explains one cycle of the Action Research model particularly well. Initially, the project (or cycle) starts with Action Planning, then progresses to Action and Experience, then onwards through Observing, Evaluating and Concluding, before finally Attending, Noticing, Diagnosing and Refocusing; and then the cycle begins again, and is repeated until such time as the original goals are achieved. Within each stage Cherry describes various options, some of which are applicable early on in the study, and some of which become more valuable as the study progresses. So, for example, the initial stage of Action Planning includes '…solving a problem or implementing and idea…', but later during the research this stage includes '…developing new strategies for data collection…'.

The process, however, is not confined to one simple cycle. Both Koshy (2002: 5) and Dick (2002: n.p.) emphasise a helical or spiral cycle, where the reflection is used to review the previous cycle and plan the next one, leading to evolving levels of design success. Dick describes the critical reflection part of the cycle as having two components: a critical review of the last stage of experimentation and planning the next one. He notes that ‘Action Research provides enough flexibility to allow imprecise beginnings while progressing towards appropriate endings’.

Such triangulation of data is how I approach the design process. The open-source Arducopter and Mission Planner UAS software which I intend to deploy produces and logs over two hundred different data streams, which I can download and analyse after flights. I will use this logging feature to ascertain what improvements I will need to make as part of the action research cycle to inform further changes or improvements that I need to make to the drone. In addition, I will analyse the video recorded from each flight to ascertain how I would like the drone to perform subsequently in order to improve the viewing experience of further flights. What elements of the video will you focus on when you analyse the footage? For example, framing, steadiness.

To arrive at a quantity of data that is reasonably reliable as a basis for generalisation, I envisage the aerial filming of several events over different terrains. The number of events cannot be fixed in advance as the exercise has a dual purpose: filming enhancement interlinked to stages of drone development, and vice versa. Klein (2012: 85) endorses the importance of what I have described when she writes that ‘Throughout the evaluation and analysis process, the researcher remains open to new opportunities and insights’. (In this regard, see also O’Leary, Strauss and Corbin, Koshky and Cherry.)

Using a ‘case study’ approach to this research is valid, particularly because it is practice-based. Walker (1986: 189) notes that writing case studies is an ideal way of disseminating action research, as it can offer a meaningful story to the reader in a style suited for readers who are interested in the practical implications of an action-research project. I want this study to be relevant and interesting to other researchers and students, and to provide a model for action research in my University Faculty.

I plan to download the various tracks on which the motorcyclists will race from the organisers beforehand. I will then convert the track data and overlay it on Google Earth images. From this, and based on my experience of riding similar terrain, I will select sites where I propose to fly the craft and record video of the action. A variety of factors will influence my choice of flying site, including but not limited to: the ability to access the site without traversing the racing line; the time of day the riders will get there; my ability to map and configure the flight beforehand; the types of shots I can get at each site; and the risk factor for the craft should something malfunction.

The target market for this research would be filmmakers and videographers who have an interest in expanding their means of production from ground-based cameras to utilising an aerial view of the action they are capturing. In particular, it would appeal to those filmmakers who are covering action-type sports and activities in regions far removed from urban or built-up environments, where access is difficult and where there are few support services. The audience would also include people who have an interest in developing, programming, and flying their own drone using their personal expertise. This is one of the reasons I propose to publish my findings on the open-source repository ‘github’ so that the findings are freely available as an open-source design solution.

It is a framework that I shall apply to a personal exploration: it is a journey I wish to take and which will test my capabilities as a designer, my skills as a craftsman, my abilities as a videographer, my analysis as a developer, and my insights as a creative practitioner.

I aim to design a UAV system which meets the unique requirements of both the sport I am trying to cover, as well as my abilities to programme and fly it whilst framing shots. I want to have an approach to this which not only can be constructed on a limited budget, but, wherever possible, uses resources which are available in the public domain. I want to undertake a personal journey where I learn about the core principles of unmanned flight and autonomous control and modify this according to my needs. I want to test my skills as a designer within the context of what I can achieve relative to my own abilities as a craftsman to construct this design. I want to try to achieve a vision I have as a creative video practitioner and see if it is possible to produce the kind of video coverage I envisage. If I cannot achieve this, I want to understand why not, whilst at the same time getting as close to what I had hoped for. I want to be able to show progress and refinement through various designs of the craft, via analysing results and trying to improve on the next version. Ultimately, however, the UAV will be designed to carry a camera in order to capture video footage that is compelling and immersive. The UAV design will facilitate the capturing of shots which linger with the action, shots which develop and continuously evolve, shots which engross the viewer so that they 'ride with the rider'.

In short, I want to create new ways of televising the sport of enduro. I want to move beyond the pictures which only 'hold up' for a few seconds in an edit and instead have shots which linger, which evolve, and which better show what the riders are going through, and the skill levels they need to have to attain their goal. I want to capture shots that are both compelling to the average television viewer, as well as aficionados of the sport.

My ultimate purpose, therefore, encompasses both a design and an art challenge: to design a cost-effective UAS that is fit to the conditions of my case study (the filming of events in inhospitable terrain) while able to present to viewers an aesthetically immersive experience of such events.

# CHAPTER 2

## Context of the Research: Literature, Development, Application

Aerial perspectives first captured the popular imagination when French balloonists soared above the earth in the mid-18th century. The awe-inspiring experience of viewing landscapes and objects from aloft separated the balloonists from the common man and woman on the ground, whose only view of the world was from an earth-bound vantage point. As Dorrian and Pousin (2013:123) describe it, the ballooning experience provided people with '…an extraordinary expansion of the point of view'. Afforded to only a few, this was a privileged perspective.

The French photographer and balloonist Gaspard-Felix Tournachon was the first known aerial photographer, capturing images above Paris in 1858. The use of film cameras which were mounted on aircraft followed in 1909. Later, wartime needs for establishing the parameters of enemy territory led to a rise in the use of aerial photography over the period of the First World War. Today, photographic, film and video cameras have been used in, on, and under a range of aerial platforms, from kites to light aircraft, jets, and drones, capturing images which have then been distributed to global audiences.

Donnelly submitted a thesis to the University of Cape Town in 2014 which examined the possibility of using aerial drones for sports photography. Whilst he himself admits that the final product he engineered did not meet his expectations, he does identify some of the problems with current forms of sports photography and how they could be overcome and improved upon using drone technology. He begins by pointing out that there is great difficulty and price attached to obtaining aerial photographs of sports, particularly those which cover terrain to which it is difficult to get a camera crew (2014: 1). As a result, large areas of the event are left undocumented. He points out that helicopters are prohibitively expensive to use as a filming platform, and that they require a two-man crew. He singles out sports such as mountain biking, which take place over rocky or mountainous terrain, as being particularly difficult to cover.

Donnelly's summary provides a valuable starting point to my project. His category of problems is familiar. How, then, to design a drone that overcomes the problems?

I found Tim Brown's book (2008) a useful guide to the design process and particularly his theory of the three stages of 'design thinking', namely, inspiration, ideation, and implementation. My research so far has focused on the ideation stage, which is to develop a prototype and undertake testing.

The prototype will face an initial test: portability in remote and complex terrains. Several authors have considered the issue, including Malandrakis, Dixon, Savvaris and Tsourdos (2016) and Tracy (2011), all of whom write about propeller design for small UAVs. Stoika and Parvu (2016) describe stabilising systems used to control pitch-angle tracking whilst Şenkul, Abdulkerim, Altuğ and Erdinç (2016) describe the design of a novel tilt-roll rotor quadrotor UAV. Kontogiannis, Spyridon and Ekaterinaris (2013) examine how small, lightweight planes can be optimised to carry photographic and video equipment and how these interface with first-person view (FPV) systems for control by a remote operator. These authors afford critique, validation, and alternatives to my own design process.

Equally valuable is Boothroyd's *Design for Assembly: A Designer's Handbook* (1980). Although there had previously been processes followed in some factories around the world which engaged with Design for Assembly (DFA), his book explicates the underlying philosophies and procedures. I am aware that these ideas relate to the production line of manufacturing products in large factories, but I feel that many of the ideas can be extrapolated to a different context for my own purpose; which is the assembly of a finished product for use in a very remote location.

Zorowski (2004) writes about how Design for Assembly is a critical part of the product design process. He maintains that 'Although difficult to achieve', the ideal product to assemble is one that 'consists of only one part' (68). This 'one part' philosophy will inform my design for a folding craft which has all parts attached, and which will be unfolded in the field, with no extraneous parts which must be packed, found, and assembled onto the main structure.

Another design principle, Zorowski espouses, is that of elimination and simplification. For example, he refers to '…eliminating unnecessary fasteners and simplifying those that are required' (64). He also reminds the designer to be mindful of the availability of tools needed for field maintenance. I shall be guided by the idea of elimination, simplification, and availability in attempting to use a limited number and type of fasteners, so that minimal tools are required to do repairs in the field. I plan to reduce the unfolding and flight preparation, and refold again for packing, down to the use of only one tool.

The last of Zorowski's principles which has relevance to my design is '…to use modular or multifunctional parts' (59). I am designing the craft in such a way that in the event of a crash, the parts which are most likely to break or deform, in fact the ones which are designed to break, are multifunctional or universal, and can be used in a variety of places on the craft. This should reduce the number and type of spares that must be carried into the field.

To turn from portability of design, I aim to conjoin the technology of design to community enhancement in the sharing of open-source software. The concept of open-source software was introduced in 1984 by Richard Stallman, then of Massachusetts Institute of Technology (MIT), who 'operated from political conviction [and] wanted a world in which software enabled people to use information freely, where no one would have to ask permission to change the software they use to fit their needs or to share it with a friend for whom it would be helpful' (Benkler 2006: 64).

The process that results in the creation of open-source software is characterised by collaboration and the product is characterised by being not-for-profit. Thanks to the Internet, many individuals can collaborate from remote locations to work collectively on a shared project. None retains rights to the entire body of work, although individuals may retain rights to their own contributions. A licence is freely given to anyone who wants to use the software.

Anyone who modifies software and distributes the modified version must license it in the same way (Benkler 2006). Many individuals can create and continue to refine one product over time.

Rao, Goutham and Maione (2016) note how the technological development of drones is driven by ‘active communities of hobbyists and enthusiasts’ (45). These online communities contribute to the development of both hardware and software used in UAVs and have had an impact on the products of companies such as 3D Robotics, DJI, Parrot, and Openpilot. Such co-operation would not be possible if companies did not provide access to their development tools and thereby encourage the public to contribute to the design process.

Thus, a dispersed community of interested participants has co-authored the design of UAVs using the internet and shared software. Rao, Goutham and Maione correctly state that ‘drone manufacturers utilise the passion and expertise of the community to create technology that best serves their need’ (83). This interaction blurs the line between professional companies and amateur enthusiasts. Allied to this is the advent of 3D printers which have allowed hobbyists and enthusiasts to manufacture drone components once they download the designs.

Such open-source design possibilities and application has seen drones beginning to being deployed in many ways, for example, in aerial terrain mapping, farming, medicine, search and rescue, and many more. Pestana et al (2019: 5) describe how a drone deployed with minimal sensors such as on-board GPS, camera and clock can be deployed over an area to map an area in latitude and longitude, height, and pictures. Zipline is a California-based company working with health facilities in Rwanda and Ghana (https://www.businessinsider.com/zipline-drone-coronavirus-supplies-africa-rwanda-ghana-2020-5) to deliver medical supplies to rural settlements while Lygouras et al (2019: 35-42) describe a system for using autonomous drones in search and rescue operations.

From the general to the particular, János Mészáros has written about using open-source hardware and software for aerial surveying. He points out that the open-source development process can be fast, because not only the developer but other users can test the code and give feedback (2014: 155). I intend to use online forums extensively in my designing and testing, because such forums can provide a large source of interested and experienced members who have often encountered the same challenges. In particular I have used two forums, DIYDrones and RCGroups. I have also been guided and kept up to date with new developments in multirotor technology via online magazines such as *SUAS News* and similar publications.

To transfer the above-mentioned observations to this project, I reiterate that it is not only the design of a drone that informs the research, but also the aerial filming and editing of ‘case studies’ of Enduro motorbike racing which, in comparison with ground-filming, should provoke a trial/error/improvement cycle of events, each with its challenges in improving the design of the drone in conjunction with the enhancement of recorded and photographic case-study race clips. The knowledge gained in the development of a ‘fit for purpose’ drone, therefore, is inseparable from the development of better filmic coverage of remote and inhospitable-terrain events.

While a literature exists on the design of drones, there is no corresponding literature of significance on the art of filming the sports event. Besides a few remarks by Candy on the creative-output potential of Practice-based Research (see, above), I am very much on my own in developing and adapting from general film studies a language of appreciation for the filming of sport.

The aerial perspective, nonetheless, is an inspiring one. The possibility of seeing ‘something afresh’ (Gynnild: 2014, 336) accounts for the allure of mobile aerial platforms for photographers and videographers. The affordability of modern-day drones and the resulting ease with which aerial views can now be accessed has led Gynnild to describe drones as a ‘disruptive technology’. In short, ‘Drones present a major opportunity to tell not just old stories from a new perspective, but a completely new way to tell a story’ (Najberg in Chamberlain, 2017: 9).

I wish to employ drones to ‘tell in a new way’ the story of certain televised sporting events. As I indicated in the Introduction, niche sporting events, such as off-road motorcycling or Enduros, have so far been covered for television in a traditional way: that is, from ground-based shooting positions and rider-mounted cameras. The only coverage from aerial platforms has been by helicopter. However, as the cost of hiring helicopters has increased and broadcast audiences and advertising revenue for similar niche sporting events have fallen, this way of covering off-road motorcycling events has often become financially unviable. The use of drones as aerial camera platforms could change this.

Aerial footage captured from a drone is different to that captured from a helicopter: drones can fly far lower and venture into spaces inaccessible to helicopters. The use of drones for Enduro coverage would avoid the need for individual camera operators working out on the route, on foot, trying to find vantage points where the riding is best portrayed, often resulting in shots of limited duration, or otherwise shots which require an inhouse editing supplement.

Drones are being used more and more worldwide for aerial filming and shots. As an example of this, Sabetghadam et al (2019: 1-7) propose a system for determining the optimal track for a drone to trace whilst used specifically for aerial filming because the trajectory must meet the objectives on aesthetic quality of the videos while satisfying several constraints imposed by drone dynamics, gimbal mechanical limits, and surrounding obstacles and terrain. Bonatti (2019), a researcher from Carnegie Mellon University, has written about developing drones which are able to understand the human/visual aesthetic, and using their computational abilities to position themselves autonomously in relation to the actors in a scene, so that the best visual experience is attained.

The drone system could address several limitations encountered when traditional forms of television coverage are used to capture off-road motorcycle racing:

- The traditional tripod mounted camera, along with the chest or helmet-mounted camera, gives a limited view of the context of the terrain. I will evaluate the drone-acquired aerial visuals to establish if they provide a more comprehensive geographical context of the terrain that the rider is covering compared to the cropped view of traditional ground-based coverage. Apart from these wide aerial views, I also aim to acquire footage which tracks the rider from the rear as he moves forward over obstacles during over a period of the race, or from alongside the rider, or from the front as they move toward the drone trajectory. I hypothesise that such drone-acquired footage will provide an aesthetic experience not possible through traditional video coverage.

- The traditional tripod-mounted camera, along with the chest- or helmet-mounted camera, gives a limited insight into the riders' experience of the sport. I will evaluate the drone-acquired aerial visuals, especially lengthy tracking shots from in front of the rider looking back at him. In addition, crabbing shots with the drone flying alongside the rider looking at the side of him over a period of time, will contrast with the typical foreshortened view of the rider acquired through traditional coverage, and will be examined for the same reason.
- I will reflect on the difference/s in the angles acquired through traditional coverage and drone coverage and consider how this 'aesthetic' impacts upon the portrayal of the riders' experience.

In considering how technology – and specifically advances in technology – can lead to new forms of creativity and art I can refer to the Primetime Emmy Awards, which are largely focussed on creative excellence in television, but also include an award for Outstanding Achievement in Engineering. (http://emmyonline.org/tech/scope_and_procedures.html)

The philosophy behind this Award is for technologies and engineering to contribute to the creative elements of television almost like 'inventing a new paintbrush', which enables a fine artist to do new kinds of painting. I postulate that the invention, innovation, development, and deployment of drones into the sphere of television sports broadcasting production will lead to enhanced ways of capturing footage of niche sports events such as Enduros.

I believe that advancement in the aesthetics and viewing experiences of sports broadcasts is often linked inextricably to advancements in technology. An example was the introduction in 1977 of a new type of video-tape recorder, the Ampex VPR-2B, which was able to give real-time broadcast quality in slow motion and, in consequence, led to the introduction, now widespread in use, of slow-motion replays in sport. A technological advance, the slow motion (slomo) replay has had a considerable influence on the art of television production.

It is envisaged that the outcome of this research will have applicability not only to the television coverage of off-road motorcycling, but also to other niche sports in remote locations, such as canoeing, mountain biking and trail running. It is envisaged, further, to put a cost-effective means of production in the hands of the ‘ordinary’ producer or camera operator, thus opening potential to grow audiences and move niche sports to the mainstream.

# CHAPTER 3

## Principles of Multicopter Flight and Unmanned Aerial Systems: From Basic to Applied

As a precursor to the research topic this chapter explains the underlying principles of both fixed wing and rotor driven flight in general, and then to extrapolate these into the realms of multicoptor aircraft. It further explores the essential elements of what constitutes an autonomous Unmanned Aerial System (UAS).

The principles of flight have been long understood since the early gliding flights of Otto Liefenstahl and others. However, powered flight, in other words an aircraft capable of taking off and flying without any sort of aids such as hills from which to launch, was pioneered by the Wright brothers in December 1903. Powered flight depends on two things to lift the aircraft into the sky, some sort of thrust for the aeroplane to create forward movement such that airflow is created across the wings; and then wings which have an aerofoil shape to produce the necessary lift of the wing and attached airframe from this airflow across them. Illustration 3.1 below shows how this occurs.

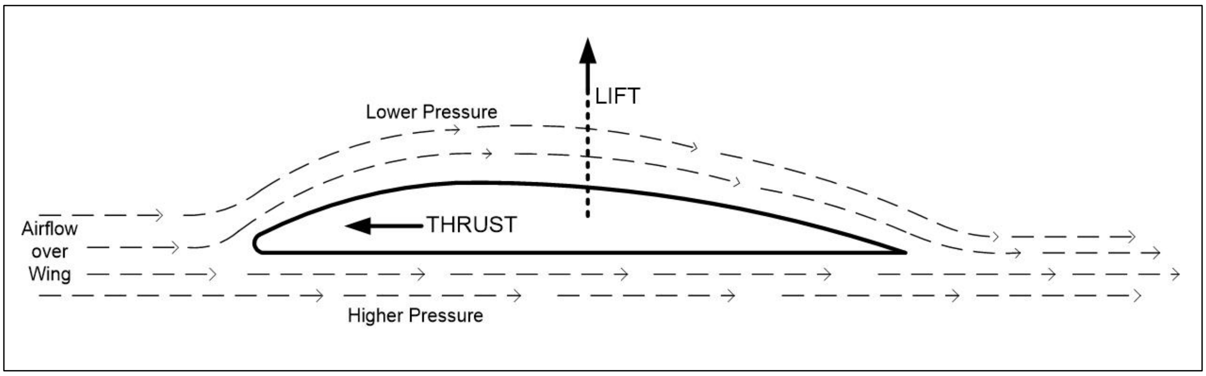
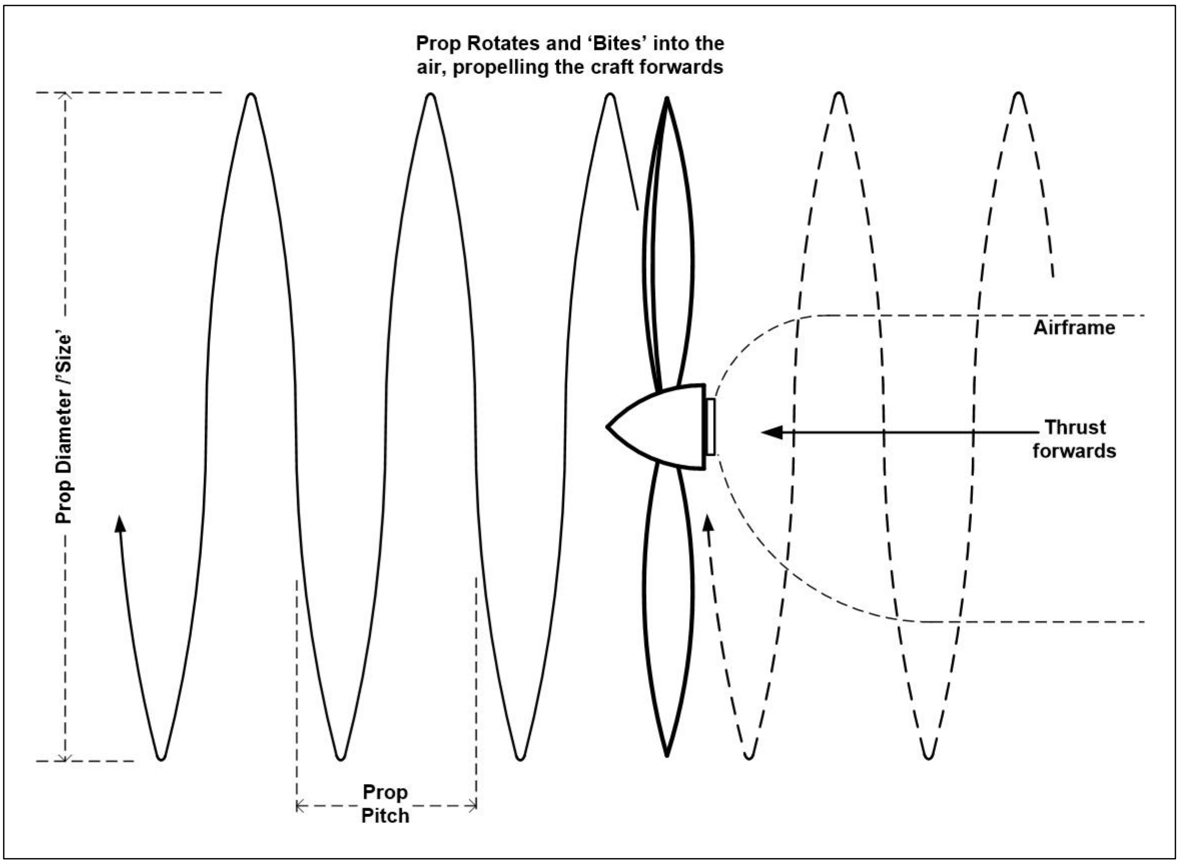



**Illustration 3.1: Lift created by airflow over an aircraft wing**

The wing moves forwards through the air (in this case moving towards the left in the direction of the Thrust) which creates airflow which hits the leading edge of the wing. This airflow then splits above and below the wing. The wing (in cross section) is shaped thus that the lower surface is flat, whilst the upper surface is curved or concave. The airflow meets again at the rear trailing edge of the wing. However, because the air has to move a further distance above the wing than below it (due to the curved shape), it means that the airflow above the wing is moving faster – and thus creating a lower pressure above the wing – than the air moving below it.  This pressure differential – low above and higher below – provides lift to the wing, and the associated airframe or fuselage of the airplane attached to it.

Powered flight relies on the aircraft moving forwards propelled by an engine and some means of providing thrust through the air. This takes two main forms, a propeller driven aircraft or a jet engine aircraft. Essentially both do the same thing; they create forward thrust. However, for the purpose of this research we can confine ourselves to propeller-driven aircraft. (Hereafter propeller = prop.)

A prop creates thrust by changing a rotational movement into thrust, much like a screw 'bites' into wood and penetrates the timber by rotating. The blades of the prop are angled like the threads of the screw, as it spins it bites into the air ahead of it and pulls the airframe forward. This principle is shown below in Illustration 3.2 below.




**<u>Illustration 3.2</u>: How Propellors create thrust**

The angle of the blades is known as the ‘pitch’ of the prop. If the blades are only slightly angled it has a small pitch, and if they are angled at a greater degree they have a higher pitch. The prop has two measurements. The first is the size of the prop, measured from tip to opposing tip. The second is the pitch and is measured by how much (theoretically) the prop would move forward with each rotation. It is an anomaly that in this day and age of the world largely adopting the metric system props are still measured in imperial units of feet and inches. So a 4’ x 2” prop, for example, would have a diameter measured from tip to tip of 4 feet, and it would have a pitch of 2 inches.

The prop is designed to work efficiently with the aircraft engine for best performance, and there are many different versions available. Simply put, the greater the pitch the more the prop is suited to low RPM (Revolutions Per Minute) motors which have good torque at low speeds, whilst smaller pitches lend themselves to higher revving motors and higher speed airplanes. A modification of this is the ‘variable pitch’ prop, which has a control in the cockpit for varying its pitch whilst in flight. During take-off when the aeroplane needs lots of thrust at low RPM and speed the prop is pitched to be coarse, and then as the plane flies higher and faster the prop is ‘trimmed back’ to a lower pitch for more efficient higher speed and altitude flight.

As the aeroplane flies it needs control to move within a three-dimensional space of the air. To do so it has ‘control surfaces’ which interact with the air passing over them, and due to resistance, these surfaces provide a change in the flight. The typical control surfaces on an aeroplane are the flaps (located on the main wings), the ailerons (located on the tail wings) and the tail rudder (located on the vertical stabilizer, or tail) of the craft. The pilot has controls which move these surfaces, and the more they are engaged or moved into the airstream the more they interact with the airflow and the more they cause aircraft to change direction.

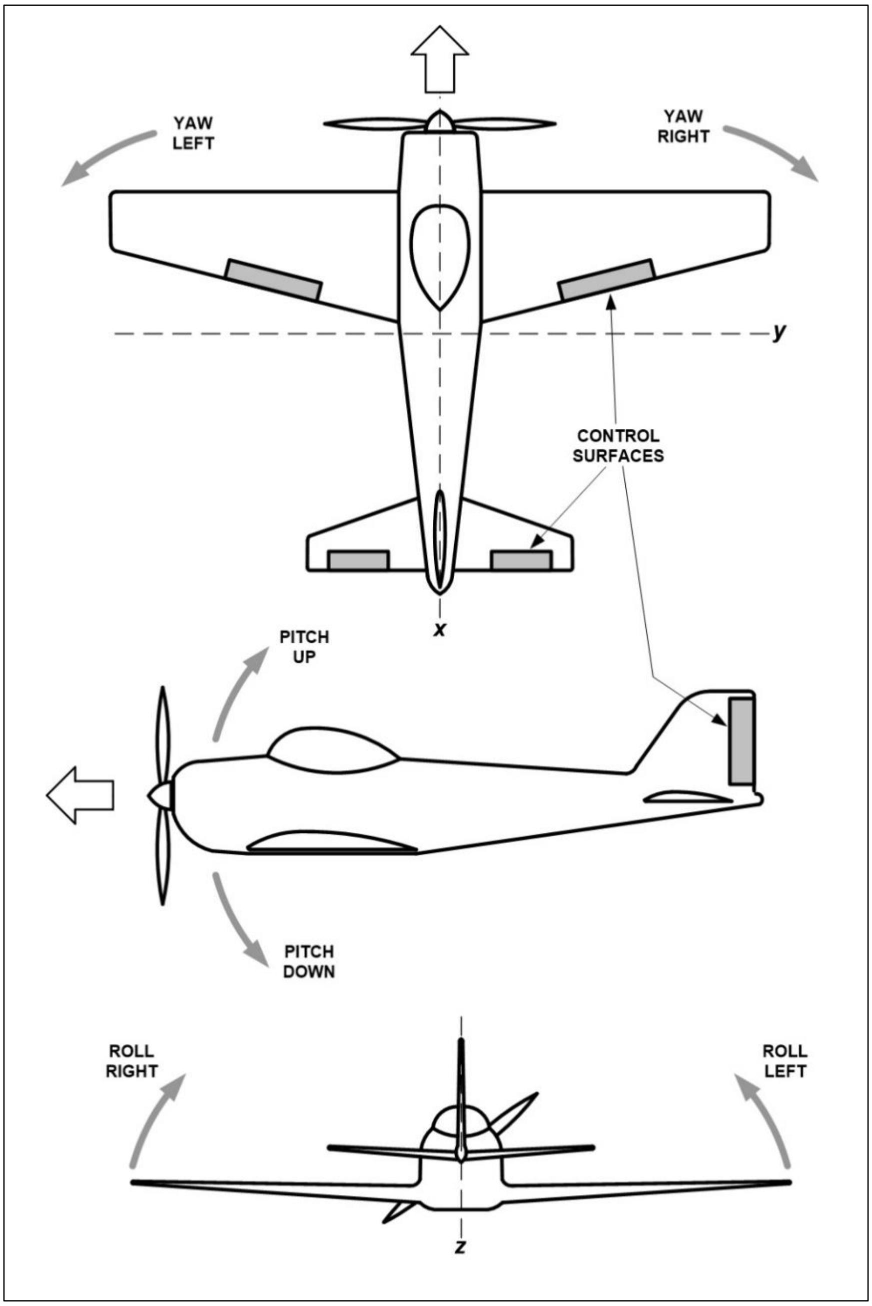
This direction change has three main axes so as to allow the aircraft to manoeuvre in a three-dimensional space, and they are common to all forms of flight. The movements are shown in the figure below. If you were the pilot sitting in the cockpit the movements would be:

Pitch: If you pitch the aircraft up, the nose of the plane will rise up relative to the horizon; pitch it down and the nose lowers.

Roll: If you roll left the left wing lowers whilst the right one rises, and vice versa for rolling right. In other words, the level of the horizon changes to your viewpoint.

Yaw: If you yaw left the plane moves its nose towards the left-hand side; yaw right and the nose moves towards the right-hand side of your view.

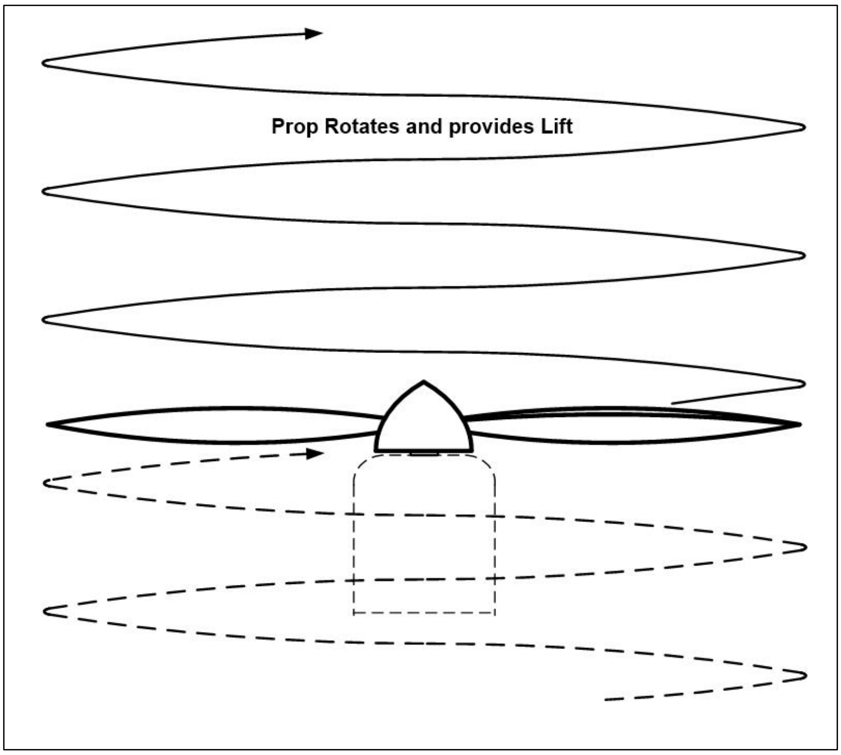
Illustration 3.3 alongside shows the various control surfaces and flight movements. In practice, these movements are not confined to only one change at a time; typically, the pilot would initiate two or more at a time. So, for example, if you wanted to change the direction on the planes heading you would employ a roll and a yaw simultaneously for safe and smooth flight.




**<u>Illustration 3.3:</u> Flight Control surfaces and manoeuvring of an aeroplane**

All of the above assumes that the aeroplane is moving forward through the air at a minimum speed; if the aeroplane is static or moving below a certain 'stall' speed it will not have any lift (or control) and plummet to the ground. If we want to create an aircraft which can remain in one place – or hover – we will need to employ different principles of flight; and thus the development of helicopters.

On an aeroplane the prop points forwards and provides thrust (for airflow) in a forward direction. However, if we rotate the prop to a vertical orientation (relative to the aircraft) this thrust is developed in an upwards direction, the prop will bite into the air above it, and with correct design lift the airframe off the ground, as shown in the Illustration 3.4 alongside.




**<u>Illustration 3.4:</u> Vertically oriented propellor provides lift**

A helicopter has a prop – now in this configuration correctly termed a rotor – above it. As this rotor spins it creates lift. It is called a rotor (with more than one individual rotor blades) because the cross-section on each blade mimics the cross-section of the aeroplane wing or aerofoil. This aerofoil rotor is moving through the air as it rotates, creating high and low pressures above and below it, and thus creating lift. Importantly it too can have various pitches, so with a coarse pitch it creates more lift, and with a lessor pitch less lift (assuming a constant motor RPM). Helicopters also have variable pitch rotors; however, with one important and ground-breaking difference (because without this helicopter flight would not be possible). Illustration 3.5 below shows the main and tail rotor positions on a helicopter. The purpose of the tail rotor will be explained further in the description of helicopter flight.

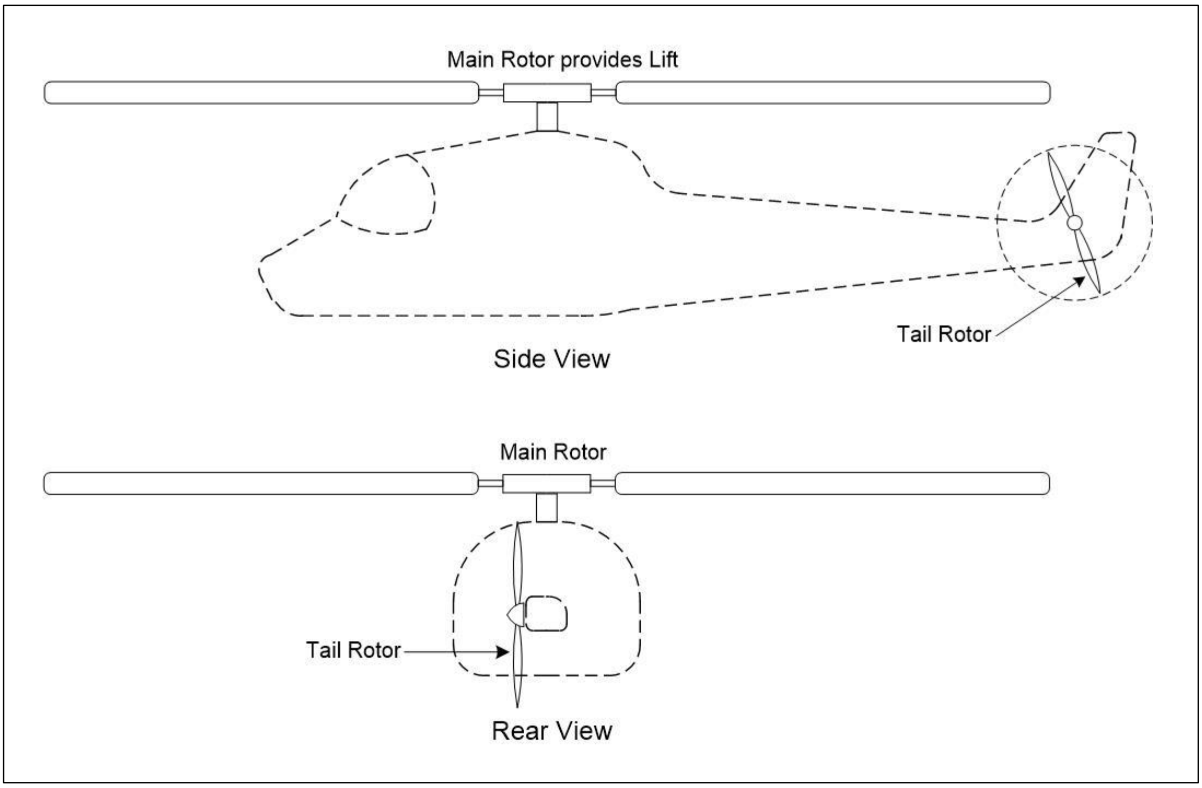
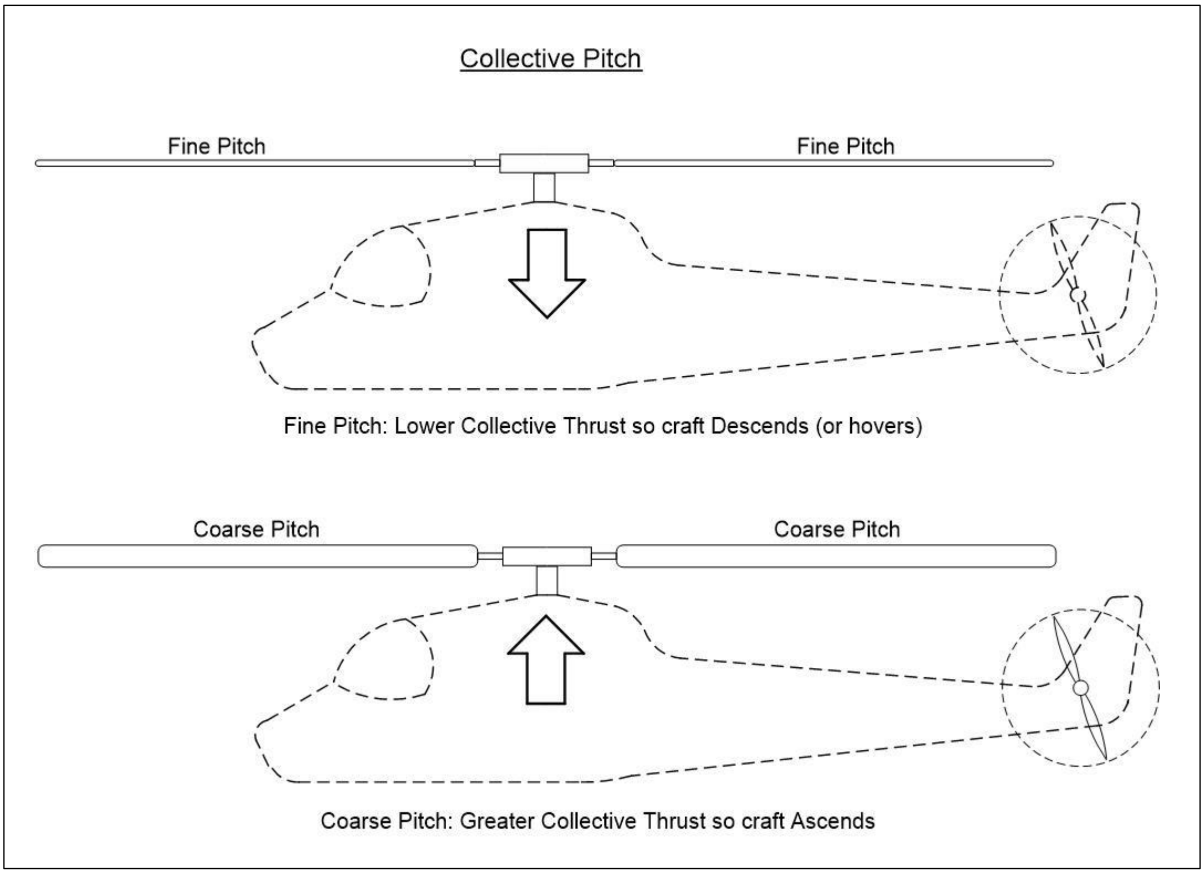


**Illustration 3.5: Helicopter Main and Tail rotors**

A helicopter has two main controls available to the pilot. The Collective Pitch changes the pitch of all the rotor blades simultaneously, no matter where the blade is positioned within the arc of its movement. So greater collective pitch means more bite of the air, and consequently more lift; and the helicopter rises. Less collective pitch, less lift, and the helicopter descends. Get the collective pitch to an optimum setting and the helicopter is able to hover, with lift balancing out the downwards force of gravity. Illustration 3.6 below shows this.

The breakthrough in helicopter flight and control, however, is the second main control, the Cyclic Pitch. What this means is that the helicopter is able to change the pitch of each individual rotor blade within the full cycle of each rotation. As an example, a rotor blade which is positioned towards the rear of the helicopter at one moment in its cycle could have a pitch which is different to when it progresses through its cycle towards the front of the helicopter. This means that there can be different values of thrust provided by the rotor towards the front and rear (and sides as well) of the airframe as each blade changes its pitch within each cycle of rotation.




**<u>Illustration 3.6:</u> Collective Pitch**

So if, for example, the rotors are pitched coarser towards the rear of the craft, and finer towards the front, there will be more lift at the rear (and less in the front) and the aircraft will pitch down (the tail rises up whilst the nose points down). Similarly, if the rotors are pitched coarse on the right-hand side of their arc, and fine on the left-hand side, the right of the craft lifts up while the left descends, and the helicopter rolls to the left. By using the cyclic pitch control we can thus recreate the rolling and pitching movements of an aeroplane. In practice, pitching forward creates forwards movement of the helicopter and pitching back creates backwards movement (relative to a stable hovering). Likewise, rolling left makes the helicopter move left through the air, and rolling right makes it move right through the air (once again relative to a stable hover). Illustration 3.7 below shows this principle.

There is one movement not covered so far for a helicopter, and that is yaw. An inherent design problem of helicopters is that the spinning main rotor transfers a torque to the airframe below it. This torque initiates a spinning movement in the airframe below it. There needs to be a way to counteract this torque, otherwise the helicopter would quickly spin out of control.

This is achieved by the use of a tail rotor, a propeller mounted on the tail of the craft which provides a thrust big enough to overcome the torque force of the main rotor. If this tail rotor is providing just the optimum amount of thrust the torque is evenly balanced, and the craft maintains its orientation and heading. This then provides the solution to yaw control. If the tail rotor provides more thrust than the amount needed to overcome the torque effect, it will move the tail in that direction, and the craft will yaw to one side; likewise, if less thrust is provided the craft will yaw in the opposite direction.

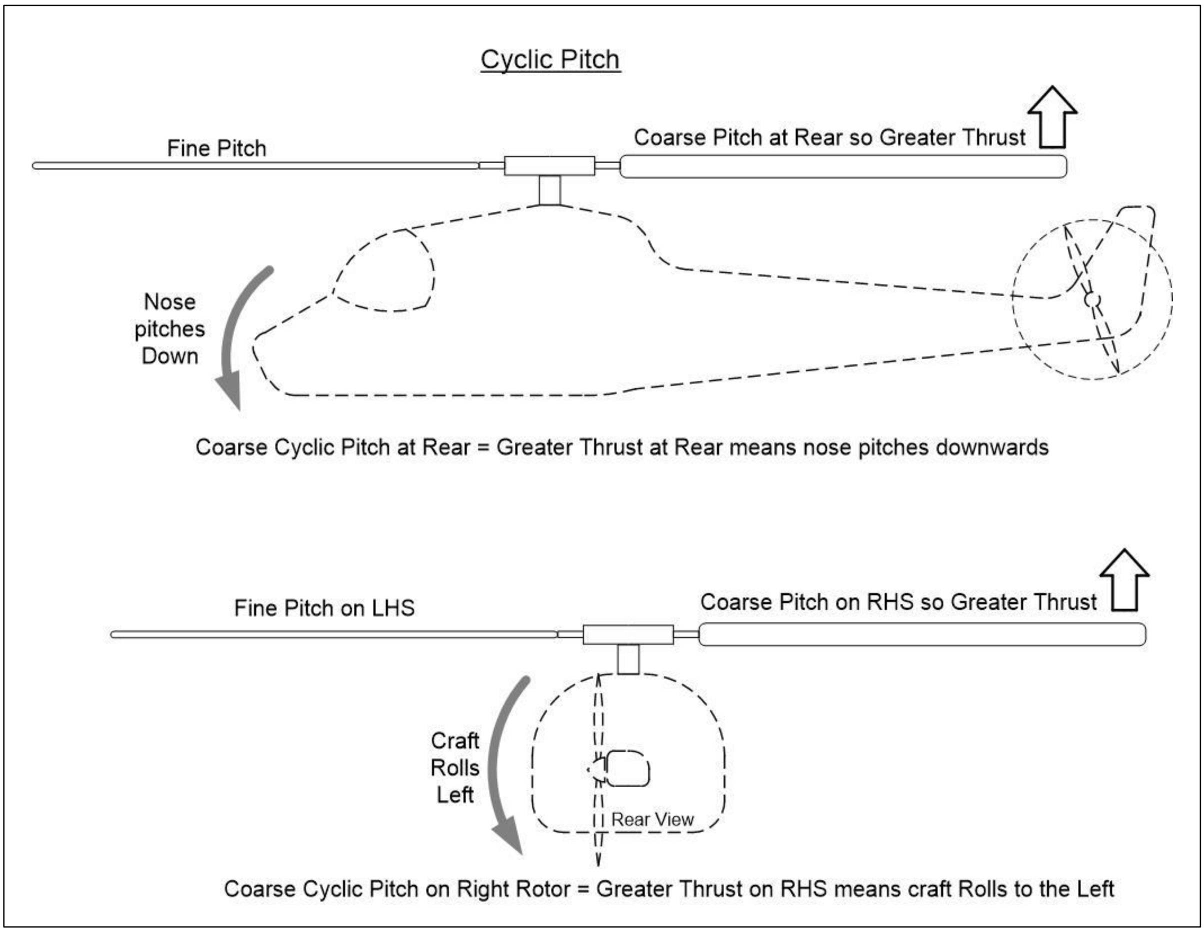



**Illustration 3.7: Cyclic Pitch**

So, in a helicopter, the control surfaces are provided by Collective Pitch, Cyclic Pitch, and the Tail Rotor.

In practice once again, the pilot would not employ only one aircraft movement to manoeuvre through the air at a time; most movements are a combination of pitch, roll and yaw. However, as opposed to the aeroplane which must move forward through the air at all times, the helicopter is able to bring new movements of flight: it can move backwards, and sideways, and importantly hover in one place. As such it was ground-breaking technology when first introduced.

As an aside we should also consider the efficiency of such flight methods since they will have relevance later in this research. An aeroplane is very efficient compared to a helicopter because the aerofoils are static and attached to the airframe. With a helicopter these aerofoils (rotors) must be spun, and to do so requires a tremendous amount of energy. The helicopter is thus less efficient at covering distance than the aeroplane – much less so in fact. If you want efficiency for covering distance the aeroplane is the choice.  However, if manoeuvrability is the prerequisite then the helicopter comes into its own. Each type of craft has its own advantages and disadvantages.

The next type of aircraft to consider is the ‘Multi Rotor’ or ‘Multi Copter’. Similar to a helicopter it has rotors positioned vertically to provide vertical lift. However, as the name implies the multirotor or multicopter has more than one (set of) rotors, whereas the helicopter only has one. A multicopter may have 3, 4, or more individual rotors (most often called props in this configuration), with each one driven by its own individual motor. Unlike the helicopter the rotors are fixed pitch, they have neither collective nor cyclic control over them. The amount of lift they provide is determined by the power – and thus the RPM – supplied to them. If you provide more power, thus higher RPM to a motor, it provides more lift; lessen the power and the RPM’s and the lift is decreased.

Multicopters are broadly classified according to the number of props or rotors that they have. A tricopter has three, a quadcopter four, a hexacopter six and an octocopter eight, as shown in the diagram below. Typically, these props (and motors) are mounted on arms away from the body of the craft, so that they can spin individually without interfering with one another. The props are normally equally spaced from each other, but this can vary in some designs. Illustration 3.8 below shows the most common configurations of motor and prop layout.

The props on multicopters are fixed pitch, but the motors can change rpm. So, if we increase the rpm's of all the motors together we provide extra lift and the craft ascends, less rpm's and the craft descends; and just the optimum rpm allows the craft to hover; like a helicopter (which utilises collective pitch to achieve this). However, unlike a helicopter which has a single motor and cyclic pitch control, we can initiate a difference in lift between individual motors to perform rolling and pitching movements. As an example, if you create higher rpm and thrust from motors at the rear of the craft, the tail rises (and the nose pitches down) and the craft moves forwards. Another example would be to create more lift from rotors on the right-hand side of the craft, the right raises up and the craft effectively rolls and moves towards the left.

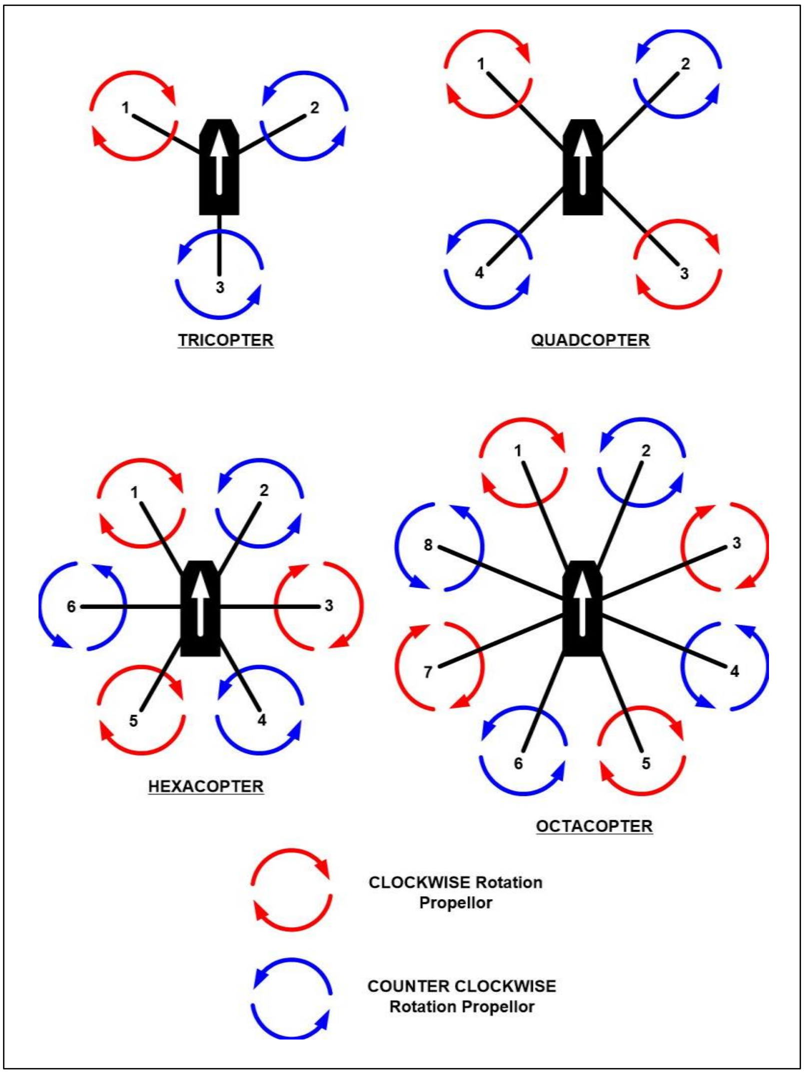



**Illustration 3.8:** **Common Multicopter Rotor configurations**

As with helicopters, multicopters suffer from the problem of spinning props creating torque onto the airframe, and thus wanting to spin it as well. The solution is to have props which counter rotate. So, for example in a quadcopter, two props spin clockwise, and two spin counterclockwise. The resultant torques from each cancel each other out and the craft does not spin. This can be seen in Illustration 3.8 above.

There is another version of multicopter airframe. Instead of having only one motor on each arm there are two, one mounted above the arm and one beneath it. This arrangement is known as co- axial, because the motors and props spin on the same axis on each arm, albeit one clockwise and one counterclockwise. So, a typical tricopter would evolve to have six motors, and is denoted a Y6 configuration. Likewise, a quadcopter arrangement would then have eight motors, and its designation becomes X8. These designs have their own advantages and disadvantages; I mention them now because ultimately the design I finally settled on for this research is an X8. Illustration 3.9 alongside provides greater clarity.

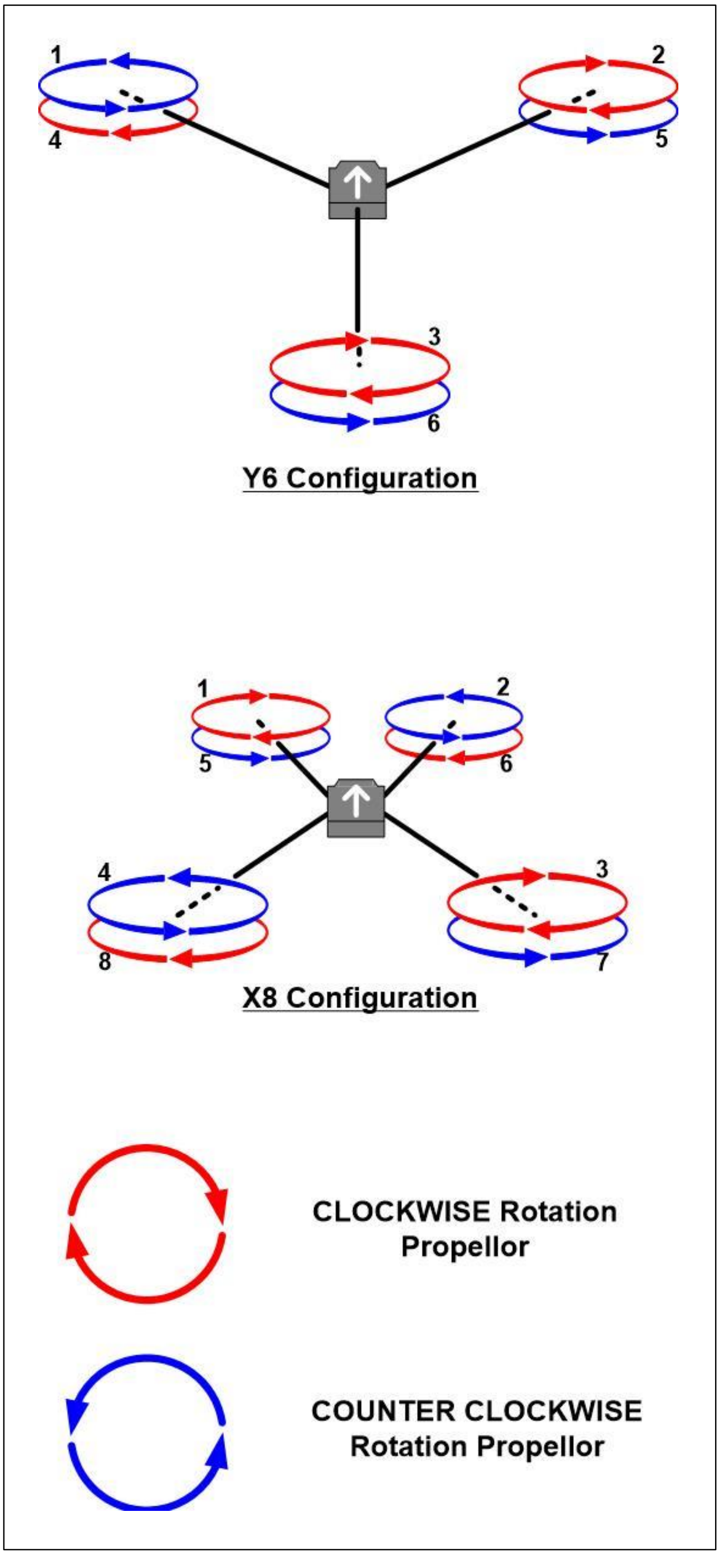



**Illustration 3.9:** **Y6 and X8 Coaxial configurations**

To create the thrust the aircraft needs some sort of power source in the form of engines or motors. In fullsize aircraft – able to carry humans and cargo – these motors are typically internal combustion piston or jet motors using some sort of oil derived fuel source (typically Aviation Gasoline or Avgas), for both aeroplanes and helicopters alike. However, if we turn to miniaturised aircraft, such as 'Radio Controlled' (RC) model aircraft, these motors can be both avgas and electrically powered, and the electrical supply is derived from onboard batteries.

Multicopters are almost exclusively battery powered electrical motors. The props are fastened directly onto the electrical motors, and – to put it simply – the motors are fed varying degrees of battery power to create varying thrust.

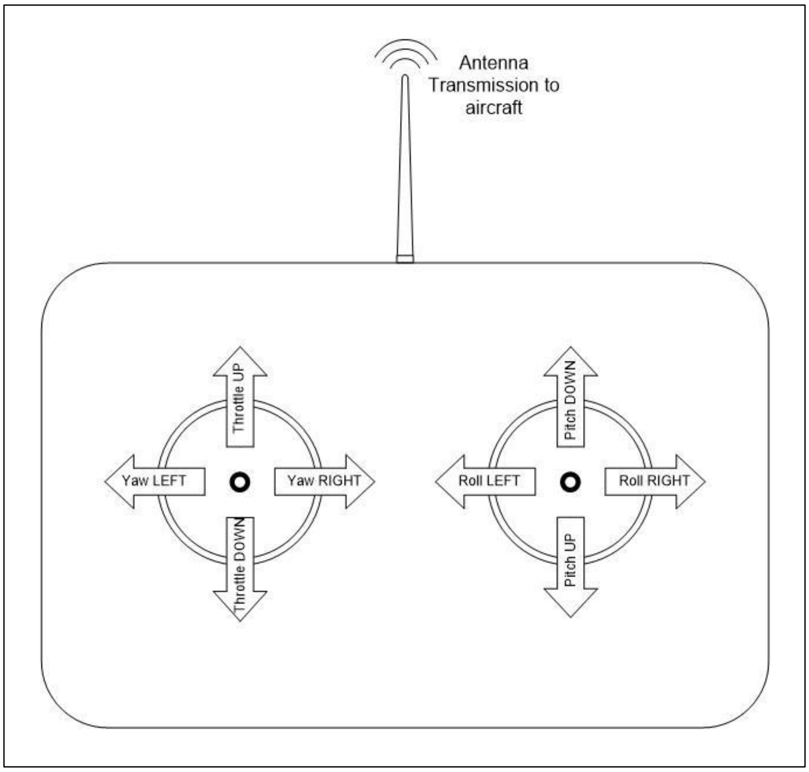
Radio control implies that the aircraft is flying whilst being piloted by someone on the ground, using a radio transmitter to send control signals to the aircraft to change its behaviour in flight. The system thus takes on the title Unmanned Aerial Vehicle (UAV). This transmitter would minimally need four different 'channels' or streams of radio information sent from the pilot to a receiver on the aircraft. These channels are (in no particular order or assignment):

Channel 1: Throttle (or the amount of thrust generated by the motors)

Channel 2: Yaw Left and Yaw Right

Channel 3: Roll Left and Roll Right

Channel 4: Pitch Up or Pitch Down.




**<u>Illustration 3.10:</u> 4 Channel Remote Controller**

These four streams of information are varied by two 'joysticks' on the radio transmitter, often (for multicopter use) arranged as per the diagram alongside. However, it should be noted than in practice there are more than four channels to control other aspects of the aircraft: for example to deploy or retract landing gear, or to trigger a shutter on an on-board camera. But I will detail those which are relevant to my needs later. Illustration 3.10 above shows a simple remote controller with four channels of control.

Gasoline-powered Radio Control aeroplanes are difficult to control and have a long learning curve before someone becomes competent to fly the aircraft successfully. Gasoline powered RC helicopters are even more difficult to fly. The added problem is that when something goes untoward the aircraft is in the air and gravity takes over, the fragile craft plummets to the ground, whereupon it breaks upon impact. This adds to the frustration and expense of the learning curve and is one of the reasons that RC pilots have remained a small select gathering of enthusiasts.

Why then the proliferation of multicopters into society? The growth of sales of these types of RC aircraft has been phenomenal in the past decade. The answer lies in the fact that electric motors – particularly the brushless types found in multicopters – have extremely good control over their speed (i.e., thrust), and with the advent of small lightweight computers which can be built into the airframe this computer can take over the final control of the aircraft. This means that this 'Flight' computer – commonly termed a 'Flight Management Unit' (FMU) - can check if the multicopter is in any way behaving outside the envelope of good flight and correct for poor pilot control or insensitivity. Essentially the computer can temper or dampen the flight command inputs from the pilot and correct for poor skills on the pilot's behalf. The on-board flight computer automates to a lesser or greater extent the behaviour that the pilot is asking of the flying multicopter. It is worth noting that this overarching computer-aided control is not limited to multicopters but is an essential integration on even the most advanced fighter jets.

This raises the question, what is 'autonomous control' and exactly how much control does the computer have over the multicopter? There is no definitive answer. At the bottom of the scale, that of virtually no autonomy, a very experienced pilot could keep the multicopter in the air and perform aerobatics with it; but this requires many years of experience and a finely tuned skill set. At the other end of the scale – that of full autonomy – by simply flicking a switch on the RC transmitter the aircraft could power up, take off, perform an advanced set of manoeuvres which may involve long flight times over great distances and include artificial intelligence in the decisions it makes, and return to the take-off site, land, and power down.

In between, there is a multitude of different types of autonomy the pilot, who now in some way becomes a computer programmer, can programme the multicopter to behave in a certain way, dependent on the type of flight envisioned and how the multicopter will change its behaviour according to objectives it fulfils along the way. This is the notion of ‘missions’; the pilot programmes a mission or flight behaviour into the computer, and the aircraft carries out this mission.

To enable it to have a level of autonomy the aircraft has to have on-board sensors which detect the behaviour of the craft, and feed back into its on-board flight computer to arrive at correction signals, which it then uses to correct the flight by altering individual motor speeds. There are a large variety of these sensors, and I will briefly explain a few of the more common ones, in no particular order:

Compass: The on-board compass senses the earth’s magnetic field and provides this information to the flight computer. This computer can compare this stream of varying information to determine heading and speed.

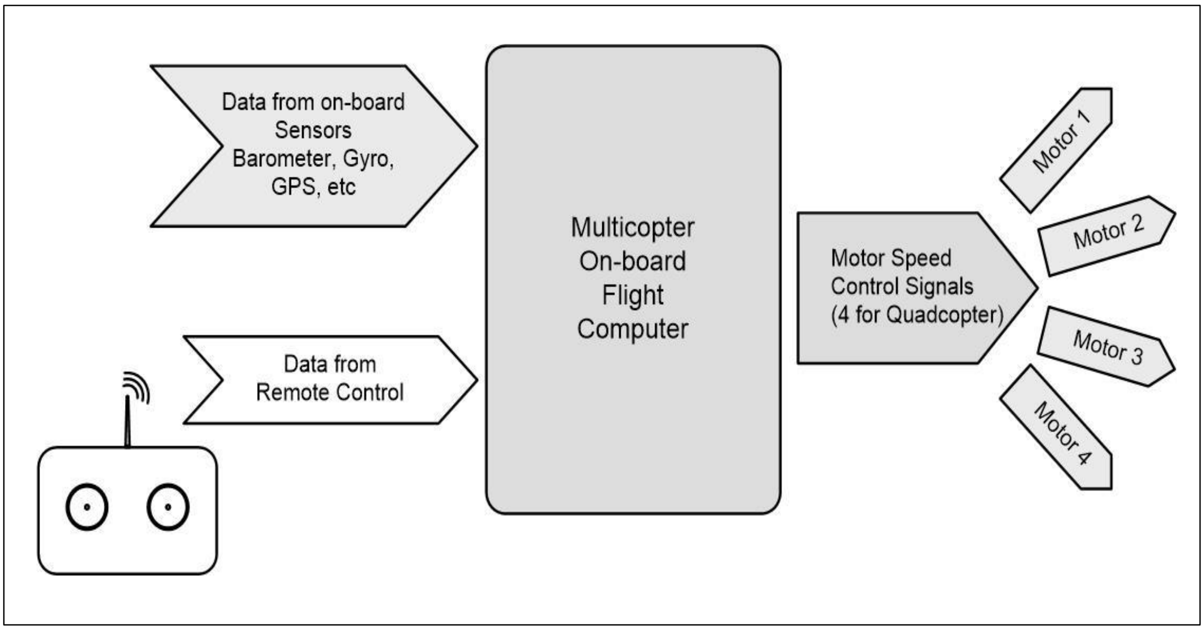
Gyroscope (Gyro): The gyro senses changes from previous flight status in all three axes of Roll, Tilt and Yaw on a continuous basis, which allows the flight computer to either make changes or confirm correct flight as anticipated. The gyro is a 3 axis (x, y and z axis) instrument, and it is updating its information quickly and constantly in flight. It uses a mixture of Inertial Measurement Units (IMU), also in all 3 axes; as well as Accelerometer instruments to gauge a change in acceleration in all the axes again.

Barometric pressure: Measures changes in air pressure as the craft ascends/descends, and the flight computer uses this information to gauge altitude, and changes in altitude.

Sonar (from Sound Navigation Ranging): Sonar is a system which sends out audio waves from the aircraft, facing downwards, and then measures the time it takes for these waves to reflect off the earth's surface and return to the Sonar unit. This time difference is then computed to give an altitude above the earth's surface.

Lidar (from Light Detection and Ranging): Similar to sonar, but the unit bounces light waves off the ground to give a measurement of altitude above the earth.

Global Navigation Satellite System (GNSS): This is a system which uses a multitude of satellites orbiting around the earth. Several of these satellites are above the horizon at any particular moment and in any particular location. These satellites provide data which can be referenced, and their position above the earth interpreted by a GNSS receiver on earth to accurately place that receiver on the earth by means of triangulation algorithms. The receiver can give a reading of latitude, longitude and altitude based upon its interpretation of the signals from the satellites. It is worth noting that Global Positioning System (GPS) is a generic term for this system, used worldwide; but in actual fact it is an American developed and maintained network. There is also a European network known as 'Galileo', a Russian system known as 'GLONASS', and a Chinese and Asian Pacific system known as 'BeiDou'. All four are collectively called GNSS but are often colloquially termed 'GPS', and a good GNSS/'GPS' ground receiver can receive and interpret information from all of these systems.




**<u>Illustration 3.11:</u> A Basic UAV flight control system**

Illustration 3.11 above constitutes a simple Unmanned Aerial Vehicle, or UAV, a pilot on the ground with Remote Radio Controller controlling the aircraft; with the aircraft taking on some of the decision-making in the flight control of the craft via the sensors and on-board flight computer. However, it is possible to couple a Ground Based Computer to the drone, to programme it to perform in particular ways. When we introduce a ground-based computer, the system becomes known as an Unmanned Aerial System (UAS). This ground-based computer now can not only programme the aircraft as to how we wish it to perform in the air but can also be used to programme into it an entire flight path (following a series of 'waypoints') and respond to outside signals or prompts. Illustration 3.12 below shows this configuration. UAV's and UAS's are commonly known as 'Drones'.

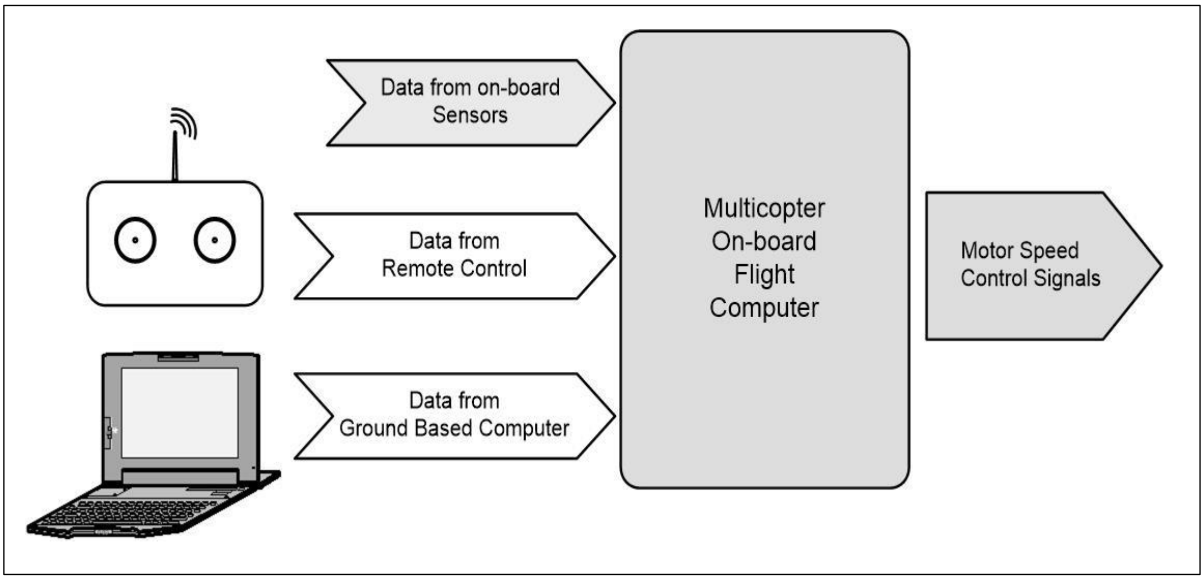



**Illustration 3.12: A basic UAS configuration**

This computer can also receive information from the drone, so that it can be logged and interpreted, and used for checking and analysis of the aircraft's flight. This programming can be either directly by a cable interface when the aircraft is on the ground and close to the ground computer, or it can be via radio signals – telemetry – when the craft is flying. Note how in the Illustration 3.13 below the communication is two-ways, so that the ground computer and the aircraft can both send and receive this telemetry data.

When the craft is flying, particularly when it is a good distance away from the pilot, or when it is completing a mission in auto, the pilot on the ground needs some sort of feedback as to

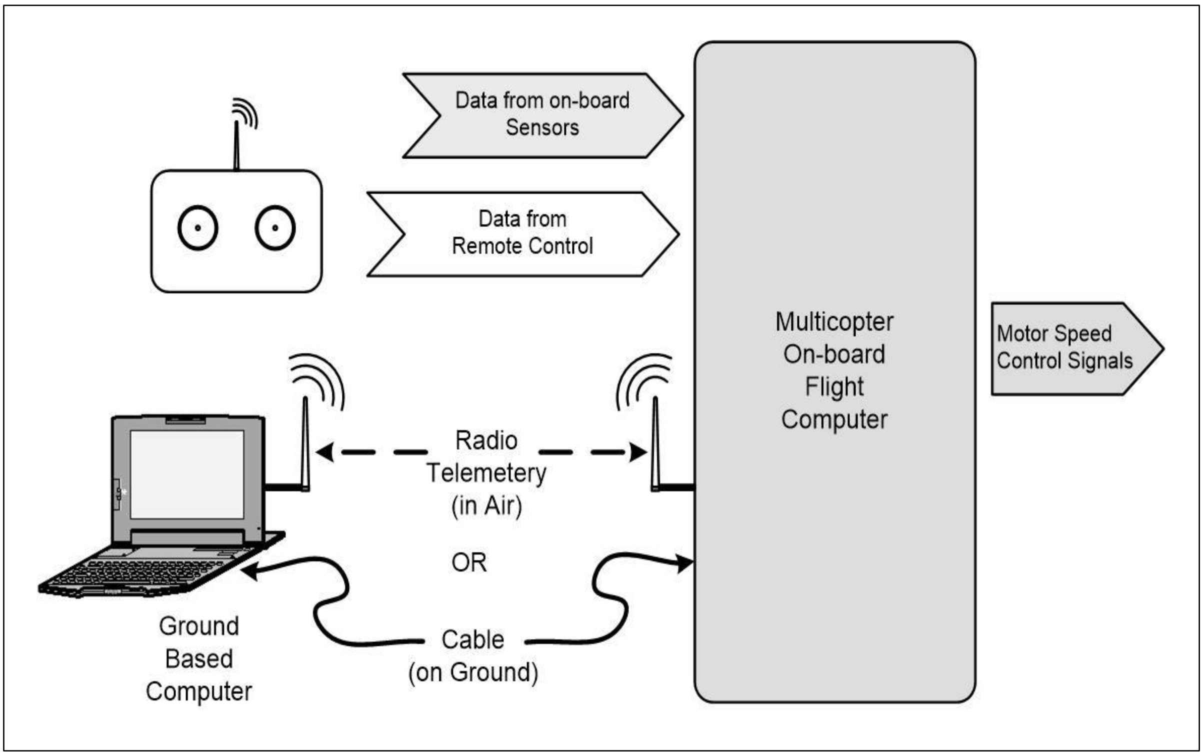
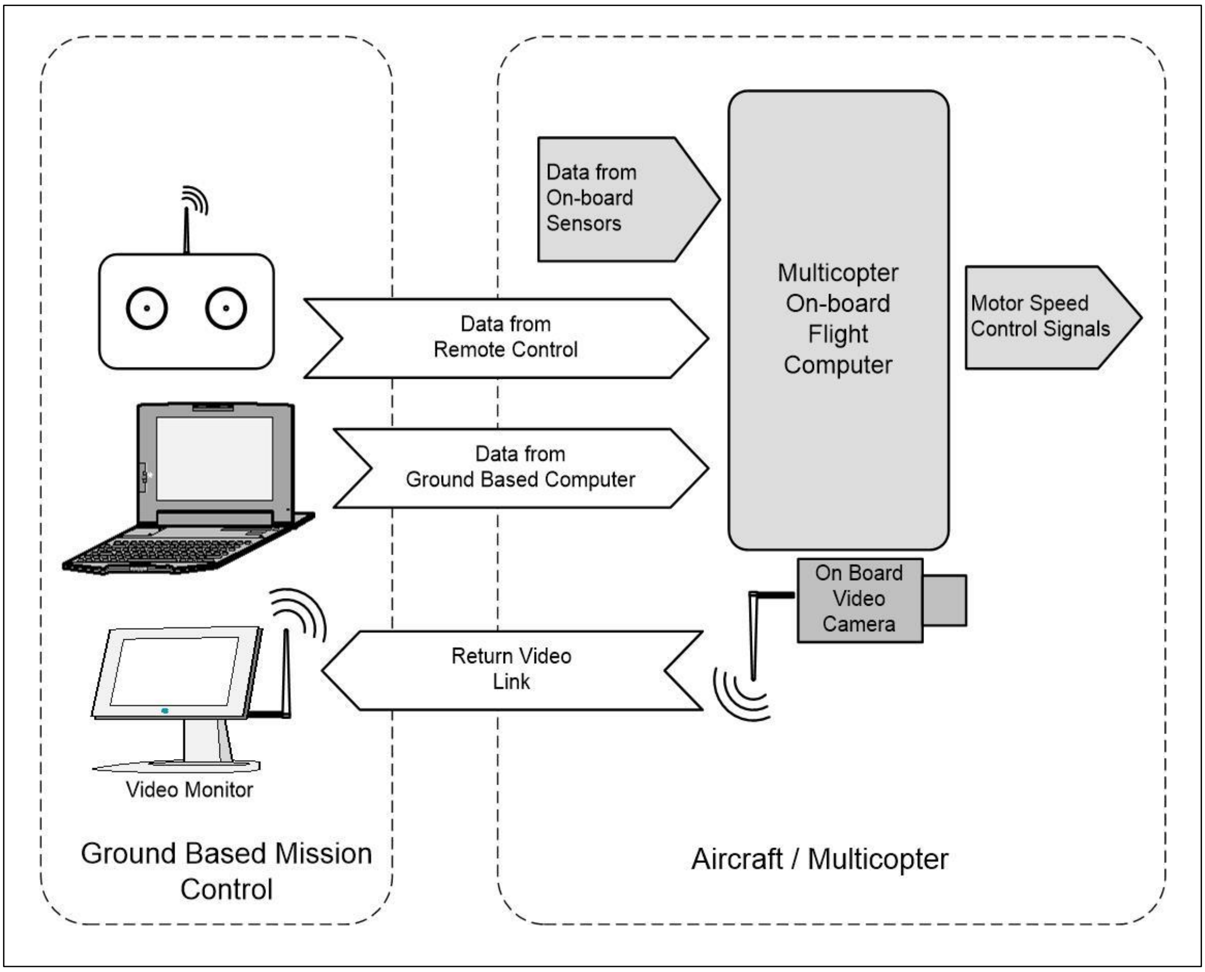



**Illustration 3.13:** **UAS with Telemetry data link**

the status of the aircraft: for example, its heading, its velocity, and its elevation. So, it is very common to incorporate an on-board video camera, which transmits images back via another radio link to a video monitor (or video 'goggles') located at the base on the ground. Now the remote pilot can get a 'bird's eye view' of how the aircraft is performing. This system is known as First Person View (FPV), and it takes a variety of forms. In absolute terms, the camera on board the aircraft typically points in the direction the craft is heading (in other words, it is fixed on the nose of the craft pointing forwards); however, it is possible to have the camera pointing at some other position to where the craft is headed by positioning it on a moveable mount – commonly known as a gimbal – which can change direction independently of the moving aircraft.

It is also very common for the telemetry data from the flight computer to be overlayed as text on top of these video camera pictures. Thus, the pilot can in one image see not only the camera pictures, but can also monitor important flight information, such as range covered, or battery power remaining; or many other parameters as are needed to manage the safe completion of any flight or mission. Illustration 3.14 below shows how this is achieved.

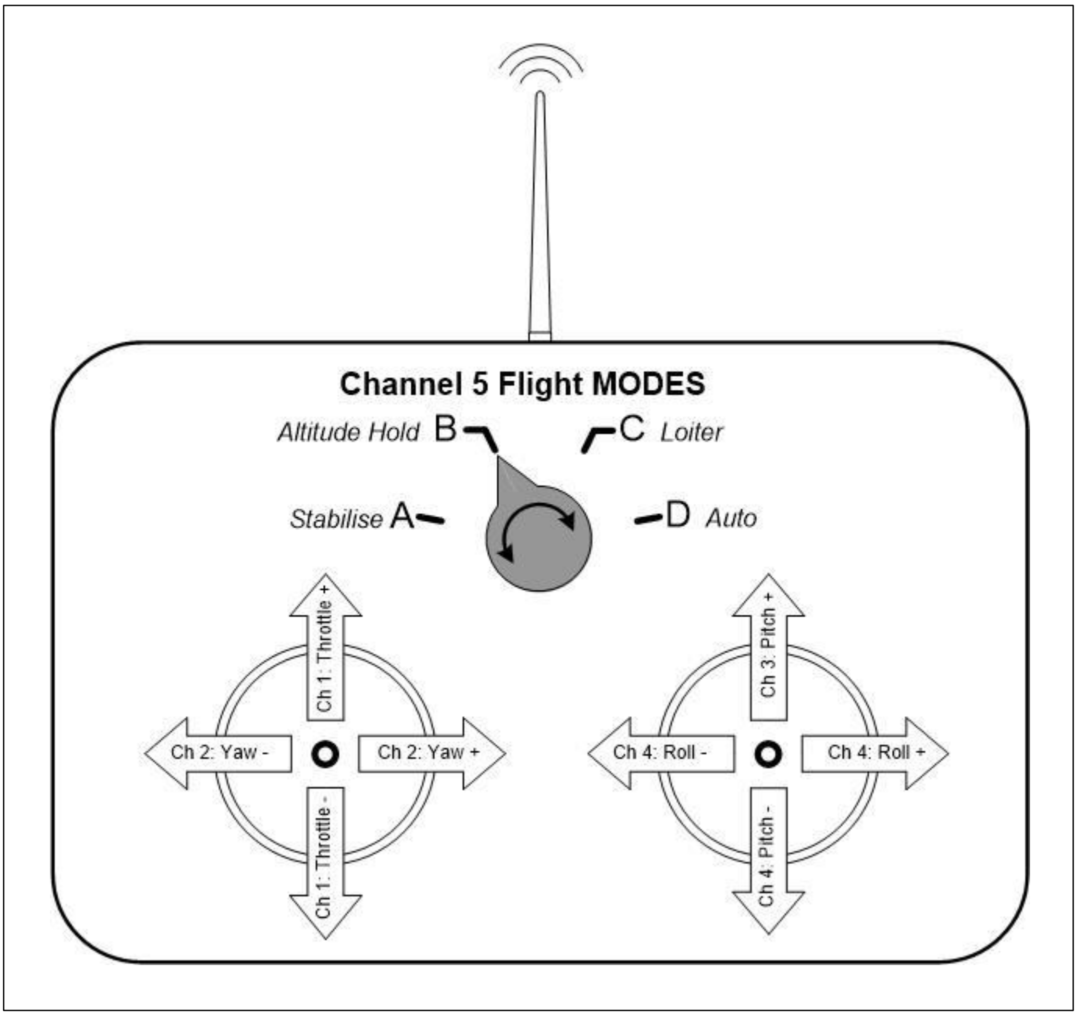



**<u>Illustration 3.14:</u> UAS with Return Video Link**

When flying in UAS configuration, where the aircraft is set up using a ground-based mission control computer, it is not necessary to be operating the Radio Control transmitter, the mission computer, as well as watching the video monitor. It is too much to try and do (for a single pilot). There needs to a certain amount of simplification, and the way to do this is to take the mission ground computer out of the system during flight and use it only for pre-programming and data download and analysis when the craft is on the ground. To do this the remote Radio Controller is manufactured with more than four channels (those needed for Thrust, Pitch, Yaw and Roll), and in reality can have many more channels. We can thus allocate these extra channels to extra functions over which we want to have control.

Imagine a transmitter with five channels. The first four (see above) are needed for basic flying. We can now programme (using the ground-mission computer to do this) the onboard flight computer to recognise changes in this fifth channel to perform various different flight characteristics. As an example, we could tell the flight computer that 'Channel 5' is allocated to 'Flight Modes' of the aircraft, and that there will be 4 different variables (for example, a switch with 'A', 'B', 'C', and 'D' positions) which will correspond to a variety of Flight Modes we programme into the on-board flight computer. Now whilst we are flying the craft (with our hands on the Radio Controller and our eyes on the video monitor) we can change the Channel 5 switch on the controller to change the way the aircraft behaves; importantly without having to operate the ground-based mission computer at the same time.

Illustration 3.15 below gives an example of this. It is the familiar four-channel Radio Controller, but now with a fifth channel added in the form of a four-position switch, which we have configured in the UAS chain to represent 'Flight Modes'. Position A is 'Stabilised' (flight), Position B is 'Altitude Hold', Position C is 'Loiter' and Position D is 'Autonomous'.




**<u>Illustration 3.15:</u> Radio Controller with Channel 5 Flight 'Modes'**

Some explanation of the various flight modes in the above example, and how the various sensors and programming contribute to the overall flight, is pertinent. Firstly, it should be noted that I am using terminology from the flight software I chose for my experiments, Ardupilot. There are many different flight control software variations, some are open source (such as Ardupilot above), but the majority are proprietary. Each version of software has its own terminology for its options such as flight modes (yet they often mean the same as some other software/terms). I am going to use the Ardupilot ones.

Stabilise: This is the most basic of the flight modes. The flight computer uses its on-board gyro and compass to correct for insensitive pilot control or erratic flight behaviour to 'smooth out' the flight. The pilot has full control over Throttle (and thus altitude), Roll, Pitch and Yaw, but the on-board flight computer makes sure that these cannot go beyond certain parameters which ensure smooth and safe flight. It literally 'stabilises' the flight. It is worth noting that in each and every flight mode there are adjustments within the software as to how much the pilot wishes the flight computer to intervene, depending on personal choice or the stage of the flight or mission.

Altitude Hold: The craft will attempt to maintain a constant altitude using its Barometric Altimeter, as well as the gyros and compass. In other words, the flight computer will receive information from the altimeter and use this to control the thrust/speed of the motors. The pilot can independently move the craft forwards, backwards or sideways (i.e., Pitch Up/Down and Roll Left/Right) and Yaw the vehicle but, as there is no control over thrust or elevation changes, the craft will attempt to maintain a steady altitude during these manoeuvres. If it is so equipped, and if the conditions are conducive to it, the craft will also use its Sonar and Lidar to inform of altitude changes and corrections.

Loiter: The craft maintains one position in the air, in other words it 'loiters' in one place as soon as this flight mode is engaged. The craft uses information from gyro's, compass, altimeters and GNSS to constantly monitor its position, and correct to remain where it is and pointing in a particular direction by slight autonomous corrections to thrust, pitch, roll and yaw. Loiter is the 'simplest version' of 'fully autonomous' flight, and once you have achieved a stable Loiter whilst tuning the aircraft, the craft is ready to perform more complex modes. Once again each of the modes is individually configurable; you could for example programme the Loiter mode to have Yaw still manually controllable by the pilot. In such a case, the craft will maintain a steady position in three-dimensional space but be able to Yaw where it is stationed, and in so doing have a 'look around' at the area below it.

Auto (Autonomous): A 'Mission' is pre-programmed into the flight computer. This mission could include various places the craft has to fly to, the altitude it should maintain along the way, the velocity at which it should progress, whether it will engage any other flight modes along the way (for example, to Loiter at certain places), and when it will return to the launch area. There are innumerable variables to programme into Auto flights. The flight controller uses its on-board altimeter, gyros, compass, GNSS and whatever other sensors which might be of assistance or installed on the vehicle. The controller can even apply other logic to decide on the vehicle's behaviour: for example, monitor battery levels, work out how far from the base it is, and how long it will take to return, and once the battery level approaches this minimum threshold, decide to abandon the mission and return immediately to base (a flight mode in Ardupilot known as 'Return To Launch' or RTL).

The Ardupilot software has different versions for different vehicles. Ardurover is used for ground-based wheeled vehicles, Arduplane for fixed-wing type RC aircraft and Arducopter for multicopter type aircraft. The software used to programme the flight computer is known as 'Mission Planner'. There is also a variety of other software I will need in the final configuration of the system, but I will detail these as the need arises.

In writing the above chapter I have relied on knowledge accumulated during my general design experience, online forums such as *DIYDrones*, publications such as *SUASNews*, and books such as *Understanding Flight* by David Anderson and Scott Eberhardt (2009).

# **CHAPTER 4**

## **Early Forays into the World of Unmanned Aerial Vehicles**

*'If you think it's going to be easy, you will in all likelihood never get it done.*

*If you think it will be impossible, you will probably find a way to do it.'*

(Donal Fitzpatrick, 2011)

I met Professor Donal Fitzpatrick, at the time Head of the School of Art and Design at Curtin University in Perth, Australia, in May of 2011. Prof Fitzpatrick was a visiting academic to the Faculty of Arts and Design at the Durban University of Technology. He had been invited over to advise our Faculty on the development of a Creative Outputs Policy in such a way that these research outputs could attract subsidy. His School was a leading proponent and recipient of such subsidies in Australia.

Over lunch one day we were chatting about what sort of research I would be interested in. I had recently finished my Masters, and it was time to contemplate my next project. I was in the middle of a photographic project (which ultimately led to an exhibition titled 'Flashpoint' in 2013) and I was telling him about it. He asked if it could form the basis of a PhD and I said that possibly yes, but since I worked and taught in video production, I would want my PhD to be video-based rather than photographic. So, he then asked what I would like to do as a PhD. My reply was to find some sort of miniature helicopter which would follow off road motorcyclists while they raced, and capture footage of them. He was full of enthusiasm for this idea, and suggested I tackle it. My reply – and I still recall it clearly – was that I had no idea how it could be done, and actually thought it to be an impossible task. He then said the words above. I have never forgotten those words, and every time I have had to 'pick up the pieces' – literally and figuratively – in my research and experimentation over too many years into this PhD I have reminded myself of them. It was not going to be easy, and it never was throughout the time I worked on this project. There were times of immense satisfaction and achievement, but these were in the minority compared to how often I would be picking up the pieces of yet another crashed and broken drone and left wondering if it were worth it, and how I would find a way to overcome the latest problem.

I still have my handwritten notes which I jotted down on a few sheets of paper back in 2012, with some thoughts of how I would like the coverage of off-road motorcycling to evolve using small flying craft (Annexure A). At the time, the only aerial footage available for this sport was from helicopters. I thought that something smaller – and cheaper – could add tremendously to the television coverage. In my notes I talk about the limitations of ground-based videos, and how it would be advantageous to have a craft which could automatically track with the rider with a camera on board. At the time, I knew nothing about drones. They were not in the mainstream yet, and certainly not as ubiquitous as they are as I sit here writing this in 2021. They were – to me at that stage anyway – just a dream.

I mentioned this to a friend of mine, a fellow enduro rider, Mark Hewson. Mark is an IT specialist, and he was similarly enthusiastic. At the time I still hadn't started much research into this dream (I was still completing my photographic essay/exhibition which had occupied me for several years and was taking up a lot of my time). A few days after talking to Mark an email arrived in my in tray from him. It was a brochure for a drone from a company called draganFLY. It showed a drone – actually a complete 'system' - for a product of theirs which could be programmed to fly autonomously. I was instantly intrigued by the capabilities of this product; here was a small drone which could be used to fly a pre-programmed path using a 'base station' and return to the user afterwards. It was mainly aimed at users who wanted to do aerial inspections of buildings and bridges, but the merits were obvious for my intended application. The cost, however, was prohibitive; at that time over R250 000.00 for the 'base' model which did not even include a camera or gimbal mounting for the camera (and that in the days when the Rand/Dollar exchange rate was far more favourable than it is now), and far beyond my means. However, it kindled the flames of my imagination.

I wondered about the costs involved, and whether there were some way to do it cheaper. Thus began an internet search into the world of drones and unmanned aerial craft and systems. The search led me to online forums for drone and radio-control enthusiasts, and the one which piqued my interest the most was a forum called 'DIYDRONES' (https://diydrones.com/). (It should be noted that at the time the word 'drone' in the forum title was being hotly debated by the members, mainly because of the negative perceptions created by the military using drones; and the forum was canvassing an alternate title. The term became a lot more common over time and is completely acceptable to mainstream society now.)

So, here was a collection of enthusiasts who were *building their own* drones. Not only were they building them, but they were also developing the software for flight; and this software was freely available as open source. It was an incredible collection of individuals, each contributing in their own way, some with small advancements and others with far larger influences. Inherently they were driven by the vision that they were at the forefront of a global disruptive technology, one which was going to change the world. I was innately drawn to their attitude, as well as their values of sharing knowledge. Most importantly, I was enthused by the fact that I could do this myself, and for a much lower cost than initially thought. The flame started to burn a little brighter.

It must be said that the vast majority of information I have absorbed about drones –and particularly UAS's – has come from online forums. In particular I have used DIYDRONES, RCGroups (https://www.rcgroups.com/forums) and the ArduPilot (https://ardupilot.org/ardupilot/index.html) groups and forums. There is a massive repository of information in these sites, and the members are very active. They are more than willing to share their experiences and information, and readily answer any queries with possible solutions to problems one might encounter during development.

On the DIYdrones site there were startup online vendors selling parts to construct drones, from electronics to frame parts and indeed complete kits. I decided that I was too much of a novice at the game to select and match up individual components to build a drone. I instead opted for buying a complete kit from one of the vendors, '3DRobotics', for a very basic quadcopter. I use the word 'basic' looking back with the experiences I have since had; at the time it was all very new to me and appeared advanced and daunting. The kit included frame parts such as mounting boards, arms and legs; as well as motors and other electronics such as the flight controller and electronic speed controllers. I had to add a radio remote controller and a few batteries and props to the order, and then wait for it to arrive from the USA. This was early 2012.

At about the same time I decided to turn this into my PhD. Actually, I enrolled for a D Tech in Design at the Cape Peninsula University of Technology, under the supervision of Prof Johannes Cronje. This is largely because the PhD which I am currently completing did not exist at the time (it was only introduced in 2018) and I felt that 'Design' was the best 'fit' for the work I wanted to pursue. I was also very fortunate to be granted funding by the National Institute for Humanities and Social Sciences (NIHSS), and this funding was a tremendous help through the years of experimenting. When the DUT PhD in Visual and Performing Arts was introduced, I sought and was granted permission for a variety of reasons by CPUT and NIHSS to transfer my studies across to DUT.

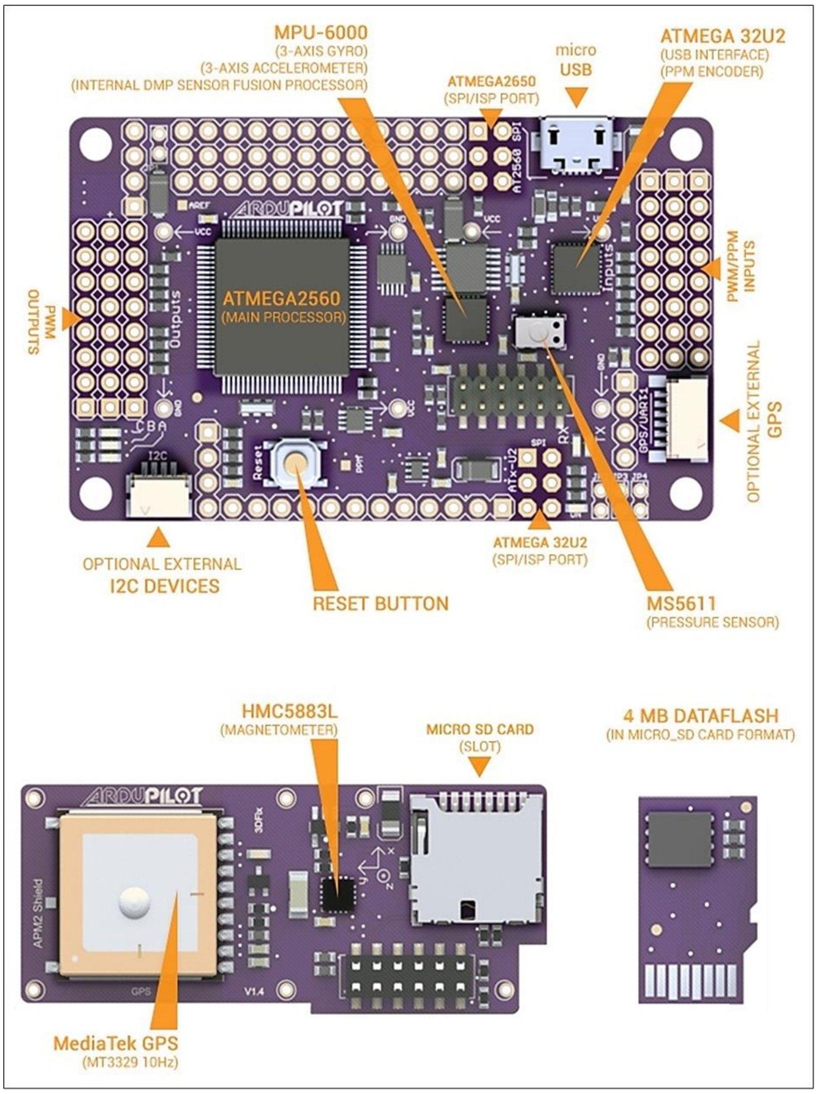



**Illustration 4.1:** The APM2 Flight Management Unit

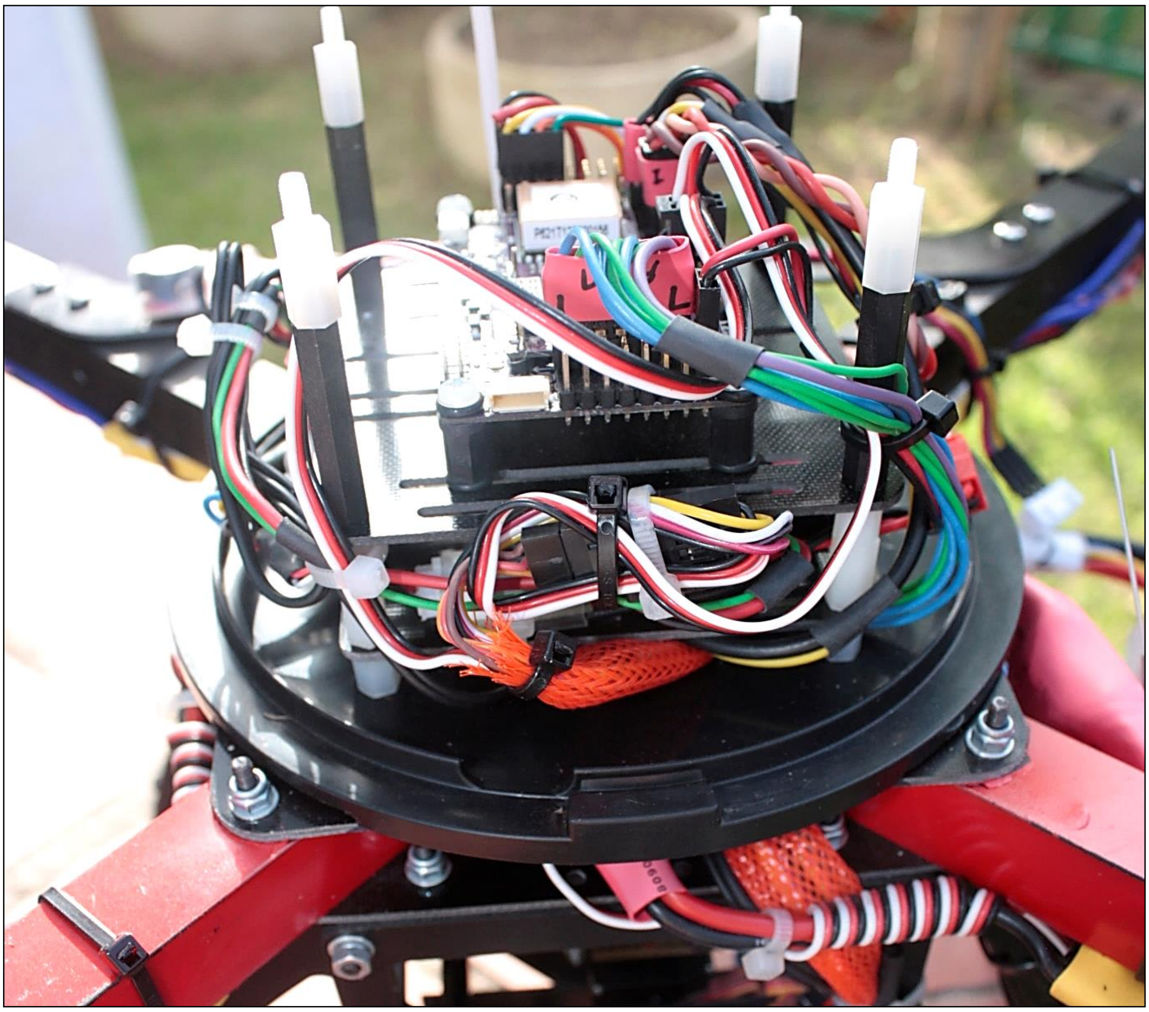
The 3DRobotics Quad kit includes an 'ArduPilotMega 2' (APM2) board. This board contains the flight computer as well as sensors such as GPS, IMU's, Compass, Gyros and barometric altimeter. It has input interfaces for the radio control receiver and other sensors such as external GPS and Sonar, as well as output interfaces for motor drive, gimbal control and the like, and is known as a Flight Management Unit (FMU). It also has a data logging card and USB ports for programming and data download. The board is designed to run the ArduPilot/Arducopter software, which is based on Arduino programming code. Illustration 4.1 above shows the APM2 board and gives some idea of the on-board components.

When the kit arrived, I began the assembly. There was still much to be done, and it took a couple of weeks. It requires that the buyer do all the cabling between the various components, as well as lots of mechanical setup. Luckily, I have a background in electronics and soldering, as well as years of tinkering and fabrication in a fairly well-equipped workshop at home. I made several modifications to the original kit – from advice on the forums – including but not limited to using an old Compact Disc case to house all the electronics. Illustrations 4.2 and 4.3 below give some idea of the assembled quadcopter, although it must be noted that the pictures show the final iteration of this particular craft, with several changes and added components from the original one. The initial quad was very basic and had just enough on it to fly.

**<u>Illustration 4.2:</u> Assembled 3DRobotics Quadcopter**

Next was to do basic checks and calibrations of the sensors. This is done via open-source software known as Mission Planner (https://ardupilot.org/planner/) developed largely by an American Michael Oborne and an Australian Andrew Tridgell. I will talk in greater detail about Mission Planner further into this research, but what is relevant now is that the software is used to communicate with the quadcopter, particularly the APM2 or flight controller computer, and set the drone up for flight. These are the basic checks:

- Calibrate the magnetometer – to the magnetic declination for the area of the world you are flying in, so that the compass reads correctly. At the same time, check for magnetic interference for drone components (such as the battery) and change these so that they have minimal effect.
- Setup and calibrate the accelerometers to the frame type and orientation which you are building.
- Configure and calibrate the various radio control channels so that the drone responds to the correct input signals.
- Calibrate the voltages on the boards, as well as calibrating the electronic speed controllers for various throttle settings.



**<u>Illustration 4.3:</u> Assembled APM2 and associated electronics**

- Check the vibrations of the craft, and if necessary, modify the vehicle to reduce them if they are over a certain limit. Vibration in the drone is very critical since even a small set of vibrations can have a decided effect on the very sensitive accelerometers.

Having checked and rechecked I decided to attempt my first flight. There was a large amount of trepidation on my part for this attempt. I have never had much of an interest in Radio Control (RC) aircraft before I started this project. I understood the basic principles involved and had friends who pursued it as a hobby. In addition, I had not grown up in the 'computer gaming' era, and similarly had never held much of an interest for these either. Why is this a problem, you may ask? The reason is that computer games (such as the Sony 'PlayStation') often use a console which is held in both hands, and largely operated by the left and right thumbs. This is the same way the Radio Controller is operated. Computer gamers thus develop an extraordinary dexterity and coordination with their thumbs. So not only did I not have the innate brain/hand connection between throttle, yaw, roll and tilt from flying RC aircraft; I also did not have the dexterity in my thumbs to do this without lots of thought. Before this project was over, I was going to have to teach myself a whole new set of skills.

However, there was no way to escape the first flight. I had told myself 'baby steps', and all I wanted to do was get the drone into the air, let it hover, and land it safely. I chose my front garden for this purpose. Our front garden is far from ideal for flying, it has buildings, walls and trees surrounding a very small open space. (As an aside, I have since done countless test flights – they could more correctly be called 'hops' - in our front garden. Every time I modify something, or repair something, or replace something, or want to check or calibrate something, or test a new craft I have built, or even just check battery condition, I have done it in the front garden.)

I set the craft up, and did all the pre-flight checks, and then 'armed' it. Now I knew that the next time I even slightly increased the throttle it could fly away. My heart was in my mouth, a huge sense of anxiety. Slight throttle, anxiety level increases in unison. Slightly more throttle, craft starts shaking and straining, anxiety higher. Slightly more throttle, craft starts to overcome gravity, more anxiety. Slightly more throttle and 'whoosh' – it rises up rapidly.

Shut throttle! Craft falls immediately to the ground, a rough landing, but thankfully nothing damaged. Catch my breath. Try again.

I must say that I have never lost this sense of anxiety every time I launch one of my drones. It is always there, particularly – as will be seen later - when I send the craft off on an autonomous mission. You have to place incredible faith in yourself that you have ‘done everything right’, because once it sets out on its own you have far less control over what happens next (there are safety precautions you can pre programme and I will also deal with these later).

Try again. Pay particular attention to throttle. Put it in the air, not too high! Bring it down a bit, not too low! Hover. Hover! I’ve got it hovering! But its drifting towards the fence, bring it back! Which thumb? Which control? Which way?  Land it! Gently! Breathe again! Try and shake off the adrenalin.

And so it began, countless hours of practice, practice, practice. A sense of anxiety each time it flew, a sense of exhilaration each time it was flying, a sense of wonder as I progressed through each of the baby steps. Countless crashes, many walks through the long grass or bush or climbing trees to recover the craft, lots of repairs to broken bits; but a sense that I could do this, I could find a way to achieve – what to me initially had the seemed to be - the impossible.

I am fully aware that the previous paragraphs have introduced some emotion into my writing, and I am also aware that dissertations should be largely fact-based and unemotional. However, I cannot write this without emotion, since I have encountered the full gamut during the time I have been experimenting. On more than one occasion, I have done round trips of almost 2000 kilometres, only to return home with not even a single second of video footage I could use. Even seemingly minor drawbacks such as having an on-board SD card get corrupted have proven to be major setbacks. And then in March of 2017 probably the biggest setback of all, our family were the victims of a home invasion. During that crime we were tied up, held at gunpoint and assaulted, and lots of goods stolen. Of relevance to this thesis is the fact that both of my laptops, as well as a hard drive which had all of my most recent work, were stolen. It was a major setback and left me depressed and dejected about the prospects for this project. I am immensely grateful to the people around me who convinced me to start again, pick up the few pieces of work I had left, and attempt to complete what I had begun.

On the other side of the coin, there were many highlights, some major and some minor; but each of them uplifting and a reason to continue. One of them happened quite early into the journey, and I will soon elaborate on this.

I live in a built-up suburban area. Our front garden was far too small to do any flights of consequence. I used local sports fields to do this, but because these fields were also used by the public and members of those sports clubs (and schools) I could only fly there during the early hours of the morning, or when the fields were not being used by the club or school such as during school holidays.  Illustrations 4.4 – 4.6 below show these locations. Of the three I used the Westville Athletics Club field the most.


**<u>Illustration 4.4:</u> Westville Athletics Club**


**<u>Illustration 4.5:</u> Westville Hockey Club**


**<u>Illustration 4.6:</u> Westville Boys High School**

The first few flights at Westville Athletics Club were harrowing. This was no longer just my front garden with a hover and perhaps a small side to side movement, all with the drone facing in one direction (which means that the controls are intuitive because they have the same effect on the drone as the position you put the control ‘stick’ in to). Now the drone was moving away from you. How far away is it, how fast is it moving? Not too far! Bring it back. Not too high, bring it down! Now it’s moving towards you, facing you. The stick movements are reversed, move the stick left and the drone moves right! Think! Concentrate! Now it’s moving sideways, move the stick left if the drone is moving left to bring it towards you…. now it's moving right so moving the stick left makes it go away. What about my surroundings? Where are the trees? Now the drone is high and it's only a silhouette…what is the orientation? Now it's far away and too small to see clearly, which stick brings it back? Intense concentration, losing control, trying to regather the drone and my senses before it flies away or crashes. So much to learn, and a very expensive 'toy' to crash if something goes wrong.

**Illustration 4.7: Crash into trees**

Some crashes. Some close calls. A few times it ends up in the trees and I have to climb the tree to recover it. Illustrations 4.7 – 4.9 alongside which show some frame grabs captured by the on-board camera; this happened quite a few times. Learning to deal with the wind which wants to sweep it away and you have to fight it. Mental note to self – don't ever fly this thing over water. So much to learn, and reading online forums isn't really going to help.

**Illustration 4.8: Crash into trees 2**

**Illustration 4.9: Recovery Operations**

After quite a few days of practice (and repairs), it was time to tackle the next step, a camera on board.

To do so I first had to purchase, and then fit, a camera gimbal. My intention was to use the ‘GoPro’ series of miniature cameras on the drones. At the time I had a GoPro2, but I would upgrade to later versions in subsequent airframes.

The first step to doing this was to install a ‘gimbal’ onto the quad frame. A gimbal is a mechanism which the camera mounts to and is designed to be able to pivot the camera. The reason for a gimbal is to keep the camera positioned and pointing in the same direction as the airframe pivots above it. You could think of it as trying to keep the camera ‘level’. So, as the craft pitches forward, the gimbal corrects by pitching backwards, and keeps the camera level. Similarly, as the airframe rolls to the left, the gimbal rolls to the right, and in so doing the camera remains level. This is necessary because without any gimbal (and if the camera was fixed solidly to the airframe) the camera would exhibit images which also roll or pitch up and down. A ‘2-axis’ gimbal (the most basic kind needed for multicopter flight) corrects for roll and pitch, but you can also get 3-axis gimbals, the third axis correcting for yaw. I will refer to this later. At the time, however, I only installed a 2-axis version which I had purchased. You can see this gimbal in Illustrations 4.2 above and 4.10 below, as well as the support for it which is screwed onto the frame of the quadcopter. This particular gimbal frame also came


**<u>Illustration 4.10:</u> 2-Axis Servo gimbal with camera**

with landing ‘skids’ visible in the pictures, I had removed the individual legs of the quad with which it had originally come. I don’t have pictures of these early quadcopter legs, but they are the same as you will see in later iterations of the multicopter, as shown in Illustration 4.17 below.

There are two major forms of gimbal available nowadays, the ‘servo controlled’ gimbal and the ‘brushless’ gimbal. At the time however, brushless gimbals had not yet been invented, so I purchased a servo type. Servos are small motors with linkages which can move back and forth; these linkages control the roll and pitch pivoting. The servos are driven (in this case) by control output signals from the APM2 flight computer board. The board has gyros and accelerometers on board, and it uses these to calculate the roll and pitch of the craft, and at the same time generate correction signals to inform the gimbal as to how it should behave.

Once it was all installed, I attached a camera, did the necessary calibrations and a quick test in the front garden to make sure everything was secure and working, and it was time to get some video in the air. At this stage, I could only record on the camera and download the footage after flight from the camera-recording SD card. As yet I could not see images whilst in flight, that would only come later once I had installed a video link and monitor on the ground.

My first flight with a camera on board was at the Westville Athletics Club. I was very aware that now, if anything untoward were to happen, it would not just be the loss of the quadcopter, but now a camera as well. In light of this I did not want to be too ambitious. Keep it above the field, not too high, land it safely. Make sure you start the camera recording before you take off, which might be strange to say, but with all the other pre-flight checks I go through beforehand something which is easily overlooked; and it just happens to be the essence of why the craft is being put into the air. And something which I have learnt the hard way over time…

After a few modest flights, time to pack up, go home, and download the card with the footage.

And there it was – the 'aerial view'. Completely different to looking at the drone flying from the ground. The field becomes a square of green. Trees spread far into the distance. Houses neighbouring the field which are hidden from view by high walls become gardens, and swimming pools, and a mosaic of properties. Roads which were merely alongside the field now have direction, and the cars on them which were 'just passing by' now seem to have purpose. The cell phone tower which was always 'up there' suddenly becomes 'down there'. A completely new way of seeing things, all from my little home-built quadcopter which is released from the clutches of gravity. It was truly inspiring. But although it seemed like I had attained a veritable Everest, I had to remind myself that I had only climbed one more rung at the bottom of a very tall ladder.

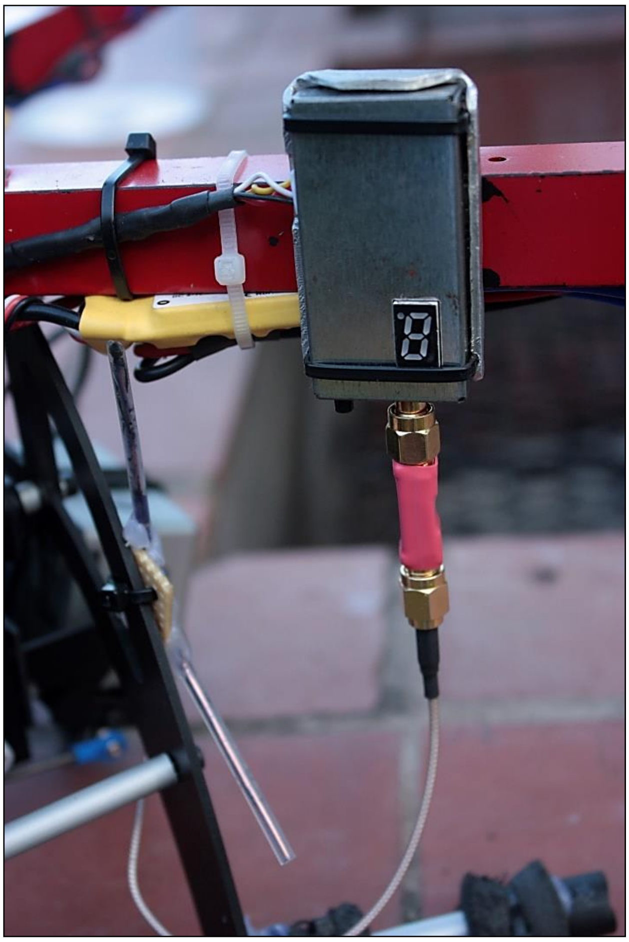
More flights with the camera on board. Still no way of seeing what I had on camera until I returned home and downloaded the card. Pushing the boundaries step by step; a little higher each time, a bit further beyond the boundaries of the field; testing my inquisitiveness but held back by my fear of losing the drone. Testing my faith in my slowly improving flying abilities.

**<u>Illustration 4.11</u>: A Bird's Eye view**

Then one day a hawk circled round, it also being inquisitive at this strange creature (see Illustration 4.11, above). There it was, proof that I had stepped out of my grounded constrictions, and was now occupying – albeit voyeuristically – another world. Literally a 'bird's eye view', except this now was my own personal bird's eye view.

The next rung up the ladder was to have a way of seeing on the ground what was happening in the air 'live'. To do so required mounting a video transmitter on the quadcopter, as well as a system for monitoring the video on the ground while I operated the controls to fly the drone.

After some research, I decided to purchase a video transmitter/receiver operating in the 1.2 Giga Hertz (GHz) range. I also decided to add a system which integrated the code from the APM2 flight controller into the video transmission. This is known as an On Screen Display (OSD), and essentially it overlays the status of various parameters (you can choose which ones) over the video image; such as battery power, flight direction and speed, altitude, and many more. I also wanted to experiment with building my own antennae for the video link, and after researching this decided to build the 'IBCrazy Vee' transmission antenna, as found in a thread on the RCGroups forum site. The video transmitter and antenna on the quadcopter can be seen in Illustration 4.12 alongside. The same thread also details how to build a matching 'Vee Ground Plane' receiver antenna, which I did as well. This is shown in Illustration 4.13 below, on the top left of the picture.



**<u>Illustration 4.12:</u> Video Transmitter and Antenna**

First Person View (FPV) is a form of flying radio control aircraft where the pilot controls the aircraft by watching the camera which is mounted on board via a form of video monitoring on the ground. Typically, this video monitor takes the form of ‘goggles’ with a miniature screen inside them. These goggles are on your head from before take-off and until after landing since you need to use your hands to put them on and off.

**<u>Illustration 4.13:</u> Receiver with Ground Plane Antenna**

FPV is most often done with a camera which is fixed to the airframe, and as the craft changes attitude in the air it is reflected in the camera and ground-based video monitor. So, as the craft pitches up (or down) the position of the horizon changes; similarly, if the craft rolls left or right the horizon tilts in the view of the camera. This means that you have good feedback from the camera as to exactly what the aircraft is doing. FPV via a camera which is gimbal mounted is a different kettle of fish altogether. There is no change in horizon because the camera is kept level and pointing in the same direction no matter whether the craft is pitching or rolling. You thus have very little feedback as to how the aircraft is behaving, and how you should correct for this behaviour. All the advice you will read or hear about trying to do FPV via a gimbal-mounted camera says it is well-nigh impossible.

In addition, FPV can only work for an aircraft which is flying forwards, even with a camera which is fixed. You cannot fly sideways or backwards, since you have no view of where you are going. From a radio-control aspect, FPV flight is most often employed by fixed wing (i.e.

aeroplane) aircraft, and some truly impressive flights over many kilometres where the aircraft disappears from view altogether for a long time are regularly undertaken by enthusiasts. This is not the same for multicopters. Although FPV is common, it's most often used by 'racing' drones where the camera is fixed to the body of the drone facing forwards, and the drone is only flown in a forward direction. I will return to this problem later in my writing as to how I overcame the challenge of flying sideways or backwards.

In most multicopter drones which are used for filming purposes, there are typically two cameras on board, and two operators. One camera is fixed to the frame and used by the drone pilot for FPV flight. The drone always flies forwards. The other camera is attached to a gimbal which can rotate/pan through 360 degrees (as well as tilt up or down) and is operated by a separate camera operator. The two are in communications with each other.

Knowing that it would be a difficult skill to learn FPV via a gimballed camera, I decided that I would need to have sight of the drone visually as well as the video pictures coming from the camera. If I were wearing goggles, I would not be able to quickly and easily alternate between watching the drone and watching the monitor. I had to find an alternative to goggles (initially, at least, I will detail changes later). What I did was build a system which would allow me to watch the monitor, or, if need be, quickly raise my head to see the drone in flight. Illustration 4.14 alongside shows this system.

**<u>Illustration 4.14:</u> FPV Ground monitoring system**

I had a video monitor which could be battery powered. These monitors normally have some sort of ‘hood’ to prevent sunlight from getting to the screen, because otherwise the video pictures are impossible to see. However, the hood which comes with the monitor was far too short for me to comfortably operate the radio controller easily. So, I built a much longer hood out of plywood (painted black inside and out to stop extraneous light, and with a foam lip shaped to the contours of my face) which clipped on to the monitor. The long hood also allowed me to see the pictures on the monitor clearly without wearing my spectacles, which I typically need for close scrutiny or reading. This monitoring system mounted onto a small collapsible tripod which I could adjust perfectly to the right height and angle of my head whilst comfortably operating the radio controller. I could watch the monitor, and then immediately withdraw my head to scan the open skies to see where the drone was and what it was doing. When I was happy I had it ‘under control’ again, I could easily shift my head back to the monitor.

To the left of the monitor, also mounted on the tripod, was a small board with the video receiver, battery for powering the system, and other electronics. At the top was the ground plane receiver antenna. I modified this system after a few flights. I found it very difficult to watch the picture on the monitor from the camera, whilst at the same time taking note of the overlayed status of the drone from the information presented by the on-screen display. There was just too much happening with the drone on which I was concentrating to allow time to shift my gaze to the information. Most importantly was the available battery power, and a few times I so depleted the battery (without noticing it) and then the craft crashed. Luckily, the on-board video transmitter also has a small microphone and audio link that is part of the transmission. I installed a battery monitor on the drone which gave an audible beep when the battery was running low. I placed this close to the microphone. Then, on the ground, I built a small audio amplifier and speaker system near the video monitor. You can see this in the small transparent box in the photographs. Now, when the battery was running low, the system on the craft beeped, and I could hear this beep via speaker on the ground-based equipment, and know it was time to bring the craft home and quickly land it safely. I continued to use a similar system throughout my subsequent drone variations throughout the course of my research because it worked quite well. There were limitations and modifications to it which I will detail later.

More flights, more practice; now trying as best as possible to fly by watching the video monitor. The experts who cautioned against trying to fly FPV via a gimballed camera were entirely correct. It was very difficult. Added to the problem was that the GoPro 2 camera I was using has a very wide-angled lens which substantially distorts the picture and gives a 'fish eye' view. So, for example, when you are high and decreasing altitude, the lens doesn't portray the ground 'rising up' below you; not until you are very close to the ground and then you suddenly start seeing changes (often too late). Problems like rolling left only look like you are 'drifting' left, because the camera stays level. There is a profound disjunct between what control you are sending the aircraft, what its subsequent behaviour is, and the feedback you get from this behaviour (and thus the next correction you make to the controls). Rather than being 'proactive' and decisive with your flying, you end up being 'reactive' to dangerous situations. I put in many hours of practice. I also crashed a lot (and repaired a lot).

A series of crashes were baffling me. Sometimes it would just seem that I would lose complete control over the aircraft, and it would just dive into the ground. It would only happen when the craft was some distance away and would be unpredictable. This was a recent occurrence and had only started happening since I had installed the video link. After doing multiple checks for loose wires or components which might be intermittent, I decided to do an experiment. I must thank my son Samuel for helping me.

I found a long straight road close to home and set up my video system near one end. Then, with propellers removed, I started up the drone, and Sam walked with it up the road. First, we did it with the video transmitter turned off. I could use the controls (and note that they varied the motors spinning by talking to Sam on his phone), and the drone was receptive all the way up the road, a distance of about 750 metres. Next, we tried the same experiment, but this time with the video transmitter turned on. When the drone was close by, the controls I was changing had the desired effect on the craft. But as soon as we got over a certain distance (about 200 metres, but this varied from experiment to experiment) the drone would cease to behave according to my control, and the motors would spin erratically. I determined that the video transmission link was interfering with the radio controls, but only beyond a certain distance. I knew what the effect was but had yet to determine the cause.

Some online research on the forums revealed the cause – sideband interference. All transmitters, to a lesser or greater degree, also emit harmonics of their base frequency known as sidebands. The first harmonic, which is double the 'base' frequency, is the strongest; and then subsequent harmonics or sidebands decrease in strength the higher you go. I was using a video transmission link of 1.2 GHz, and its first sideband was at 2.4 GHz. This is almost exactly the same frequency of the radio controller. What was happening was that when the drone was close to me the radio control frequency was strong enough to be received and properly interpreted by the drone, but as the craft moved further away from me this received 2.4 GHz signal strength would decrease as well. At a certain distance the 2.4 GHz sideband from the 1.2 GHz video link would 'swamp' the incoming control signal and override it. This led to the loss of control. It was a choice I had made as to what video link I would use, and I had chosen a low frequency one believing that it would give me a better link over distance. The first solution was to purchase a 'Low Pass Filter' (LPF) for the video link (this can be seen in Illustration 4.12 as a red extrusion below the video transmitter and before the antenna). This LPF is tuned to 1.3 GHz; in other words, it only allows frequencies below this to pass through it (for transmission by the antenna) and attenuates or blocks all frequencies above that. This solved my problem of the 2.4 GHz sideband and losing control over distance.

Another problem I was having was losing the video link intermittently. Having stable and continuous video when flying via the monitor is absolutely essential. When the craft was rolling or pitching the video would break up. More research led me to realise that the polarization of the 'inverted vee' antenna I had built was the problem. All antennas are designed with a polarisation, which can be either horizontal, vertical or circular. Both the transmitter and receiving antenna must have the same polarization for the signal to be effective. With the vee antenna the signal was sent out at 90 degrees to the antenna and was horizontally polarised. This was fine as long as the craft was flying level or close to level. However, as soon as the craft rolled or tilted significantly this transmission would now be at a different angle to the receiver, and I would encounter signal breakup.

More research led to the understanding that I needed to have a circularly polarized antenna, so that changes in attitude of the craft don't have an impact on either the transmission or reception direction. These antennae are known in the RC world as ‘mushroom’ antennae. I decided to change to this system, and at the same time decided to purchase a transmission link of a different frequency, 5.8 GHz. Although this higher frequency would not have the same effective transmission distance, it would still be enough for my needs. This different receiver and mushroom antenna can be seen in the photographs of the system in Illustrations 4.13 and 4.14 (for a while I was running dual systems for experimentation with reception and distance until I had determined the best course of action, that is why both the ‘old’ and the ‘new’ are in the photographs). The ‘mushroom’ system greatly improved the consistency of the video link. As an aside, there are plans online as to how to build these yourself, but at the 5.8 GHz range they are quite difficult; and so instead I chose to purchase readymade ones since they are more accurately reproduced by machine, industrially.

During all my modifications and experimenting I had noticed a new attribute about the quadcopter; it was becoming more sluggish to my input commands. It would need more throttle to gain altitude and descend far quicker. It was also more difficult to land, and trying to maintain a stable hover required wider variation in throttle input. One day after a landing which tipped the drone on its side (a problem I will write about later) I picked it up by the arm which was extended into the air. I was surprised at how warm the arm was. I then felt the motor and it was very hot. Feeling the other motors confirmed they were all running very hot. They were working too hard to keep the drone in the air. This was a consequence of adding ever more weight in the form of gimbal, camera, video links and other associated equipment. The drone needed more power. I had two options, either get bigger motors, propellers and battery; or otherwise get more motors. I chose to do the latter and upgrade the drone from a quadcopter to a hexacopter. This required purchasing two extra motors, electronic speed controllers and arms (I would repurpose the 4 motors and arms from the quad) as well as a new body which would accept six arms.

Even though the quadcopter only had 4 arms, it still occupied quite a large ‘footprint’. If I stored it somewhere it took up quite a large space and needed a car boot for travelling. Knowing that space would be an issue further into my studies I decided to research drones which fold up. During this research I found a company in Thailand, jDrones, who sold a kit for a folding hexacopter which would marry with the arms I already had from the quadcopter.

I purchased this kit. I don't have any of my own photographs from this drone, but I have included one from jDrones' online catalogue at the time, shown in Illustration 4.15 below.

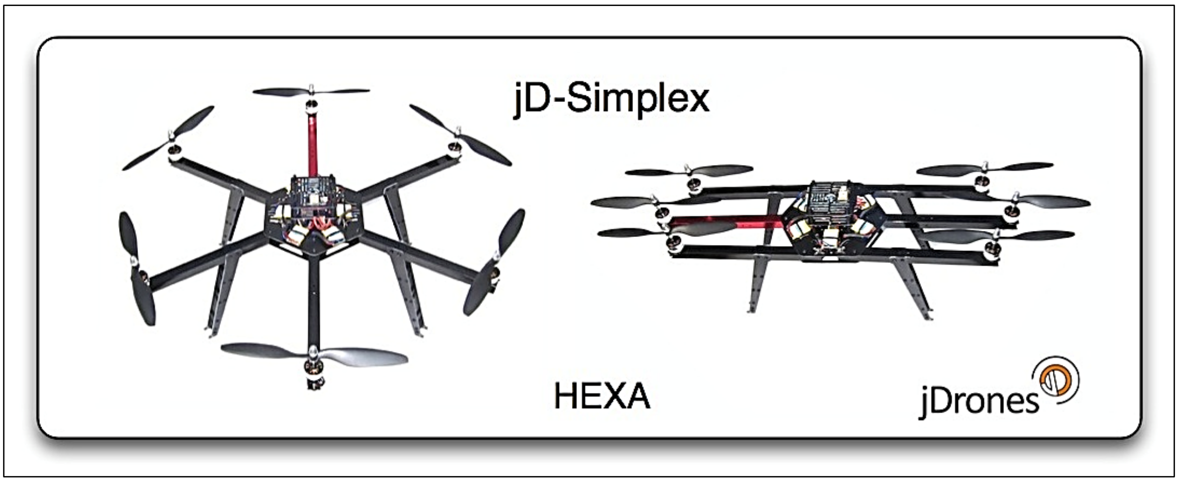



**Illustration 4.15: jDrones folding Hexacopter**

The kit duly arrived, and I disassembled the quad and built up the new hexacopter; using the original flight controller, video link, gimbal, camera, and 4 arms and motors. Unfortunately, the quality of the new drone parts supplied, particularly the body plates, was very poor. They were very thin and made of inferior material. Whereas the original quad had survived – with repairs – a multitude of crashes, this new drone only survived a few and was soon irreparable. This is the reason I don't have any photographs of it, no sooner was it built that it was consigned to the scrap heap.

Two other points are worth noting about this drone. Although it was 'folding', the folded footprint was still large. It still required the boot of a car for transport. Also, to fold (or unfold) the drone required that you not only loosened some nuts and bolts, but you had to remove them completely and reinsert them in new holes on the frame. These are very small 3 mm nuts, bolts and washers. The potential for losing them out in the field in long grass whilst you did the assembly was very high. I have learnt from doing emergency repairs to motorcycles which have broken down in the bush that you have to be very particular as to where you put parts as you disassemble to make sure they don't get lost. I did not like the system the designers of this drone had chosen; the potential for losing small items was just too great. This knowledge would greatly influence my later designs for the drones I would eventually build, and I will also discuss this later.

I decided to keep it simple at this stage, and rather than having a folding drone I would stick to a tried and tested robust system whilst I still improved my skills. Since I had been happy with the original 3DRobotics quadcopter quality, I ordered the frame plates for one of their hexacopters. When these arrived, I transferred all the electronics, motors and arms onto these frame plates. This drone became a workhorse for my practising, and I still have it to this day (albeit with further modifications). These Illustrations 4.16, above, and 4.17, below, above show a version of the 3DRobotics Hexa I built.

**<u>Illustration 4.16:</u> 3DRobotics Hexacopter**

**<u>Illustration 4.17</u>: 3DRobotics Hexacopter**

As I worked through all the glitches in the system and the equipment became more dependable, my confidence grew. I was still having problems trying to fly FPV with a gimballed camera, but my idea of the monitor from which I could quickly look up to find the drone in the sky was working quite well, to the point that I felt I could recover the drone home should I lose control via the monitor. It was time to take my foray into the world which I had set out to conquer, following motorcycles in the bush.

I chose a site which I knew quite well from riding in the area, near Stockville Road in Marianhill, shown here as a Google Earth image Illustration 4.17 alongside. I knew that there were not many trees to crash into in this particular place, and I could also get quite close with a car and all my equipment. I have to thank my friends Mark Hewson and Travis Van Schalkwyk for assisting me by riding their bikes for the experiment. There are some frame grabs which I captured as still images from the video which are Illustrations 4.18 alongside and 4.19 below.


**__Illustration 4.17:__ Google Earth image of Stockville Rd area**

**__Illustration 4.19:__ Frame grab 2 from Stockville Rd flights**

It proved to be a difficult day. I was nervous and tense. Now, for the first time, I was trying to follow a moving target. Also, up until now I had been flying over flat fields, but here the course went uphill on the outward leg, and downhill on the return. To compound this problem the furtherest part of the course which Mark and Travis were riding (a ‘simple’ up the hill and then back down again) was further than I had flown previously. This meant that the drone was very small visually when it was far away, and difficult to see the orientation of it, which meant that I had a few mishaps thinking I was bringing it back to me (for example) and it would actually move away (and get smaller!).

**Illustration 4.18: Frame grab 1 from Stockville Rd flights**

Another problem I had was that the monitor was setup in such a way that I could glance up from it to see the course and the hill straight ahead of me. There were a few times when I would lose control of the drone, only for the control to return a few moments later. At the time I did not understand why, but later experimenting gave the answer. It would only happen when the drone was quite far away (and thus signal strength from the radio controller diminished) and the drone passed in line with the centre column of the monitor tripod. This metal column was absorbing the radio control signal and creating a ‘shadow’ when the column was positioned between the radio controller in my hands and the position of the drone. For those moments the drone would not receive any signal, only for it to return a few moments later.

Added to this, the gimbal was behaving erratically. The video pictures had a constant shimmer to them, which resulted in jerky images on the monitor. The gimbal had been through quite a few cycles of crash/repair/and replace components, and it was finally showing its age. Servo gimbals are notorious for this once the little motors and control arms get old and exhibit some ‘play’ in their mechanism. (I will discuss the alternative soon.)

Depending on how you judge success, the success of this day could be debated. I was flying too high relative to the riders (which was exacerbated by the fisheye view of the GoPro 2 camera) because I was erring on the side of caution and not wanting to crash into the ground (which did happen at one stage and required a long walk up the hill to recover the drone). I had difficulty following the moving riders and keeping them central in frame. The pictures were jerky from the gimbal with the drone losing contact because of the tripod column shadow mentioned above. But there was one brief moment - a frame grab is shown in Illustration 4.20 alongside - where I was tracking the two riders from the side as they descended the hill.

**<u>Illustration 4.20:</u> Frame grab 3 from Stockville Rd flights**

Whilst it was very brief, it nonetheless replicated to a certain extent the vision I had had inside my head as to what kinds of shots I wanted to achieve with the system. Very brief, very fleeting, but inspiring. Another rung up from the bottom of the ladder.

I was to start measuring success in another way, and it was not apparent on this day but was to become more important to me as my time of experimenting went by. I brought the drone home in one piece, without having to do any repairs in the field (even though it had crashed, the long grass had softened the blow, and I was able to fly it again after a software reset). Now this may seem to be a very low bar to set, but it actually was quite difficult to achieve, as I was to find out. One may ask why? The answer is that I was experimenting, and the drone was experimental. And experiments sometimes fail, and in a complex system even one small component or setting failing can lead to the system failing. This  would not be too bad if the drone were a car on the ground; failure would mean it would just sit there. However, substitute this car for a flying aircraft and failure means it falls out of the sky, sometimes with dire consequences. Add into this equation that the drone has to be built as light as possible, so strength of materials are sometimes compromised, and failure can lead to long and expensive repairs. This nature of dealing with experimental flying craft – particularly in remote areas where backup is non-existent - was to have a massive influence on my future design thoughts. I remember returning from a trip to Lesotho where my son Scott had assisted me, and we had flown for 3 consecutive days. Not everything had gone right, particularly through no fault of ours on the last day (I shall write about this later). In the car on the way home, he asked me how I felt about the days we had worked. My answer? 'I thought it was a great success, we did not have to open the toolbox once!' Success is sometimes measured in strange ways.

After more flights with the hexacopter it was time to move on. Although this aircraft had improved over the original quad in respect of power, it still was not enough. On very windy days it was 'fighting' too much to counter the wind. Also (as with the original quad, too) it had issues with the arms and legs of the drone coming into shot as the drone rolled and pitched. It was far too large and needed a car boot to transport. And the gimbal was erratic and by now outdated, since newly invented brushless gimbals were overtaking servo gimbals in performance and reliability. So, the next stage was to design and build a drone – actually an entire Unmanned Aerial System – more suited to my needs. However, before I get into this design, I need to explain some of the components of the entire process and system, which I will do in the next chapter.

# CHAPTER 5

## Deconstruction of the Research Title, and Analysis of the Project Parameters

I need to explain some of the terminology in the context of my research, as well as the software I have been using. For illustrative purposes I include the original title to my research, with certain words or phrases in bold and the sub-sections numbered:

Capturing (5.1) **New Forms of Video Footage** in (5.2) **Remote Locations** through the (5.3) **Design, Development and Deployment** of an (5.5) **Autonomous**, (5.4) **Open Source**, (5.5) **Unmanned Aerial System**: A Case Study of South African (5.6) **Enduro Motorcycle Racers**

### 5.1 New Forms of Video Footage

I am an Adjunct Professor in the Department of Video Technology at the Durban University of Technology. We prepare students for working in the television production industry. Amongst my other duties, I have been the sole lecturer and assessor for the camera and lighting modules of the course for more than 34 years. As such I have remained current with new technologies and techniques for camera treatment and operation in the film and television industries. I have continued to work in the television production industry during this time, both nationally and internationally. A recent example of this is as a camera engineer for the Host Broadcaster at the 2018 FIFA World Cup in Russia. I have produced, shot and edited many videos of enduro motorcycling over more than 40 years, as well as taking thousands of photographs of the sport in this time. I count among my friends and acquaintances many people who are actively involved in this coverage as well. I watch programmes on motorcycling with a critical eye and am aware of how content should be created not only from a camera shot perspective, but also from the audience engagement point of view. Being an avid enduro motorcyclist for more than 45 years has also prepared me to know what can and cannot be done with camera angles and shots of the sport, as well as what direction future developments might take.

There are three traditional ways of collecting footage of enduros; the ground-based camera, the on-board camera, and the aerial helicopter shots. A brief discussion of each in turn.

**<u>Illustration 5.1:</u> Handheld Camera Example 1**

**<u>Illustration 5.2:</u> Handheld Camera Example 2**

The ground-based camera is a camera person operating on foot, with the camera either mounted on a tripod or on the operator's shoulder (known as 'handheld'). Tripod mounted camera shots are inherently more stable than handheld, but this requires that the operator carry a tripod into the bush and find place to erect it. So, most of these operators choose to shoot handheld, because they can easily move along the trail from one vantage point to the next. Unfortunately, the handheld camera is not very stable, and is susceptible to shaky shots particularly when zoomed in to a narrow angle. For this reason, most operators choose to work on a wider-angle lens setting, but this means they need to be close to the action for the shot to be engaging. However, being close to the action means that the riders are only in view for a few seconds, and the shot can only last these few seconds in the final edit of the programme. Nonetheless, ground-based cameras are the staple of programmes produced and have been for many years. They are also a good alternative from a budget perspective, since the camera operator can walk to many locations along the trail during the course of the race and get a lot of different angles of the action.  Illustrations 5.1 and 5.2, above, and 5.3, below, show some examples of frame grabs from some of the videos I have shot using a tripod mounted camera.

On-board cameras are used extensively by broadcasters around the world for a variety of different events, but particularly for motorsport. The cameras are miniature, and when used for live sport such as car or motorcycle racing around a track (for example F1, or MotoGP) include a video link. However, the type of on-board camera used for enduros only records on a card in the camera, and the footage is downloaded later for editing. The most common of these is the GoPro series of cameras.

**<u>Illustration 5.3:</u> Handheld Camera Example 3**

GoPro dominates the market because it provides reasonably priced, reliable, rugged cameras. The cameras can be used both above and below the water (with a water-housing which comes with the camera). GoPro also produces a whole range of mountings for its cameras.

For enduro use there are three typical ways of mounting the camera, all of them facing forward. The chest-mounting straps the camera to the rider's chest. Then there are two different helmet mountings, one goes on the front of the helmet above the goggles and below the peak, and the other mounts on top of the helmet. Each way of mounting the camera has its pro's and con's.

It might seem obvious to mount the camera on top of the helmet for the best view, but this option is seldom chosen for off-road motorcycling because the camera is prone to damage – or being knocked off the helmet completely – by low hanging branches or bush. Most riders thus choose to mount the camera just above the goggles under the helmet peak, or otherwise on the rider's chest. The problem with these mountings though is that parts of the rider's attire always intrude into the shot, either the helmet peak or otherwise the underside of the helmet. Also, the handlebars are always in shot, but this can be an advantage because it gives a feeling of 'the rider's viewpoint' of the race.

GoPro cameras work best from an audience perspective when the rider is following another racer. The audience has something to focus on and watch the riding style and technique of the rider in front. The cameras also work well when the racer with the camera is faster than the rider in front, and is 'chasing them down' and eventually pass them. The pictures from these cameras are also interesting when the terrain being traversed has a lot of variation in it, such as twisting and turning through the trees in a forest. It must be said though that the pictures become less interesting once the terrain opens up, and really only holds interest for avid riders whilst the average viewer becomes bored.

**<u>Illustration 5.4:</u> On Board Camera Example 1**

**<u>Illustration 5.5:</u> On Board Camera Example 2**

Nonetheless, GoPro cameras have become the de facto standard for action sports enthusiasts the world over. Many videos are posted to YouTube and social media every day by snow skiers, skate boarders, cyclists, parachutists, and the like. In some sports the cameras are unrivalled, such as surfers riding 'inside the tube' (i.e., with the wave breaking over the head). No other camera or mounting comes close to revealing what this is like, and some of the most famous of said videos have been recorded at Skeleton Bay in Namibia. The videos recorded at this site are both surreal and breath-taking, for both surfing aficionados and the average person.

The Illustrations 5.4 and 5.5, above, and 5.6, alongside, are frame grabs from a video which I recorded myself during an enduro event in 2017, with a GoPro camera mounted on my chest. Note how the bottom of the helmet intrudes consistently into the shot.

**<u>Illustration 5.6:</u> On Board Camera Example 3**

Helicopters provide ‘the aerial view’, a view which gives a better perspective than the ground-based camera with regard to the terrain the riders are traversing, and also the speed at which they are travelling. The shots can be either tracking with the riders as they move along, or the helicopter can hover in one place whilst, for example, the rider tackles a tricky technical mountain pass. Helicopters provide major benefits for shot acquisition, not only from the fact that they are aerial but significantly because of the variety of locations they can access in the very remote areas which enduro races are held. The helicopter can quickly deliver the camera operator from one area of interest to another, a journey which might take several hours by vehicle or be totally inaccessible altogether by any other means.

There are downsides to the helicopter, though. The first of these is the inability of the camera operator to get close-up pictures of the competitors. There are two reasons for this. The helicopter rotors create massive downforce which results in tremendous ‘wind’ or ‘prop wash’ below it. Anyone who has ever been on the ground near a helicopter when it comes in to land or takes off can attest to this. As soon as this happens in an area which isn’t paved, the prop wash creates huge amounts of dust, leaves, debris or dirt swirling around. This would be completely unacceptable to impose on a rider who is trying to 'read' the terrain. It is worth noting that this problem exists not only for off-road racing, but occurs over water, for example with canoeists. The prop wash can create a lot of disturbance, spray and ripples on the water, and this interferes with canoeists 'reading' the water and their subsequent approach to the lines they would choose.

Another issue the helicopter creates when flying low over a rider is the noise it creates. Motorcycle enduro racers rely on a variety of sensory inputs, and one of these is the sound or 'revs' of the engine. If you cannot hear this it is very off-putting, because it guides the throttle inputs you are making. When the helicopter is flying low in can easily override these audio cues from the motorcycle.

The question thus posed is why not have the helicopter fly at a safe altitude (for the rider) and the camera operator merely zooms in to a tighter lens angle to get the close-ups? The reason is because the helicopter generates a lot of inherent vibrations when it is flying. These vibrations in the airframe are transferred through the camera operator into the camera. When you are shooting 'wide', the effect is negligible on the picture frame; however, as soon as you zoom into a 'tight' shot the vibrations result in jerky or shaky shots.

**Illustration 5.7:** **Helicopter with Gyrocam mounted**

There is a way to overcome this, but the technology is very expensive, costing in excess of $1m (over R15m with current exchange rates) (https://ruggedvid.com/airborne-gimbal-camera-interface-guide/), and this excludes the price of hiring the helicopter per hour! Systems, known variously as 'Gyrocam' or 'Heligimbal', have been developed where the camera is mounted on an image-stabilising apparatus which the camera operator, sitting in the helicopter, interfaces with to pan, tilt, zoom and focus the camera. An example of one of these systems is shown in Illustrations 5.7, above, and 5.8, below. They are used very successfully on ‘big budget’ productions such as ‘Dakar’, the ‘Tour De France’ and wildlife documentaries. These ‘Gyrocams’ are truly remarkable from a technological perspective, and they can provide incredible close-ups of, for example, animals in the wild whilst the helicopter hovers high above. Unfortunately, they are beyond the budget reach of most enduro racing television coverage, and even the ‘cheaper’ version of helicopter with camera operator on board is very expensive, to the point that locally only one race per annum, the ‘Roof of Africa’, an international event held in Lesotho with an international audience, can afford the budget to hire one.

**<u>Illustration 5.8:</u> Close up of Gyrocam ‘pod’**

If we consider the cheaper option of camera operator seated in the helicopter capturing images with a camera on the shoulder, what then are the type of shots the helicopter aerial view can achieve?

Normally what happens is that the side door of the helicopter is removed, and the camera operator sits in the doorway – often on the floor of the helicopter with feet on the landing skids, but obviously strapped to some fixed mounting in the helicopter

**<u>Illustration 5.9:</u> Camera Operator shooting from Helicopter Example 1**

for safety and with the camera tethered as well – and shoots out of the helicopter in a sideways direction. This means that the camera operator can capture images of anything which is alongside the helicopter, but not anything which is in front of or behind it. This means that as the helicopter flies forwards, the operator can track any racer flying alongside and below it. Alternatively, the helicopter can hover in one place, and the pilot can position it so that the operator has a clear view of what is happening. As noted previously, these shots are quite wide, and cannot 'develop'; they retain the framing throughout. The helicopter can to a certain extent arc around a rider on the ground who is stopped, for example having crashed or is suffering a mechanical breakdown, but such an arcing movement cannot accommodate a moving rider because the helicopter is large and quite cumbersome.

**<u>Illustration 5.10:</u> Camera Operator shooting from Helicopter Example 2**

It is also possible for the shots to be from the front of the rider moving towards the helicopter, or from the rear moving away; but these shots are very brief if the helicopter is hovering because the rider quickly disappears beneath it or moves rapidly into the distance. It is difficult to acquire moving shots of riders coming towards or moving away from the helicopter. Remember, the camera operator is sitting in the doorway on the side of the craft. To achieve these shots the pilot is required to position the helicopter sideways to the movement as the rider, and then fly the craft sideways at the same speed of the rider. Whilst

**<u>Illustration 5.11:</u> Camera Operator shooting from Helicopter Example 3**

this is not impossible, it requires great skill on the part of pilots, because they are unsighted as to where they are going (they have to look out of their side window to see their flight path) and they also have to maintain the same speed of the rider, which means they are looking over their left shoulder to see where the rider is. Pilots regard this as a risky manoeuvre and rarely employ it.

Notwithstanding the above, any television producers who are given a substantial budget to produce a programme on enduro racing will immediately look to see if they can afford helicopter coverage, even for just a portion of the day or race (helicopters are costed per hour) because helicopters contribute so much to the overall look and feel of the programme with the shots they can acquire. The Illustrations 5.9 – 5.11, above, are frame grabs taken from video showing some of the typical shots that can be captured. The shots are provided by my good friend, David Fisher, from an event he covered in Boston, KZN, in 2015. Dave has many years of experience flying as a camera operator in helicopters, both nationally and internationally.

There can be little doubt that the aerial view of sports, and enduro riding in particular because of the terrain and landscapes and how the rider is performing, is compelling. It was this motivation behind my early thoughts on drones – how could I recreate the aerial view of my favourite sport, but at a much lower cost? Once I began the journey, though, I started wondering – can I just replicate the helicopter aerial view with a drone, or could I take it into other realms of camera shots and television production? This is my thesis. Could I be pursuing a 'new form' of video creativity, driven and inspired by new forms of technology (as stated in an earlier chapter)?

Before I attempt to provide an answer to this question, I need to provide a very brief and rudimentary explanation of camera shots and angles, and how they are combined into a final television sequence or programme.

Cameras can provide a variety of shot ‘sizes’; they vary from a wide angle (or ‘shot’) to a long shot, to a medium long shot, to a mid-shot, to a medium close-up, to a close-up and finally to a big close-up. If we think of framing a human, the wide shot would show the person in the distance of a landscape, and each shot progressively brings the person closer and reveals more detail about the person, until the big close-up might only have parts of the face in the frame.

Cameras can also provide moving or tracking shots. If we return to the human as subject, if this person were static, we could track the camera in to them (and they get larger in frame) or we could track the camera away (and they get smaller). Note that this is different to zooming in or out, the perspective and psychological effect on the viewer is different too. If the people were walking, we could track or move the camera alongside them, or we could follow them from behind as they walk away from camera, or have the camera moving backwards as the people walk towards camera. These are all basic tracking shots. Tracking shots can also be combined into more complex movements, such as an arc where the camera moves in a circular motion around the subject.

The camera can also change height. If it is at the same height as the human’s head, it is called a ‘neutral’ angle or height. But it can go higher than the human, in which case it is called a dominant shot; or it can go lower, in which case it is called a submissive shot.

Cameras can also ‘develop’ shots. A developing shot is one where the camera framing or operation changes the emphasis within the frame. For example, a shot might start close on a subject, and then zoom out to reveal something else in frame on a wider angle. It is not just changing the lens angle which constitutes a developing shot. We might have two subjects in frame, we start off focussing on the far subject (with the near one out of focus or blurred) and then ‘pull focus’ to the near subject (whilst at the same time putting the far subject out of focus). Thus, we can shift emphasis for the viewer within one shot. There are many different ways we can develop shots.

As producers or directors, we then edit these shots together into a sequence, and eventually into a final programme in its entirety. Each shot is carefully constructed not only in its singularity, but also to 'fit' with the shots which precede it and are subsequent to it. We control the viewer's response to the programme by how we cut the various shots together. Typically, we would start with a wide angle or 'establishing' shot, and then intercut the various other pictures we have - the close-ups, the tracking shots, the high and low angles, and so forth. (There are obviously many other elements which go into programme-making, such as sound which is used to guide the viewer in a pleasurable way through the programme, I am only writing from a very rudimentary camera perspective.)

Would it be possible to combine a variety of shots together into one long, lingering shot of riders by using the drone? Could I have a combination of shots – wide shots, establishing shots, close-ups, tracking shots, high shots, low shots – a developing shot which encompassed many elements, and which holds far longer in duration than is typical? Now, I do not profess to be the originator of this type of shot. There are producers and directors who specialise in long, lingering shots, where not only the shot size and perspective changes, but elements with the scene come and go on cue, but these shots are very carefully scripted, blocked and rehearsed many times to get them right. Such shots are not common, because they are tricky to execute and produce.  I was proposing that this principle could be applied to enduro racing coverage. I am also of the opinion that this type of shot will also hold the viewers' attention very well, because it consistently introduces new elements and new perspectives of the action.

I offer two examples of this idea. The first can be viewed in the attached video, and some frame grabs are included below, in Illustrations 5.12 – 5.20. It was shot as 'proof of concept' very early in my experimenting on my father's farm in the Drakensberg, and I must thank my son Scott for being my rider 'model'. I cut out a short course on the farm and set the drone to fly autonomously through a series of 'waypoints' which I had marked. It must be noted that Scott was not riding this as a race where he would be changing speed, accelerating and braking as a rider would do; I asked him to ride at a consistent speed because I was still early on in my experimenting. I just wanted to see if 'I could make this work'. The shot lasts about 50 seconds, and the following frame grabs should be seen only as selected moments from beginning to end, for explanation of what the rider and drone are doing. Note also that I am describing this from a camera perspective, so when I talk about the camera panning, it is the equivalent of the drone yawing.

Illustration 5.12: The shot opens with a high altitude, wide angle. This is the establishing shot. It reveals the terrain and the rider. The rider is moving away from camera, and the drone moves forward in synchronism, a typical tracking shot.

**<u>Illustration 5.12:</u> Experimental Lingering shot Frame Grab 1**

Illustration 5.13: The rider changes direction and starts moving from left to right in frame. The drone also changes direction, and flies sideways to track the rider from the side. The drone also moves into a closer shot and starts to change altitude to being lower.

**<u>Illustration 5.13:</u> Experimental Lingering shot Frame Grab 2**

Illustration 5.14: The rider changes direction again and starts moving towards the drone. The drone changes flight direction to moving backwards and sideways, to a point beyond the course which has been set out. The drone continues to go lower in altitude.

**Illustration 5.14:** **Experimental Lingering shot Frame Grab 3**

Illustration 5.15: The rider changes direction again and starts riding right to left in frame. The drone slows down its sideways movement and begins yawing or panning left to keep the rider in frame. It has also moved to a very much lower altitude.

**Illustration 5.15:** **Experimental Lingering shot Frame Grab 4**

Illustration 5.16: The rider continues to move from right to left in frame. The drone continues to move sideways to track the rider, and goes to its lowest altitude, just above the ground. The rider is much closer.

**Illustration 5.16:** **Experimental Lingering shot Frame Grab 5**

Illustration 5.17: The rider enters a long straight section. The drone yaws or pans right to left, and then begins to move forwards and over the track. The drone then tracks behind the rider, which is moving away from it, in a low altitude close angle.

**<u>Illustration 5.17:</u> Experimental Lingering shot Frame Grab 6**

Illustration 5.18: At the end of the straight the rider does a 180 degree turn to the right and starts moving from left to right in frame. The drone pans right to follow the rider; at the same time it starts moving and tracking left.

**<u>Illustration 5.18:</u> Experimental Lingering shot Frame Grab 7**

Illustration 5.19: The rider moves away from the drone, and then turns left again. The drone continues to fly left, whilst panning to keep the rider in frame. It also starts gaining altitude slightly. The drone flies left and forwards until it is positioned above the course again.

**<u>Illustration 5.19:</u> Experimental Lingering shot Frame Grab 8**

Illustration 5.20: The drone is positioned above the course. The rider starts moving towards it, and it starts flying backwards to compensate and track the rider. The shot finishes with the rider disappearing below the drone.

**Illustration 5.20: Experimental Lingering shot Frame Grab 9**

And there it is, concept proven. One long lingering developing shot, with multiple height changes, multiple flight direction changes, multiple yawing or panning, multiple shot sizes of the rider, and multiple tracking directions. This could not be achieved by a helicopter for reasons stated above, neither could it have been covered by a ground-based camera in any effective way.

I must add that this was a day where I came home elated. (As I will write later, it had been quite a difficult day.) Up until this, it had all been a dream inside my head. What had begun as a seemingly impossible dream was slowly becoming possible.

Unfortunately, though, this was only an experiment, with certain parameters set up by me to make things a bit easier. The ground was flat, and Scott was riding at a consistent pace. How would it work with the realities of people racing, with the terrain being undulating, with the event 'beyond my control'? This was the next learning curve which I will write about later, but before then let me present another example. This is recorded at a race held in New Hanover, KZN, in 2017. The course which the riders traversed (in the area where I chose to shoot) went up a hill, at the top turned right and went down the other side of the hill, then at the bottom the riders turned left, went through a valley, and then turned right and went down a second hill. This part of course is a sort of 'M' shape. The Illustrations 5.21 – 5.32 are frame grabs from a video of one of the sequences I shot that day, which is linked in Chapter 7. It is worth noting that this sequence involves multiple riders, who are riding at varying speeds. This scenario presents its own challenges, but at the same time presents opportunities for captivating coverage of the racing as one rider catches and then passes a slower rider in front. This 'lingering' shot lasts 1 minute and 9 seconds (of footage which can be used in a final edited programme).

Illustration 5.21: The shot opens at a high altitude, with the drone hovering in one place. A set of riders appears in frame from behind the trees at the bottom left of frame and starts climbing the hill left to right relative to the drone's position. This is the establishing shot. As the riders pass by up the hill the drone pans to follow them.

**<u>Illustration 5.21:</u> Real-world Lingering shot Frame Grab 1**

Illustration 5.22: The riders continue to climb the hill, the drone starts moving forward, into a tracking shot which follows them from behind. The drone starts to lose altitude. In this image one rider has already reached the top of the hill and turned right, but our attention will be focused on the rider dressed in black who is slower and still climbing the hill, and the rider behind him in white who happens to be relatively faster.

**<u>Illustration 5.22:</u> Real-world Lingering shot Frame Grab 2**

Illustration 5.23: The drone has reached the top of the hill and has decreased altitude. It has begun moving sideways to follow the riders. The rider in black turns right at the top of the hill, and the drone starts moving backwards to follow him in a tracking shot. The drone is positioned close to the course.

**<u>Illustration 5.23:</u> Real-world Lingering shot Frame Grab 3**

Illustration 5.24: The rider in black starts catching up with the drone, and the drone pivots or pans to the right and also starts flying sideways left-to-right to keep him in frame. Its altitude now starts hugging the contour of the hill.

**<u>Illustration 5.24:</u> Real-world Lingering shot Frame Grab 4**

Illustration 5.25: The drone completes its left to right panning and starts flying forwards down the hill behind the rider in black. The faster rider in white suddenly appears in shot below the drone, in an excellent close-up. The drone continues to fly at an ever-decreasing altitude as the hill slopes down.

**<u>Illustration 5.25:</u> Real-world Lingering shot Frame Grab 5**

Illustration 5.26: The riders continue down the hill, and the faster rider passes the slower one. The drone continues flying forwards, and still lowering altitude.

**<u>Illustration 5.26:</u> Real-world Lingering shot Frame Grab 6**

Illustration 5.27: Towards the bottom of the hill the riders turn left into the valley to cross a small river. The drone pans left, and starts flying sideways left to right, still decreasing altitude.

**<u>Illustration 5.27:</u> Real-world Lingering shot Frame Grab 7**

Illustration 5.28: The riders continue into the valley, riding left to right. The drone tracks them by flying left to right as well, but now at a very low altitude, barely skimming along the tops of the grass and bush.

**<u>Illustration 5.28:</u> Real-world Lingering shot Frame Grab 8**

Illustration 5.29: The faster rider has crossed the river and is climbing up the other side of the valley. The slower rider is still entering the river itself. The drone is still flying left to right sideways but is starting to gain a bit of altitude again to get ready to film the other side of the valley.

**<u>Illustration 5.29:</u> Real-world Lingering shot Frame Grab 9**

Illustration 5.30: The faster rider turns right and starts going down the adjacent hill. The drone pans right to follow him, and then starts flying forwards behind him as he goes by.

**Illustration 5.30: Real-world Lingering shot Frame Grab 10**

Illustration 5.31: The faster rider goes down the adjacent hill. The drone flies forwards behind him and down the slope, but rises in altitude to reveal the landscape and let the rider disappear from shot.

**Illustration 5.31: Real-world Lingering shot Frame Grab 11**

Illustration 5.32: Whilst still climbing in altitude the drone pans left to reveal the slower riding coming down the adjacent hill. The shot ends at a high altitude panning right to follow this rider.

**Illustration 5.32: Real-world Lingering shot Frame Grab 12**

This then is a real-world example. A race, with racers going as fast as they can without compensating for the drone as occurred in the experiment with Scott. Similarly, we now have hills and valleys rather than flat terrain; we have multiple heights and altitudes, multiple backward, forward and sideways tracking directions, multiple panning movements, multiple-size shots from wide to close-up, and different action from the point of view of slower and faster riders, and one actually overtaking the other. Once again, all this is not possible with a helicopter, while a ground-based camera would only have covered a fraction of this part of the course. Thus, I offer, a ‘new form’ of video coverage.

## 5.2 Remote Locations

Enduro races are held in parts of the world which are far removed from human habitation. Yes, the start and finish areas might be accessible by vehicle for administration and access to support crews, but the riders themselves spend many hours in the saddle traversing the veld. These remote areas have no road access – not even what might be classified as ‘4 x 4’ vehicle access – and very often there are not even footpaths close to where the riders are required to go as part of the racecourse. This fact has serious implications for how to cover the sport from a television perspective and is a significant factor in how I chose to tackle my research. Illustration 5.33, above, gives an example of one of the sections the racers traverse.

**Illustration 5.33: Racers climbing a Remote mountain in Lesotho**

The enduro course is ‘marked’ by the organisers of the event beforehand. In some cases, this marking can be fluorescent indicators, either by sticking decals onto prominent landmarks close to the course, such as a tree, or otherwise spray painting ‘dots’ onto rocks where there are no trees or bush. Increasingly, though, the course is simply a GPS ‘Breadcrumb’ track which is given to the participants before they start, and they follow this track on a GPS device mounted on the motorcycle.

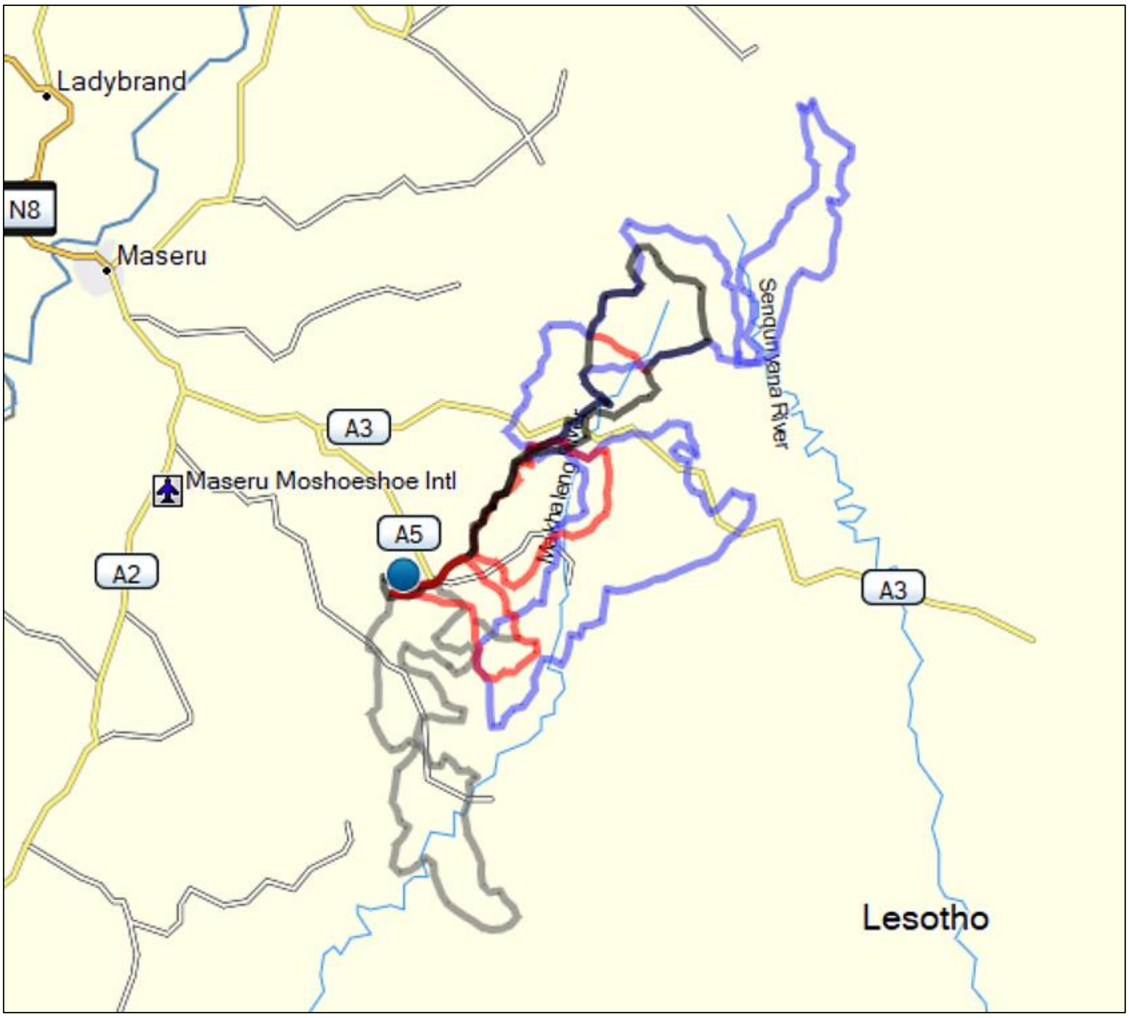
These devices are manufactured by Garmin, which has developed a reputation for small, accurate, rugged and affordable GPS receivers. Garmin also provides software which can be downloaded for free, where you can observe, plan and compile various tracks and courses. The software is known as ‘Basecamp’ (https://www.garmin.com/en-ZA/software/basecamp/). You can go for a ride with your Garmin receiver, record the track that you have ridden, and then download it to Basecamp afterwards. You can then ‘edit’ the ride in the Basecamp software, perhaps stitching together rides from different days, or deleting portions of the ride you don’t want to include and then compiling a different course.

The organisers of the race thus compile the day’s course which the riders have to follow. This course is made available to the racers shortly before the race starts, they download the relevant sections each day (if it is a multi-day event), and it is displayed on their on-board device which they follow turn by turn, section by section.

I offer an illustrative example. This example is taken from a race staged annually in Lesotho, the ‘Roof of Africa’; it is a three-day race typically held in early December each year. I have chosen this example because Lesotho has particularly remote areas, and it is very mountainous which increases the challenge both for the riders themselves, and for me trying to access the course.

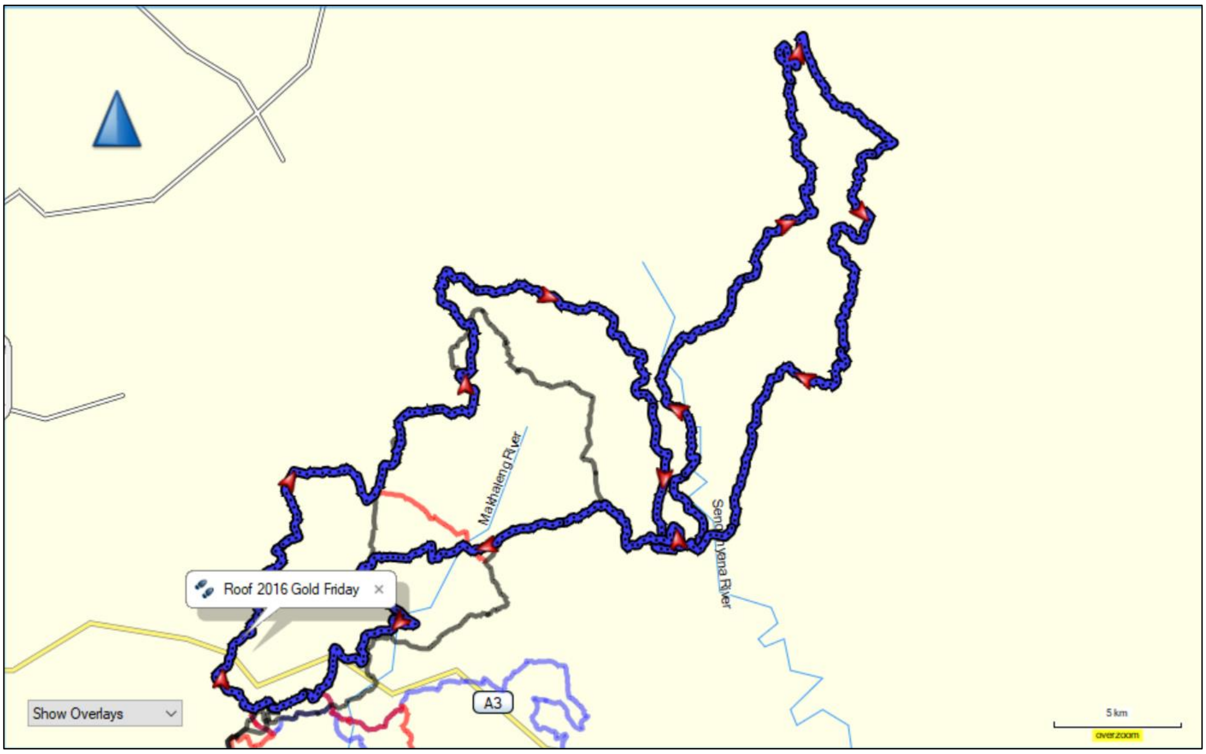
The Basecamp image, Illustration 5.34, below, (note this is not the whole Basecamp interactive page, but just a portion of it which I cropped from the entire page) shows the courses for all three days, indicated by the blue, red and grey ‘loops’ for the riders, all starting and finishing at the same point. Note also that I have simplified the course for the purposes of this example, because there are actually 3 classes of riders – Gold, Silver and Bronze – which have three separate but at times common courses to follow.

You can ‘click’ on any of the stages to highlight it, as shown in Illustration 5.35 below. This gives an indication not only of the course for that class for a particular day, but also the for direction which the riders will traverse. This direction is very important for me, since it greatly informs where I will choose to go to film with the drone. Early on in the stage, and I have less time to setup, map and test before the first riders come through; later in the stage

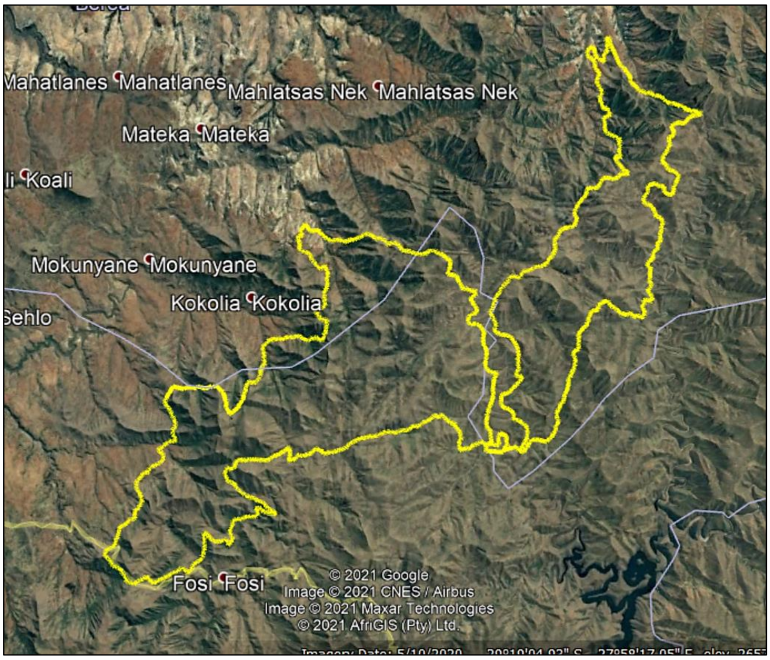



**<u>Illustration 5.34:</u> Basecamp image showing race courses for 3 days**

means I have more time to get this done. However, if I can catch the riders early in the stage when they are grouped more tightly together (because they leave at close intervals in the morning), this maximises my opportunities for capturing footage. It is often advantageous from a video perspective to get groups of riders together. As the day progresses the riders become more 'stretched out', so there are fewer of them in groups and while you have to await longer intervals for shooting between riders. Also, although choosing to go to a place which is early in the stage means that you have to get up and get going earlier in the morning (typically a 4 am start in Lesotho), your shooting day finishes earlier and you can get back to your accommodation (which might be a couple of hours away from where you were shooting), complete any repairs to the drone, charge batteries, and get organised for the next day in daylight.

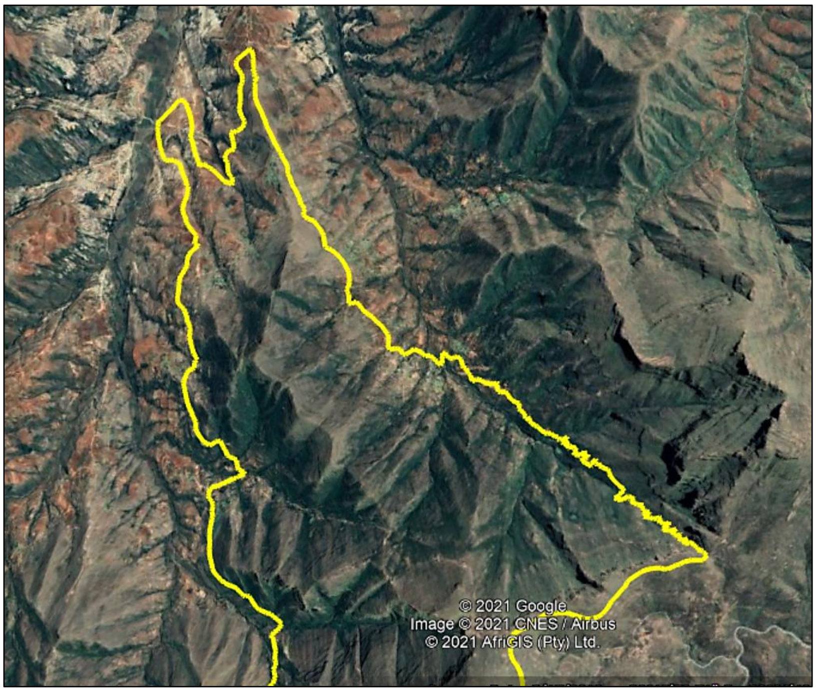



**<u>Illustration 5.35:</u> 'Gold' course for one days racing highlighted in Basecamp**




**<u>Illustration 5.36:</u> Google Earth image of Gold route shown in Illustration 5.35**

Basecamp imports and edits data in .gpx format (a proprietary Garmin format). Note, though, that the format only shows major roads, rivers and anything bigger than a village. It does not show contours, such as whether a region is mountainous or flat, and it is a map, not an image. If you want to see images of the area the best source is 'Google Earth', which displays satellite images of the earth. Google Earth is also free software to download (https://www.google.com/earth/), and it is by far the most useful tool I have at my disposal when deciding where to fly. You can export the Basecamp .gpx file format into a .kml file format which can be interpreted by Google Earth, and then overlay this with the satellite images. I have taken the same highlighted course from the Basecamp image above, converted it to .kml, and overlayed it over the relevant section of Lesotho in the Google Earth image Illustration 5.36, above. The course is shown as the yellow line.




**<u>Illustration 5.37:</u> Closer view of Illustration 5.36**

Suddenly, from seeing the satellite images, it is apparent just how remote the area is, and also how mountainous it is. Even this image doesn't do it justice, however it is possible, however, to 'zoom in' to the course to get better detail. Note that the free consumer version of Google Earth doesn't provide very fine details; the data is limited unless you opt for commercial subscription use. If you zoom in too far it merely becomes grainy and pixelated. Many is the time I wished I could see just a little bit more detail, but I have found some workarounds which help and which I will explain later. In Illustration 5.37, below, I have zoomed in a little, into the top right-hand corner of the entire course shown in Illustration 5.36. Now mountains and river valleys are more pronounced and apparent.

Zooming in some more, to the bottom right-hand side of Illustration 5.37, reveals greater detail of the course, shown in Illustration 5.38, below. Now footpaths and smaller settlements or kraals become visible. Here it shows the course winding and twisting down what appears to be a river valley. Looks can be very deceptive, though.

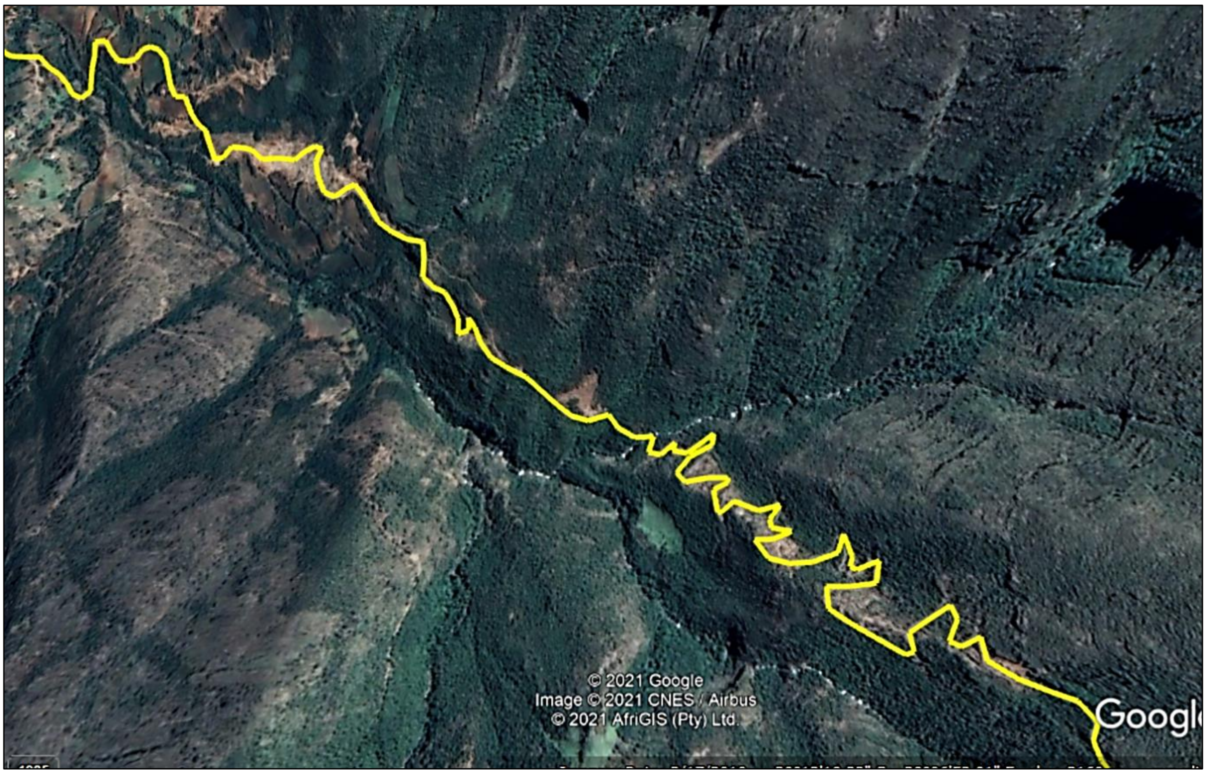
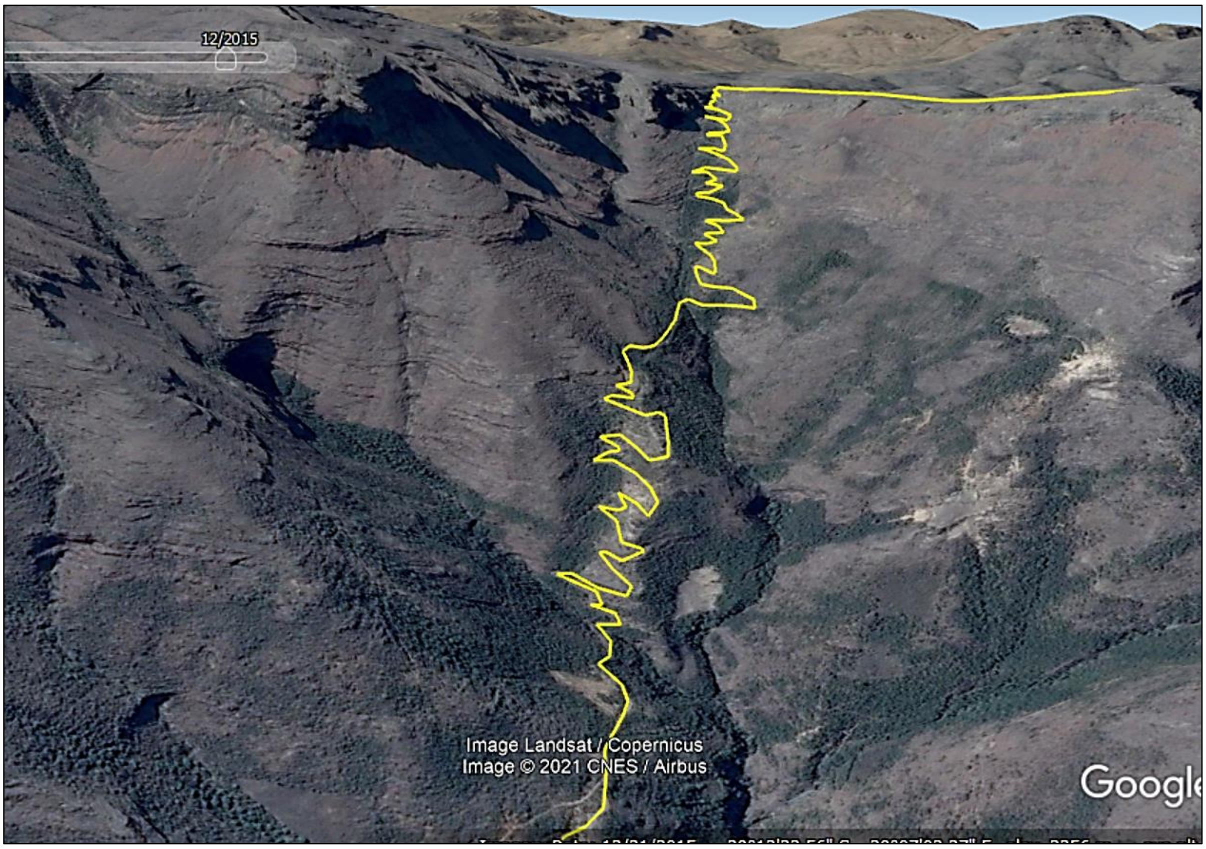



**Illustration 5.38:** **Closer view of Illustration 5.37**

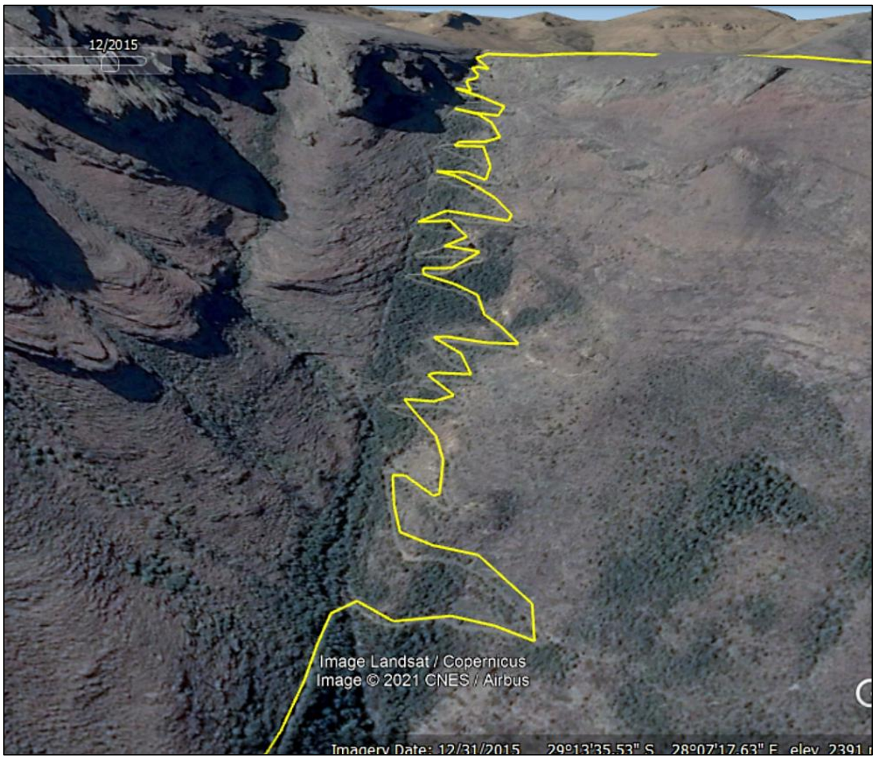
Google Earth shows an ‘overhead’ satellite view as its default setting. However, it is possible to take the viewpoint down lower, all the way down to ground level, if needed. Google Earth has latitude, longitude and altitude co-ordinates amongst its data, so it automatically reconstructs the overhead images into lower viewpoints of the terrain. It also allows you to readjust in which direction you are looking, the default view is ‘North up’; but you can swing your viewpoint around to any point of the compass. There are toolbar buttons to change this compass heading or height setting (aside from many other tools which you can employ, some of which I will discuss later).

Take the example from Illustration 5.38, above. From the image looking directly down, it seems like the riders wind down a valley. However, if I switch the viewpoint to being lower altitude (looking ‘at’ the mountains rather than ‘down onto’ them), and also change compass heading, it suddenly becomes apparent that the riders are not riding along a river valley, but rather climbing a steep mountain, as shown in Illustration 5.39, below.




**<u>Illustration 5.39:</u> 'Lower' view of Illustration 5.38, looking South East**

Zooming in even further, as shown in Illustration 5.40, reveals more detail, and also just how steep the last part of the climb is. Now the riders complete switchback after switchback to get to the top of the climb, and then reach the top plateau where they turn right. It would take them quite a while to

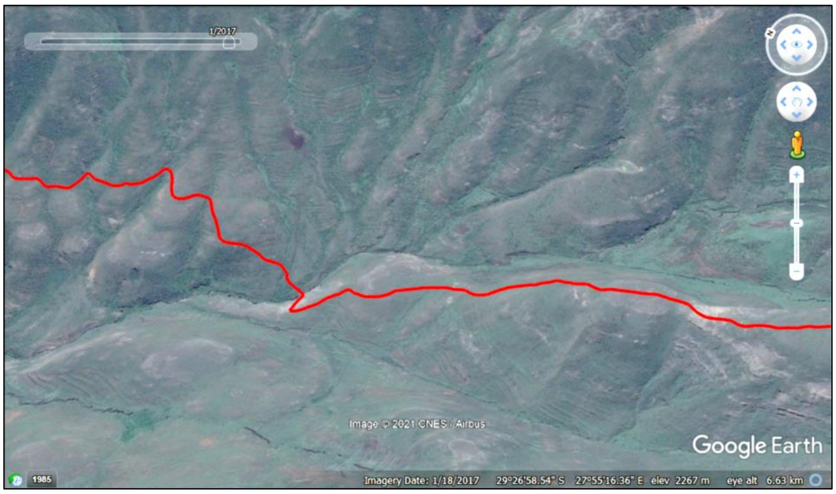



**<u>Illustration 5.40:</u> Close up of last section of climb from Illustration 5.39**

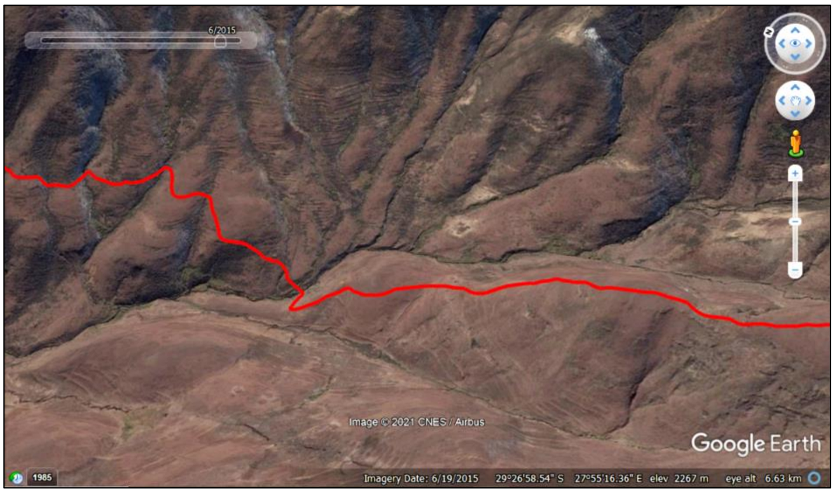
complete this last climb and would be physically draining. A far cry from what looked initially like a meander along a river valley (in Illustration 5.38)!

Google Earth updates its satellite imagery on a regular basis. How regular? It depends on various factors, but typically remote areas seem to be less current or regular than built-up parts of the globe. Typically, there will be at least one update per annum. Also, the default setting when you open an image is the last 'clear' image; in other words, there may be more recent imagery but the area may have been covered in cloud and not very clear. There is however a databank of all the images of that area going back to the very first which Google Earth captured, and this is accessed by the 'History' button on the toolbar, and a 'sliding scale' which allows you to 'go back in time'. This is a very important feature for me, and I use it extensively.

The clarity of the image too, is very important to me. I am looking for access, for footpaths, for signs of habitation, for geographical features on a scale smaller than the highest resolution that Google Earth can give me, or any clues that might indicate any of the same. At certain times of the year (such as spring and summer) the bush can be overgrown, and the footpaths are non-visible from the satellite above. However, come winter, and the undergrowth is far



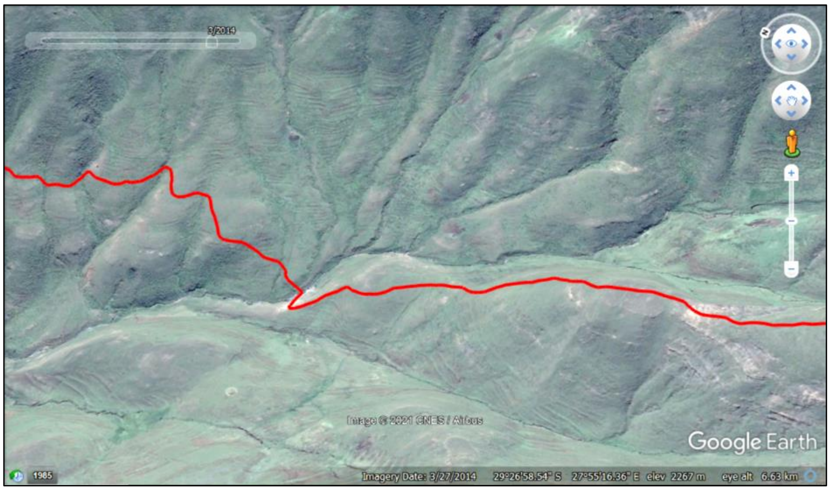

**<u>Illustration 5.41:</u> Google Earth image of area, January 2017**




**<u>Illustration 5.42:</u> Google Earth image of the same area, June 2015**

less, and you can see this footpath. At certain times of the day the sun is directly overhead, and there are limited shadows. If the satellite captured the image at this time of the day, the image would be ill-defined. Capture the image at a different time of day, say early morning or late afternoon, and there is more clarity in the image because the shadows reveal so much more detail.

The Illustrations 5.41 – 5.45, (above, and alongside), show the exact same Google Earth terrain (with a red racing course traversing it), taken at different times by the satellite over a period of years (January 2017, June 2015, March 2014, April 2013 and November 2012, respectively). Note how the images from 2017, 2014 and 2012 are ill-defined, because of the seasonal undergrowth and the time of day. The image from 2013 is all in shadow from a nearby cloud, and virtually unusable. But 2015 is quite clear, because it is taken in winter and the time of day is such that the shadows of




**<u>Illustration 5.43:</u> Google Earth image of the same area, March 2014**


**<u>Illustration 5.44:</u> Google Earth image of the same area, April 2013**


**<u>Illustration 5.45:</u> Google Earth image of the same area, November 2012**

the terrain are more revealing. You can more easily see signs of human habitation, such as the terracing bottom left of the image, which shows an area of cultivation. Cultivation means that there will be people living nearby, and footpath access. This is just an example of some of the tricks I have used to see just what a particular area of interest looks like in my planning.

Preparation for a Lesotho trip starts well in advance. The last few days are reserved for planning where I will eventually end up shooting on each day. Since enduros are a test of a rider's ability to read the (previously unseen) terrain and react as fast as possible to it, the organisers only release the course a few days ahead of time. This avoids riders going out to the course and practising and familiarising themselves with it so that they can ride it faster in the actual race. But it also means that I have a very limited time to decide how each day will be planned. So, I spend the last few days and nights before the trip pouring over the Google Earth images of the course, scrutinizing it in fine detail bit by bit, to make my decisions. These decisions are driven not only by the photogenic potential of the images at various places but, importantly, how I will gain access to the course, and then be able to leave afterwards. Note that I try not to ride on the actual course, this is because the competitors are racing, and I don't want to hold them up in any way should I be on the course at the same time as them. I may stretch this personal rule slightly if I can get on to the course, and access the filming place, well before they are due to get there, but then I will still have to find another way out once I have finished filming and there are still competitors on the racecourse. This means I have to scout for alternative access to and from the course. Typically, in my planning I will identify two or three possible places to fly and shoot, and leave the final decision to when I am there and able to look at them 'on the ground'.

I am describing a Lesotho trip because not only is the event held over three days of racing (traditionally a Thursday, Friday and Saturday), but also because it is the furthest I have travelled for this research. For local KZN events I normally only go there and back in one day. A Lesotho trip begins with the planning and checking beforehand, then packing the vehicle with our motorbikes, gear, drone gear, and everything needed into the vehicle on the Tuesday night. We then leave early Wednesday morning. I say 'we' because for these long trips I like to have someone capable with me to help (I will mention who these people are as I discuss specific years later). If the trip is without incident, we arrive at the Maseru border post around lunch time (it is a trip of over 600 kilometres). Getting through the border post can take anything between 15 minutes and a few hours, and this is unpredictable. Once through Immigration we travel to our accommodation. Although most competitors choose to stay in hotels in Maseru, I choose to stay closer to where the action will be over the next few days, for example Roma or Ramabanta. We would normally get there early afternoon. The rest of the Wednesday afternoon is taken up by travelling out to the various places I have chosen with potential for coverage and seeing which of the various options is most viable for each day. Viability has various factors, some mentioned above, but also includes where will be a safe place to leave the vehicle while we are out in the mountains, and then just exactly how we will ride to the shooting area on our motorcycles. I will try and befriend the people where we intend to leave the vehicle the day before, such as a security guard at a dam, and alert them to the fact that we will be arriving very early in the morning on a particular day.

Each of the subsequent days starts before dawn. The actual race begins at 6 am, and we need to be in place earlier than the arrival of competitors at that particular spot. We drive out to the place chosen to leave the vehicle, unload the motorcycles and all the gear, and then ride to the shooting area.

Accessing the racecourse is impossible with a vehicle, even a ‘4 x 4’. There are no roads in most places, only footpaths; and in Lesotho even these can be treacherous. The only way to access the spots are on foot, or on an enduro type motorcycle. Allied to this you need to be very experienced to do this, particularly when loaded with backpacks and all the equipment. Thankfully I have a lot of experience riding off-road, as do the people I choose to take with me. As an aside it is worth noting that when riding enduros you wear – by necessity because it is such a dangerous sport – a lot of protective gear. However, since a large part of the shooting day will be walking and moving around in the heat, we choose to forego a lot of this protective gear. I ride in a tee shirt, short pants and hiking boots. The only protective gear I ride in (for filming, not for racing) is a crash helmet, goggles and gloves. It is very dangerous should either of us have an accident, so we take extra care and ride slowly to our destination.

Illustration 5.47, below, gives an example of the bike I ride, the clothing I wear, and the backpack which I have to carry together with the essentials for the day.

**<u>Illustration 5.46:</u> Heading out into the mountains for a day of drone shooting**

If you ask people who frequent the Maluti mountains, or locals who live there, 'What is the weather like in Lesotho?' you will commonly get the answer '4 seasons in one day'. I have often encountered this. I have been doing an annual trip to watch the Roof of Africa for many years and experienced vastly different conditions. Some Decembers we have had 38-degree temperatures, and yet in December 2018 large portions of the race course were covered in snow! In December! The height of our southern African summer. The real problem, though, is how quickly the weather changes; cool calm mornings can very quickly change into afternoon thunderstorms and high winds up in the mountains. In 2006 I was caught (on my own) out in the open in the area southwest of Semonkong. I endured three incredible storms that afternoon, two of which included hail. There was no cover, and lightning was striking areas close to me. Small streams which I had crossed on my bike on the way in now became raging torrents within minutes and were too dangerous to cross on the way out. I was trapped in the mountains and spent a very soggy night in a local broken down kraal. It was a humbling lesson to me – don't ever underestimate how quickly and radically the weather can change in Lesotho, and always go prepared for the worst. There is no cellphone coverage in most parts; neither is there any internet coverage (I will write more about this problem later). You are on your own.

This is why I have always made it a policy to take someone competent and resilient with me when I go out into the mountains with my drone and equipment. In addition, we go well-prepared. The following list gives some indication of what we carry with us (aside from the drone equipment):

- Rain jackets, and ponchos (sometimes we end up wearing both at the same time!). The rule in Lesotho is as soon as you feel the first drop of rain you put on your rain gear, because there are buckets about to follow a few seconds later! As well as a few ‘ziplock’ bags to store sensitive electronic components in if the rain gets very heavy. We also have waterproof covers for the backpacks.
- Food, typically biltong, nuts, energy bars, dried fruit; things which take up little space, but can last for a few days if necessary, and come in waterproof packaging.
- Sunblock and sun hat, and a shade system of some kind. I use a small tarpaulin I have modified to hitch onto a bike and stretch out with two lightweight collapsible poles. This is not only to provide shade for us from the sun, but importantly too for shade over the laptop screen which you cannot see very well whilst programming in direct sunlight.
- Fluids – energy drinks, water and most importantly a flask of tea! One advantage of Lesotho is you will always find drinkable water close by in the many rivers.
- A small medical kit and emergency blankets.
- Emergency tools and spares for the motorcycles, as well as the helmets, gloves and goggles.
- Garmin GPS devices, as well as any notes I have made beforehand on how to access the various points I need to get to. I laminate these notes at home and ziptie them to the handlebars of the bike before we ride out.
- When all stored and carried in two backpacks, which also carry all the drone gear, each backpack ends up weighing about 30 kilogrammes.
- We wear clothing which is suitable for being outdoors, and importantly pants with either buttoned or zipped pockets. The main rule is when you lock the car before you

leave on the bikes you put the car keys into a zipped pocket, and you never open this pocket until you return to the car. It is far too easy to lose your car keys whilst scrambling over rocks in the mountains.

Illustration 5.47, below, shows a typical setup taken on one of our forays into the mountains to film.

**<u>Illustration 5.47:</u> Setup for a day's drone shooting**

Lesotho is a spectacular and picturesque place. The air is clear, the rivers are clear, there is a notable and welcome silence, and the countryside is largely unspoilt. Subsistence farmers and shepherds dot the land. The people in these remote areas are hardy, self-sufficient, helpful and incredibly friendly. But the countryside is harsh and unforgiving. There are numerous rivers, but mountains dominate. There is almost nowhere which is level, and rocks litter every bit of the terrain. This last point has particular importance for my drone designs, and I will write about it extensively later.

## 5.3 Design, Development and Deployment

Before I begin the explanation of the design of my drone, or more specifically the Unmanned Aerial System (UAS) because it encompasses more than just the drone per se, I need to outline the shortcomings that I had encountered up until this point. Some of these, I have already alluded to, but I will repeat them again. These are points I had to address, following on from the experiences and findings of the first three drones that I built, the quadcopter and the two hexacopters which I wrote about earlier on:

### 5.3.1 Camera View

I had had problems with the arms, legs and props of the drone coming into camera viewpoint when the drone was rolling or pitching aggressively. I would need a system where the camera was placed such that these components could not intrude into the shot.

### 5.3.2 Power

The previous drones were underpowered to a certain extent. In as much as they could handle calm conditions, as soon as the wind got up, they were unable to cope adequately with the radio control commands. This was particularly evident if the wind was blowing away from where I had launched. To bring the drone 'back home' (which of all movements could be classed as the most critical one) ended up with the drone straining and 'fighting' the conditions. This was simply because the motors and power systems were too small; to counter this I would need stronger motors (and the ancillary equipment which drives them) and bigger batteries. Let us be reminded that the winds in the Lesotho mountains are very strong; not only that, but they gust unpredictably and also swirl tremendously in the ravines, valleys and steep escarpments.

### 5.3.3 Size

Although the drones themselves were quite lightweight, they were in fact quite big. They occupied a large 'footprint' or 'envelope'. I have touched upon this previously. If I were to take a drone out into the mountains in a backpack using a motorcycle, the drone would need to be much smaller, or otherwise fold up into a relatively small package for transport, and then fold out at the flying location for flight.

### 5.3.4 Backup

There must be a level of redundancy built into the drone system. What this means is that there should be backup systems on the drone ready to take over should the primary system fail. Whilst it would be difficult – and expensive and much unwanted weight – to have a backup for every primary system, the most critical ones should have backup or redundancy. There should also be a way for the drone to recognise that a system has failed, and seamlessly transition to the backup one. Imagine for example that a motor failed when the drone was far away from me with a ravine in between where I was and where something goes wrong. Without this failed motor supporting the relevant arm (or 'corner') of the drone it would subside on that corner, flip over and fall into the ravine. It might take a long hike on my part to recover the (by now broken) drone. Far better to have a backup motor/system on that arm, so that another motor could take over and get the drone home to me. This redundancy goes beyond mechanical parts failing; there should be backup systems for critical electronic parts, too.

### 5.3.5 'Natural' take-off and landing areas

One of the biggest problems I encountered with the early drones was when I tried to take off or land from an area which was not either relatively level or smooth. The main on board flight computer likes to have IMU inputs showing that the drone is flying level (if it is stationary in the air). It is also expecting to be level just before it takes off, and it is level as it comes in to land (assuming that the landing is done as a vertical descent, which is preferable). There are two problems which arise when you are flying in remote areas. The first is ground which isn't level. This means that the drone is sitting on a slope before it takes off, and when it does take off it does so at an angle rather than vertically. This can be countered by judicious use of the controls as it takes off to 'bring it into line' so it isn't really that much of an issue. A far bigger problem is the reverse situation, when it comes in to land on ground which isn't level. The drone can be considered to be in a state of stasis or equilibrium when it is hovering in one place, with the thrust of the props perfectly counteracting the forces of gravity. This is the situation when about to land: the drone is brought close to the ground and allowed to hover just above the ground, before the throttle is cut and it lands. The issue is that it doesn't take much to upset this critical equilibrium, and if one of the legs/feet touch down first it transmits this force through the leg and into the drone, which then tips onto its side. As it tips over the prop on the other side (which is still spinning from momentum even though the throttle has been cut) it digs into the ground and starts a whole new set of forces through the drone. Often if this happens it breaks the prop as well. In worst case scenarios, the drone flips completely over, breaking more props or damaging other components. This doesn't only happen on smooth, level surfaces, because the drone comes down level, and all four feet/legs touch down at the same time. It only happens when one foot touches down before the other. And it doesn't only happen on sloping or non-level surfaces. Even if the ground is level but has rocks on it, one foot can touch down on a rock before the others with similar consequences. And remote regions of KZN and Lesotho are all sloping, and rocks are in abundance. This was to be one of my biggest challenges. It happened so often that I could not ignore it in my purpose-built designs. It required that the drone have independent suspension on each leg, so that when it touched down it could absorb the shock transmitted into a single foot, and not re-transmit this force through the rest of the frame.

Another common problem in these remote areas is the length of the grass. Strangely enough, this isn't a problem in Lesotho (which is largely devoid of lush vegetation and trees because of the harsh climates in the mountains) but is very common in KZN. Not only is the grass long, but it is very tough, and grows in tufts which anchor it well into the ground. The bottom line is that long grass and spinning props don't go together. Well, actually, they do go together, very well in fact, and this is the problem. When the grass gets caught by the prop it gets sucked into the area below the prop, where the motor is, and then tightly wound around the motor shaft as it spins. Very tightly, so much so that it is almost impossible to extricate without removing the prop first. My solution during the design phase was to have very long legs on the drone, so that the props were raised above the grass during take-off and landing. This had moderate success and I will detail later how I overcame it. The obvious question posed is why not cut the grass beforehand? The answer to that is that would take some while and I would have to carry some sort of cutting implement with me (dangerous if you have an accident riding to the site because it might impale you), and also, I am working often on private property (in KZN) and don't have rights to cut the grass. I did try and kick the grass flat (with my hiking boots), but it is very tough, and takes quite a bit of kicking. Also, it lasts well enough to place the drone in the place you have kicked flat for a short while, enough time to take off; but by the time the drone returns from its flight it is almost upright again, the grass being amazingly resilient. Added to this is that in windy conditions it is well-nigh impossible to place the drone down exactly where you had taken off, and the problem is compounded. I spent many minutes disentangling tightly wound grass from motor shafts. I had also tried to lay out a piece of fabric tarpaulin, but it had to be very heavy and be pegged down to be any sort of help; and this meant I had to carry extra things out into the mountains, so I scrapped that idea. The best I could do was try and find a take-off and landing spot where the grass was not too bad, but this was not always feasible because it would sometimes stretch as far as the eye could see.

Oddly, I also had problems where grass was short and 'groomed'. Here the grass has 'runners' which spread laterally. The feet of the original drones I built had small, sharp protrusions to them. Occasionally these sharp edges would snag on the grass on lift-off and hold that foot for a moment longer than the other ones which were now already in the air. This would throw the drone off as it attempted to take off. Also, occasionally a similar problem occurred on landing, particularly in high winds where the drone cannot land perfectly vertically. The drone would land with a sideways component to its flight, a foot would snag in the grass, and the drone would tip over as it landed. I would need to address the shape and construction of the feet when designing for working out in the field.

#### 5.3.6 Symmetry

As shown previously in the section 'New Forms of Video', the craft needs to fly forwards, sideways and backwards to capture the shots. I should make something clear, however; it is not flying *exactly* forwards, sideways or backwards (except on the odd occasion, for brief moments). One can think of it as 'veering' towards the front, back or sides of the drone. In other words, it must be able to fly in any orientation of a 360-degree circle around the drone. Not only that, but it must be able to transition to a new orientation of flying seamlessly and without any change in flight characteristics. Think of it as the craft flying in a straight line from A to B, but along the way it is yawing to different orientations to keep the front of the drone (and, therefore, the camera) facing wherever the rider happens to be. The drone might be flying from A to B in a straight line, but it is flying forwards, backwards and sideways along the way to get to B. This means it must have the same flight characteristics no matter which way it is pointing. So there has to be a symmetry to the craft, in particular the axes of the various motors and propellers. It is possible to build a drone which has non-symmetrical difference between its motors and it will fly; however it will not have the exact same flight characteristics in various orientations of flight, and as it transitions from one to the next it will exhibit anomalies in its flight behaviour. This was also quite a challenge for me, because even if the craft is non-symmetrical when it is folded for transport, it should become symmetrical once unfolded for flight.

#### 5.3.7 Autonomy

Also as discussed previously, it would be extremely difficult, and well-nigh impossible, to fly the drone via FPV when it is oriented away from the direction of the flight path; you simply cannot see where you are going because the camera is facing away from where the drone is flying to. The drone will have to fly autonomously along a preselected flight path. It should be stated that there are different kinds and levels of autonomy, and I will deal with these later, but suffice to say I need to be able to program in the latitude, longitude, altitude and speed of the drone for multiple parts of the flight (called 'waypoints'), and then the drone flies along this pre-set course. While this is happening the operator, observing the camera, orientates the drone by yawing it to keep the rider properly framed in shot, trusting that the drone is flying in the right direction, at the right height, and at the correct speed.

#### 5.3.8 Ease of Assembly in the field

This refers to the preparation of the drone from its folded configuration for transport in the backpack, to unfolding it for flight (and then folding it again for transport back to base). This process must be simple and fool proof. To keep it simple, I made it a prerequisite of my design that I would need only to use one tool for the process. To keep it foolproof I made it a prerequisite also that all the parts would be captive; in other words, there would not be any fasteners such as nuts and bolts (which are inherently tiny and which would need to be removed and reinserted). This meant that such components could not be 'lost in the grass' if I had to put them down and pick them up during assembly. Another aspect of being foolproof in assembly is that the various components should have built in alignment 'stops', so that it is assembled consistently every time without any chance of misalignment of the parts you are unfolding. Yet a further aspect of this requirement is that the parts which are being unfolded, particularly those which are safety critical, should have locking mechanisms to lock them into place.

### 5.3.9 Crashing

I came to the unavoidable conclusion that the drone was going to crash. It was an experimental system, and experiments fail particularly when you are 'stretching the envelope'. Now, to make the drone able to withstand crashing without any damage would have required structurally strong and heavy components, which are the antithesis of drone design where weight is an overriding consideration for flight (this is common to all forms of flying). So, I analysed the crashes and what was being damaged the most. This happened to be parts which are at the extremities of the drone: the props, motors, motor mounts, arms and legs. As the drone nose-dived into the ground these parts typically impacted first. This led to several design prerequisites.

The arms, motors, motor mounts, legs and props must all be exactly the same, no matter where they are positioned on the drone. This leads to a 'one size fits all' philosophy, and means that I only have to carry a limited number of spares for these parts out into the field. If these parts were all different, I would have had to carry individually different spares. Now, this may seem like a simple enough problem to solve, but it is not, particularly when you have what starts out as an asymmetrical-folded drone which becomes symmetrical after unfolding, as I will explain later. (It should be noted that a 'one size fits all' principle cannot be applied to the props, because, as seen in an earlier chapter, drones require props which spin clockwise and counter-clockwise. However, what I did want was all the same *size* props.)

Another consideration is to regard these parts as both sacrificial and offering protection to critical components and systems. By sacrificial I mean accept the fact that they are going to bend or break during an impact. So, make it easy to change them for spares you carry out into the field. By offering protection I mean design them in such a way that they become 'crumple zones' to absorb the impact and force, and not have this force transmitted to the main body of the drone which would be far more difficult to repair out in the field (much like motor cars have crumple zones to protect the passengers in the event of an accident). I am pleased to note that I have never had to replace any of the main frame parts of my drone designs, yet I have replaced multiple props, legs and motor mounts.

### 5.3.9 Other Design Objectives

There are many of these, and I will deal with several of them as I get to the actual construction of the drones. However, I will touch on a few of them in this section first.

#### 5.3.9.1 Choice of materials

I had been happy with the quality of materials used in the two drones I built from the 3DRobotics kits. They used substantially thick carbon-fibre frame plates and aluminium arms. I was less happy with the frame components of the JDrone which quite simply lacked the strength for my applications. I decided to use the same construction materials for my own designs as the 3DRobotics ones.

There were, however, a few drawbacks to using aluminium arms. The aluminium is a hollow square ‘box’ tube extrusion, and longitudinally hollow square tubing is very good at resisting flexing and is rigid, which is good. Unfortunately, the aluminium used is fairy ‘soft’ in engineering terms, and also the wall thickness of the extrusion is thin to save weight overall. This leads to problems with holes drilled through it which are subject to constant or repetitive force. The holes tend to ‘oval’ (from being circular originally) as the bolts through them apply a sideways force onto the holes. An example is the legs of the craft which are mounted to the arms: every time the craft lands it jolts this force through the leg mounting bolts, and the bolts wear on the soft aluminium and start the process of ovaling the holes. This gets progressively worse. The solution might seem to be to make the bolts tighter, so that there is more friction between the leg and arm to stop this slight movement each time it is jolted. But tightening the bolts tends to collapse the thin walls of the arms, which compromises its longitudinal rigidity. I would have to address this problem when using square box section aluminium arms.

5.3.9.2 Mass-produced, cost-effective components

Although I have quite a well-equipped workshop at home for manufacturing both mechanical and electronic parts, some processes can be tedious. As an example, I have a 'manual' lathe and milling head. So yes, I can make parts to tight specifications, but it takes time. If I have to replicate many parts of the same size and specification, it would take long hours. I could save time if I could buy 'off the shelf' items, particularly if there were many of these all the same. An example are the small 'spacers' or 'standoffs' of which I would need over fifty for each drone. These are mass produced and quite cheap to buy in bulk. So, I would use items such as these. However, these spacers only come in preset sizes, so I would need to design the drone around what was already available size-wise. This design choice is prevalent in many different components I would need, from mass-produced electronic boards to wiring to connectors and a whole host of similar essentials. Rather than 'reinvent the wheel' I would buy 'off the shelf' items. There were many times, however, in which I would need to build parts from scratch, simply because of the requirements of my particular drones. An example are the gimbals. Although there are a multitude of gimbals on the market, none of them would work in the configuration I required. Sometimes I was able to purchase an item that was not quite what I needed and modify it to my needs.

5.3.9.3 'Over Engineering'

There are times when I could save weight (and a few cents) by going with the 'bare minimum' of the various components, but I chose to 'over engineer' for those 'just in case' type of scenarios. An example might be a nut and a bolt. I could use a normal nut, but I chose to instead use a 'nylock' nut with a washer, to minimise the chance of it loosening over time or from vibration. Yes, a 'nylock' nut with a washer is a few milligrammes heavier than a normal nut and multiplied by many this can add a significant amount of weight; but I made the choice to compromise weight for safety and reliability. Another example is the thickness of wire used for high current applications (such as the motor drive wires). If my calculations showed I needed a particular gauge wire for the current I calculated, particularly if it was 'borderline', that I would use wire one gauge thicker which could carry a higher current. Yes, this thicker wire was slightly heavier (and once again multiplied by the number of wires can have weight significance), but I would trade this off against the scenario of what the calculated thickness might do, and then under some extreme scenario if it did not, the craft would fail. ‘Over engineering’ is a common approach to engineering design of products during the experimental phase, and as more data are collected on individual components or sub-assemblies this data would inform the final design criteria.

5.3.9.4 Function versus Form

This is the age-old dilemma of all designers: how to make something functional whilst still exhibiting good aesthetics or form. I am of the opinion that functionality should never be sacrificed at the altar of form, and yet it is often prevalent in products we purchase. It is something I am particularly sensitive to. Woe betide the teapot designer who designs a beautifully curved spout to the teapot, but every time you pour the tea it dribbles down the side of the pot or cup! To my mind the form of the teapot is not its aesthetic shape, but rather the controllable arc of tea as it pours, the balance in your hand as the pot empties, the natural grip on the handle; everything else such as shape, colour and texture of the pot are secondary. Which is not to say that you cannot build a teapot which does all of the above, but its function is paramount.

I had a similar approach to the drone, and the final result was not aesthetically appealing (other than to students of engineering). Each aspect of it was developed with function primarily in mind, and no thought was given to how it ‘looked’. There are times when there is a natural crossover, for example, the countersinking of bolts to minimise aerodynamic turbulence; but this was an engineering decision with the added ‘advantage’ of looking better than having protruding bolt-heads on surfaces. (I will write quite a bit about this later.) Once again, the form of the drone does not come from what it looks like as a finished product; to my mind the real form comes from the aesthetically pleasing videos it produces. That is all that matters. Function begets form.

## 5.4 Open Source

Yochai Benkler is an author and professor at Harvard University focussing on the fields of information technology law as well as the internet and society. In *The Wealth of Networks* (2006) Benkler asserts that peer production and sharing is the new model of production and that free, or open source, software is the driver underlying this shift away from traditional models of production. He describes what he calls 'commons-based peer production' as 'radically decentralised, collaborative and non-proprietary; based on sharing resources and outputs among widely distributed, loosely connected individuals who cooperate with each other without relying on either market signals or managerial commands' (60).

'Commons' can be understood as the opposite of individual ownership of property and, as such, usage and disposal of intellectual or actual property is vested in the group. Benkler describes various types and parameters of commons with the open access commons of the Internet being characterised by an absence of governing rules. The term 'peer production' refers to 'production systems that depend on individual action that is self-selected and decentralised, rather than hierarchically assigned' (62). This is a kind of 'uncoordinated nonmarket behaviour' (63).

The concept of open source software was introduced in 1984 by Richard Stallman, then of Massachusetts Institute of Technology (MIT), who 'operated from political conviction [and] wanted a world in which software enabled people to use information freely, where no one would have to ask permission to change the software they use to fit their needs or to share it with a friend for whom it would be helpful' (2006: 64). He began to release bits of code and allowed anyone to use and modify it provided they then distributed it again in the same way as he had.

The process that results in the creation of open-source software is characterised by collaboration and the product is characterised by being not-for-profit. Thanks to the Internet many individuals can collaborate from remote locations to work collectively on a shared project. None of them retains rights to the entire body of work, although individuals may retain rights to their own contributions. A licence is freely given to anyone who wants to use the software. Anyone who modifies software and distributes the modified version must license it in the same way (2006: 64). Many individuals can create and continue to refine one product over time.

János Mészáros has written about using open-source hardware and software for aerial surveying. He points out that the open-source development process can be really fast, because not only the developer but other users can test the code and give feedback (2014:155). For Benkler, free software is ‘without a doubt, the most visible instance of peer production at the turn of the twenty-first century’ (2006: 68).

Forums provide for peer-review and accreditation. Forums provide moderation and ‘the primary function of moderation is accreditation’ (Benkler, 79). In some cases, the moderators themselves are peer-reviewed. I have used online forums extensively in my designing and testing, because they can provide a large source of interested and experienced members who have often encountered the same challenges. In particular I have used two forums, DIYDrones and RCGroups. I have also been guided and kept up to date with new developments in multirotor technology via online magazines such as *SUAS News* and similar online publications.

I have found online communities and open-source software an invaluable resource in my research and design process. I reviewed a multitude of open-source software options before reaching a decision that was appropriate for my research and design aims. I needed to choose an open-source flight controller which ran open source code and so I chose the Ardupilot code, running on Ardupilot Mega (APM), or Pixhawk flight controllers. There are other open-source flight controllers such as OpenPilot, MultiWii and KK. I based my choice on a variety of reasons: Ardupilot is supported and developed by a commercial company, 3DRobotics; it has a very large online community in the form of Diydrones and Arducopter which provide informal peer review; it has many derivatives from third-party vendors and thus provides cheaper forms of the hardware; and it integrates with a variety of other platforms such as telemetry devices, on screen overlay devices, and GNSS devices (to name a few). Allied to this, Mission Planner/Arducopter allows you to interface with the code and download logs of the flights so that you can analyse a variety of performance indicators which allow you to troubleshoot elements of the drone which might not be optimal. Proprietary flight control software, such as that found in commercially available 'off the shelf' drones, does not have this accessibility of code. Most importantly, it supports autonomous flight and can be connected to a Ground Control Station (GCS) using open-source Mission Planner software. Ardupilot is derived from the Arduino code which is an open-source prototyping platform used to write the software. I will show some of the detail/setup that Mission Planner provides in the section 'Unmanned Aerial System'; below.

I am choosing to use open-source software and hardware for a variety of reasons. Firstly it has cost implications, and I am hoping to produce a design which is both cost-effective and can be replicated with relative ease by someone who has access to a fairly well-equipped home workshop. Secondly, by using open-source code I am able to recall various forms of data (known as 'logs') after flight and testing, so that I can analyse the performance of various parameters of the craft, and in so doing de-bug and improve on the performance. Thirdly, there is a large network of enthusiasts who provide informal peer review and who are always more than willing to assist in analysing these logs.

Fourthly, where open-source hardware is used there are often replicas of the various boards and components available from vendors, which are far cheaper than the originals, so this also has a cost impact.

One of the main reasons, however, of choosing to employ open-source software is the ethos of open source, which is that anything that is taken and modified should be put back into the creative commons for others to use and derive benefit. My own outlook on life has always been to help wherever I can with the skills and talents I have at my disposal. This extends beyond my personal life to the work environment as well and is one of the aspects of lecturing which I enjoy. My intention (with the approval of DUT) is to put all my design work into the public domain once I have finished, so that others can benefit from my research and designs.

I have used the following Open Source code on my drones:

- ‘Mission Planner’ (https://ardupilot.org/planner/).
- ‘Arducopter’ (https://ardupilot.org/), the flight software specifically for the multicopter I designed and am flying.
- Er9X (https://code.google.com/archive/p/er9x/), open-source code developed by enthusisasts to improve on the stock firmware which comes loaded on to the Turnigy 9x radio controller. There is an accompanying piece of open-source software for editing and personal configuration of this this code, known as EePe, (https://code.google.com/archive/p/eepe/).
- ‘Storm32’ (http://www.olliw.eu/storm32bgc-wiki/Downloads), open-source code for the camera gimbal I am using.
- The ‘SiK’ telemetry radio (https://github.com/ArduPilot/SiK), running a ‘Mavlink’ protocol. SiK is a derivation from the use of the SiLabs Si1000 radio chip.
- The Electronic Speed Control (ESC) for the motors has been flashed with ‘SimonK’ (https://github.com/3drobotics/solo-esc-simonk/releases) open-source code. This software allows individual configuration for the motor control tailored specifically for drone use.
- The overlay of status on the video monitor uses ‘On Screen Display’ (OSD) open-source code (https://code.google.com/archive/p/arducam-osd/wikis/minimosd.wiki) and loaded onto a small board on the drone known as ‘MinimOSD’.

In addition, I have used freeware (i.e., not open source but still free to use without the need for paying a subscription) from the following vendors:

- ‘eCalc’(https://www.ecalc.ch/xcoptercalc.php), freeware available online for predicting the performance parameters of a multicopter. Using drop down menus you can enter various design details such as battery size and capacity, motor models, frame mass, etc., and eCalc will then output results such as the flight time you can expect, the current draw on your batteries, and other considerations.

- Vibration-sensing software for measuring vibrations on drone parts, such as when balancing the motors. The software is known as ‘iSeismometer’ (https://iseismometer.soft112.com/) and is loaded on to your phone. I built a small test jig, and then balanced each motor. When a motor is out of balance it produces vibrations, and these vibrations are transmitted through the motor arms into the body of the craft, and ultimately into sensitive IMU’s of the flight controller, which can affect performance. Vibration minimizing is extremely important on a drone, and to this end the props are also balanced, but this is done with a mechanical prop balancer. The setup jig for the iSeismometer motor balancing is shown in Illustrations 5.48 and 5.49, below.
- Basecamp and Google Earth (detailed previously).

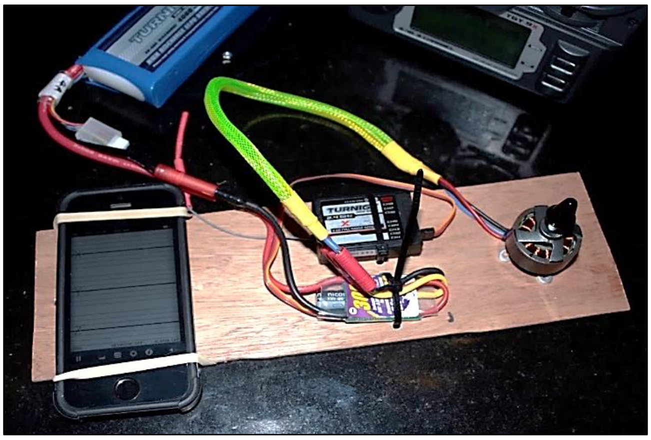


**Illustration 5.48: Vibration testing jig**

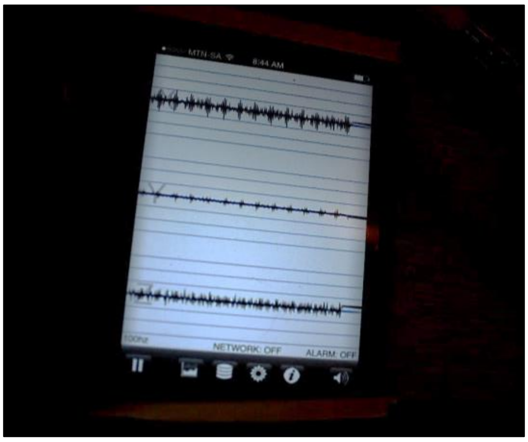


**Illustration 5.49: iSiesmometer readout**

## 5.5 Autonomous, Unmanned Aerial System

It should be noted that the abbreviation ‘UAS’ is used both as ‘Unmanned Aerial System’ as well as ‘Unmanned Autonomous System’. Because of this inconsistency if have chosen to use the term Autonomous, Unmanned Aerial System because it is all inclusive. However, what we are essentially talking about is an aircraft which flies autonomously.

My UAS will comprise of six basic parts:

- The multicopter/drone.
- A Radio Control system.
- A Ground Control Station, in this case a laptop running the Mission Planner software.

- A two-way radio telemetry system.
- A radio Video Link feeding visuals from the multicopter to the ground.
- A video monitor on the ground for the operator to watch.

The heart (or more correctly, the ‘brains’) of the entire system is the Mission Planner software. Mission Planner is used for:

- Uploading the relevant Arducopter firmware to the flight computer on the drone.
- Configuring the drone’s on-board sensors (magnetometer, IMU’s, barometric altimeter, GPS, etc.).
- Configuring the Radio Control channels and calibrating them as inputs to the drone.
- Tuning the drone for optimum performance.
- Setting parameters for correct behaviour and performance and uploading changes to these settings where necessary.
- Monitoring data and performance in real time during flight.
- Downloading performance parameters (known as ‘flight logs’) from the drone after flight.
- Comparing and analysing these data logs.
- Preparing, creating and adjusting autonomous ‘missions’.
- Uploading previous missions or downloading and saving current missions.

I will explain a few of the ways in which I have used Mission Planner in my research. (Please note that it is an extremely powerful tool, and I will only be ‘scratching the surface’ in what I describe below.)

Illustration 5.50, below, shows the ‘Home’ page, or landing page, when you open Mission Planner. It is known as officially as the ‘Flight Data’ page. On the top right is the ‘Connect/Disconnect’ button to connect the telemetry to the drone (being green it shows the telemetry is connected, even though it says ‘disconnect’ in this image that means I push/click the button to disconnect next). When you connect the telemetry, the software downloads the current parameters and status of the drone, which is then displayed in this screen.

The top left is the Head Up Display (HUD). This shows a graphical image of what the drone is currently doing. I will show more detail of this in a further Illustration.

Bottom left is the ‘Flight Data’ display, and it has various tabs you can access. Once again, I will explain more in further Illustrations.

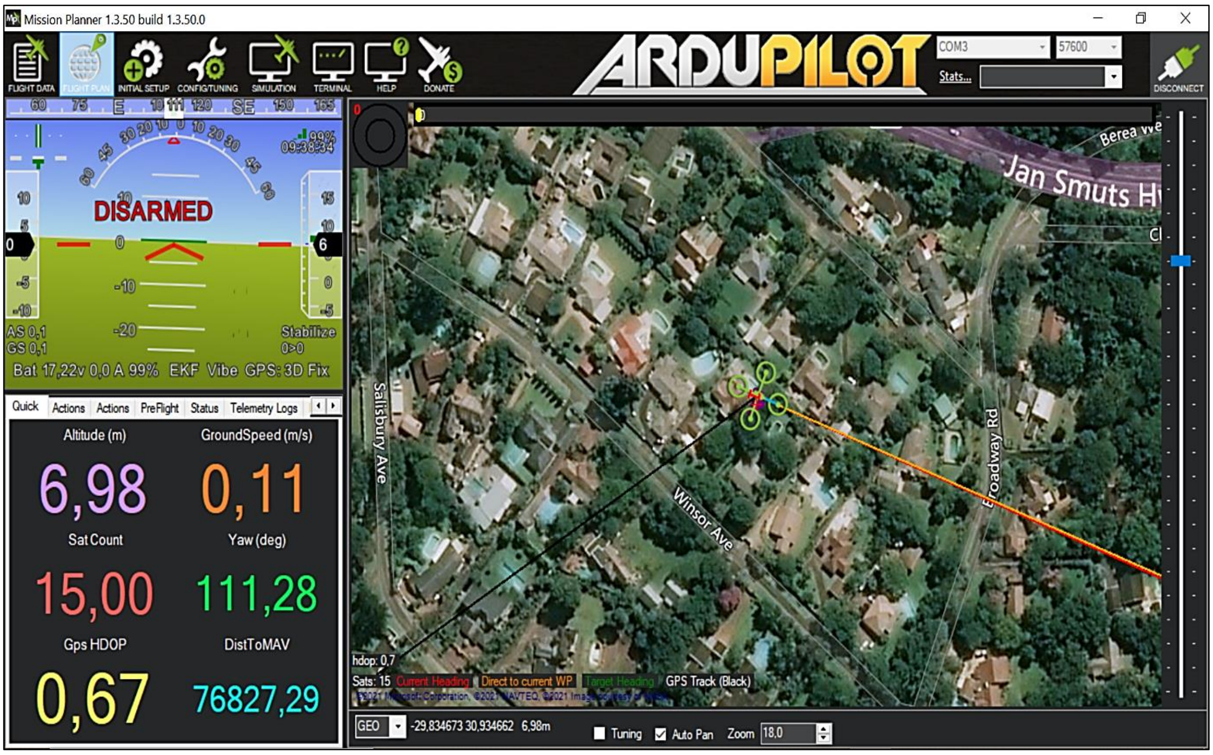


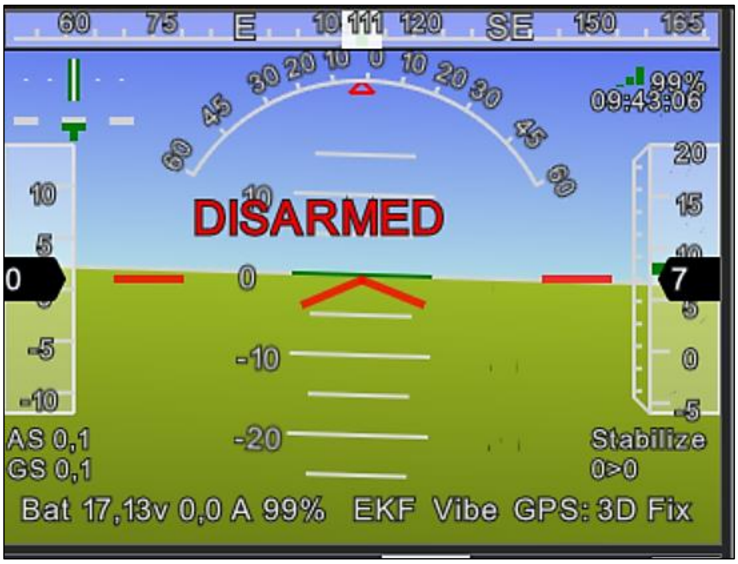
**Illustration 5.50: Mission Planner Flight Data page**

On the right, and almost filling the screen, is a satellite image showing the location of the drone in real time. Currently it is showing the drone at my residence. You can zoom in or out of this image by using the scroll bar on the right-hand side (or the scrolling wheel on the computer mouse, which is often easier). You can also access sub-menus of this screen by right clicking your computer mouse.

Illustration 5.51, below, shows the HUD in more detail. This is a data-driven graphic generated in real time, and constantly updating via telemetry. What it shows is:

- The Compass Heading across the top of the display.

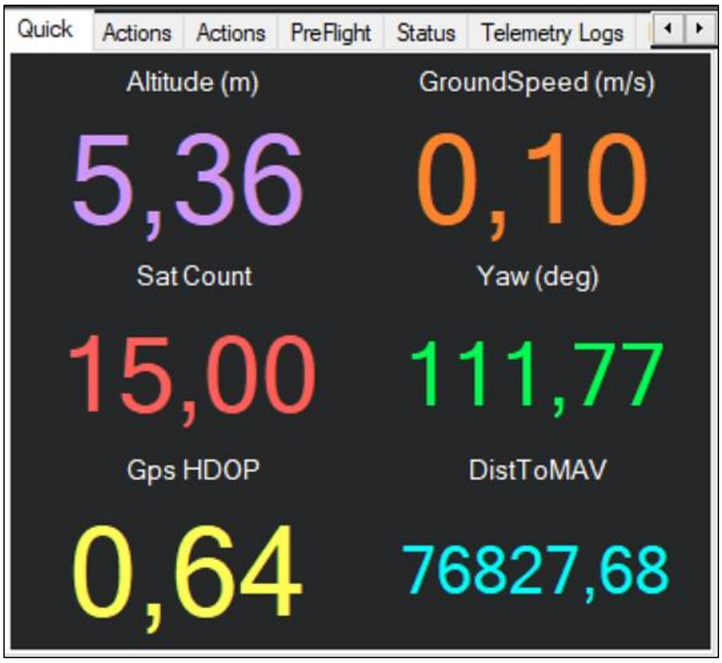
- The Roll angle of the drone, a curved display top centre; and, as assistance, the level of the horizon (where green meets blue).
- The Pitch angle of the drone, a series of horizontal lines through the middle of the display; and, as assistance, the position of the horizon (as the green moves up it means the drone is pitched down, and vice versa).




**<u>Illustration 5.51:</u> Mission Planner Head Up Display**

- The Altitude on the right-hand side (showing 7 metres in this case), and the Airspeed on the left-hand side (showing 0, in this case because the drone was just sitting on a wall outside my study while I downloaded these images).
- The telemetry Signal Strength, top right (showing 99%), and the GPS Location Time, also top right (showing 09:43).
- Various data at the bottom, shown in white. These parameters are essential conditions the drone has to fulfil before it can fly, and if they are in red the drone will be prevented from flying by the software until the conditions have been corrected. The conditions are, from left to right, Battery Level (showing 17.3 volts), Battery consumption at this moment in time (showing 0.0 Amps because the drone was just sitting static at the time), Battery capacity (showing 99% available), Extended Kalman Filter (EKF, a very important component of the algorithm for inertial navigation), Vibe (for ‘Vibrations’ to check that these are within acceptable limits for the IMU’s) and GPS Fix, showing ‘3D’ which means that the accuracy of the satellite reception is good enough for flight, in latitude, longitude and altitude.
- Above the bottom data on the right-hand side, it shows ‘Stabilize’. This is the flight mode engaged at the time, and I will explain this in detail later.

Illustration 5.52, alongside, shows the Flight Data display in more detail, and in this picture the 'Quick' tab has been opened. You can configure various parameters into this display, depending on your needs. I really only refer to two of these parameters when I am out flying, the Sat (for satellite) Count and the GPS HDOP.



**<u>Illustration 5.52:</u> Flight Data display, with 'Quick' tab opened**

The Sat Count shows 15,00 in this case. It is showing how many GNS satellites it is currently receiving information from. Note that this is GNS (which is an abbreviation of GNSS, Global Navigation Satellite System) which is a broad term that includes GPS, Galileo, Beidou and Glonass satellites, because the navigation system can intersect all four networks. The number of satellites which can be 'seen' varies continuously throughout the day because they are orbiting above the earth, and continually appearing and disappearing above the horizon. The quality of the signal is also affected by both their position and anything which intrudes into view. So, the higher they are above the horizon the better their accuracy of information; and anything such as trees, buildings or even cloud cover can obstruct their view and degrade their signals. Essentially the more satellites, the better for GPS accuracy and positioning.

The GPS HDOP (shown in Illustration 5.52, above, as 0,64) is the critical information for me. HDOP stands for Horizontal Dilution Of Precision and is a measure of how precisely the drone can position itself according to the satellite data. More visible satellites, and higher signal strength from them, leads to a more precise positioning and a lower HDOP number. I have a rule that I will not fly until the HDOP drops below 1,00. Anything above this and it is too risky to fly. Incidentally, Sat Count of 15 and HDOP of 0,64 as shown are very good figures; often when I fly, they are worse than this but still acceptable.

Illustration 5.53, alongside, shows another tab in the Flight Data display, in this case the Status tab. This is a constantly updated set of data monitoring more than 200 parameters of the drone's performance (more can be accessed by scrolling to the right along the bottom scroll bar).

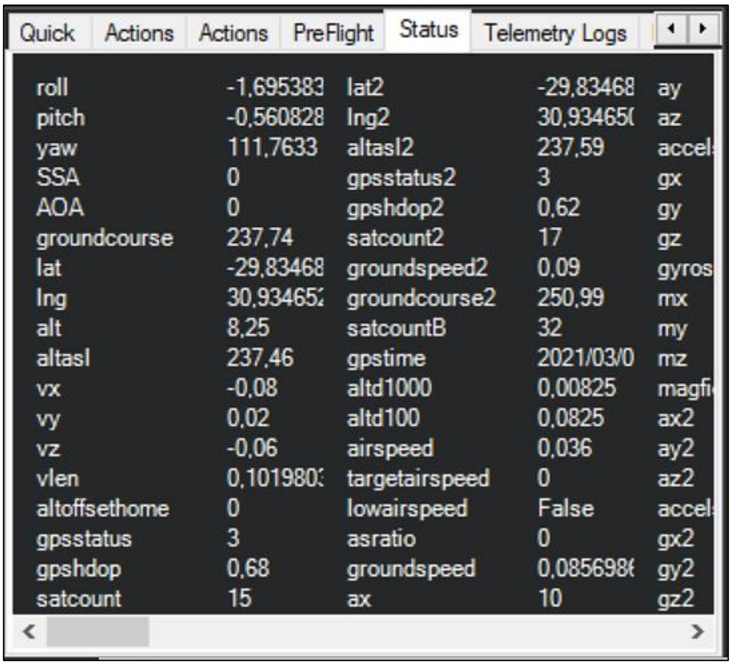



**Illustration 5.53:** **Flight Data display, with 'Status' tab opened**

Illustration 5.54, alongside, shows the 'Telemetry Logs' tab of the Flight Data display. You can use this to download a saved data file and see what a previous flight looked like, overlaid on to Google Earth. An example of this from one of my flights is shown in Illustration 5.55, below. This is the same example of which I showed pictures from in the earlier section 'New forms of video', and were taken from an enduro race I covered in New Hanover, KZN, in 2017. You will note that the elevations of the drone don't quite match up with the Google Earth image; there are slight inaccuracies when integrating the two. That is why there are only red dots on the right-hand side of the picture. It seems as if the drone has flown into the ground but in actual fact it is just skimming along the height of the grass down into

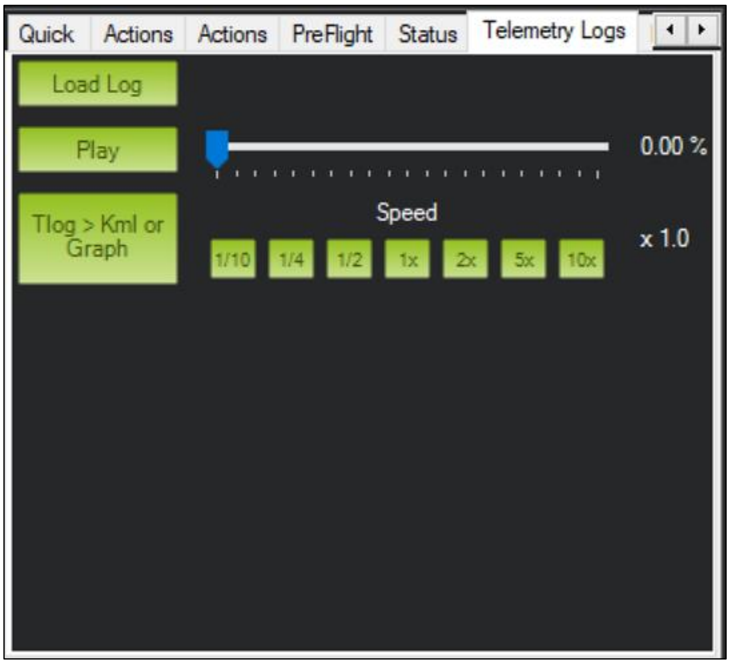
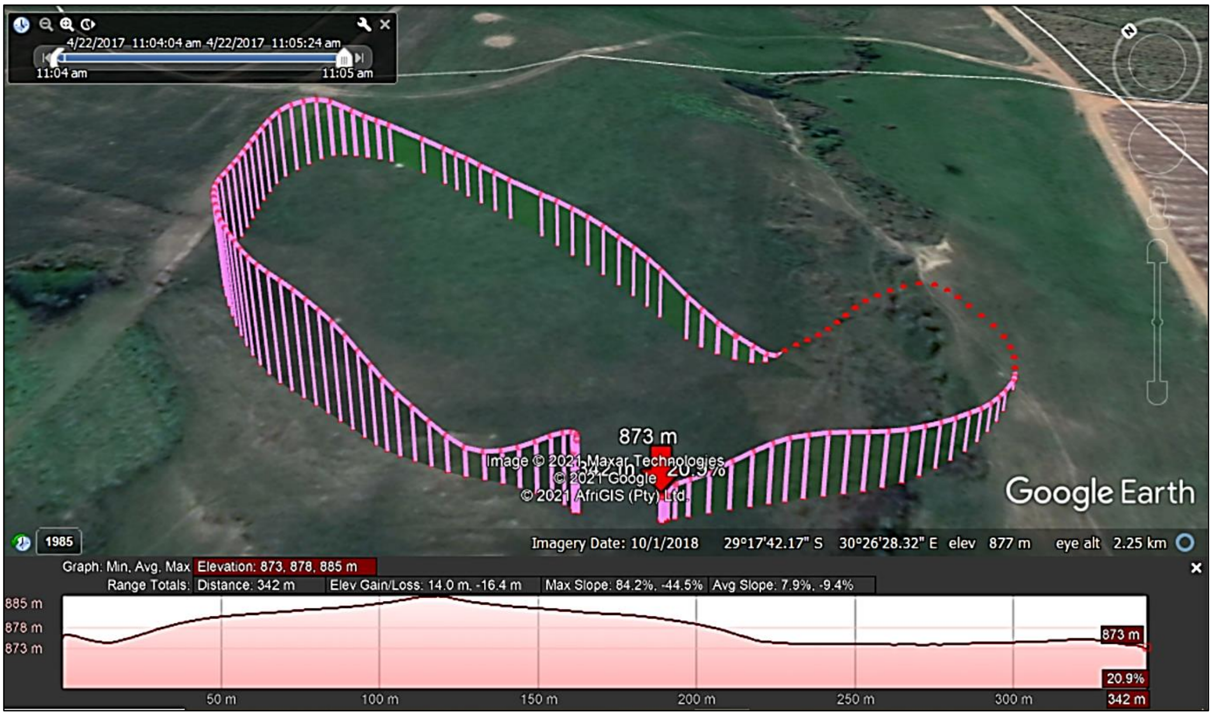


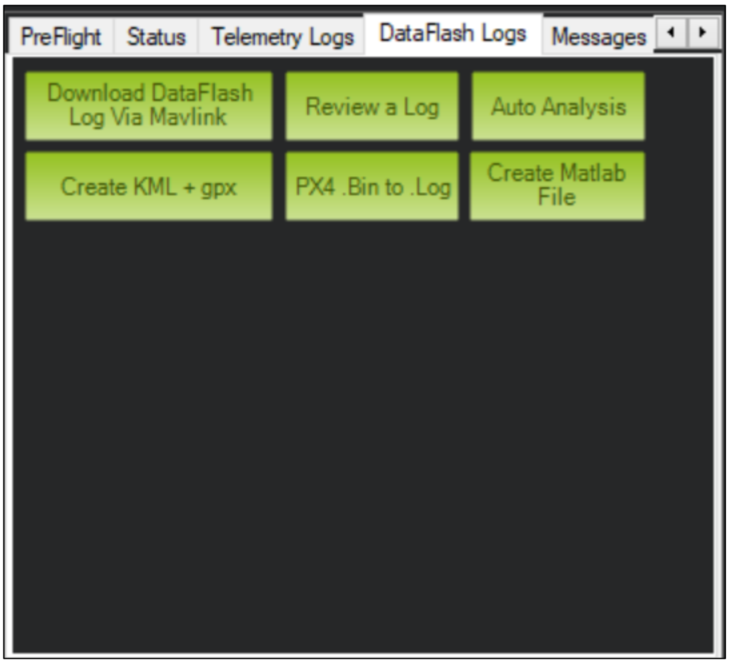

**Illustration 5.54:** **Flight Data display, with 'Telemetry Logs' tab opened**

the river valley. At the bottom of the image, I have graphed the pre-planned altitude changes of the drone as it flies along.




**<u>Illustration 5.55:</u> Telemetry Logs integrated into Google earth image**

Illustration 5.56, alongside, shows the 'Dataflash Logs' tab of the Flight Data display. The flight computer on the drone records all its data onto a microSD card. You can then download this data for analysis. I have shown an example in Illustration 5.57 below, but this is really only a small sample of what can be displayed. You can call up hundreds of different parameters, and graph them against other ones, to determine how the drone has performed. It is particularly useful, I would say essential, with experimental vehicles to try and improve on their performance. It becomes the most important tool to try and decipher the reasons for poor




**<u>Illustration 5.56:</u> Flight Data display, with 'Dataflash Logs' tab opened**

performance or a crash, since you can see what systems either failed or did not perform as expected. I have used this dataflash analysis extensively in two ways. Firstly, I have tried to interpret the data myself. But secondly – and this is the value of online forums – I have submitted the data to forum members when I cannot fathom what has gone wrong. Their input, from looking at the data, has determined the cause or pointed me in a new direction of sleuthing. I have to credit online forum members more experienced with data analysis than myself for a great deal of assistance during this research.


**<u>Illustration 5.57:</u> Dataflash log download example**

Just as an example I have chosen in Illustration 5.57, above, to graph the Pitch (in green), the Roll (in blue) and the Yaw (in yellow) of the craft through a series of flights. I have done this example to illustrate the large Yaw movements of the craft compared to the Roll and Pitch during its flight. This is to show how much the drone is rotating around its yaw axis as I attempt to follow the riders throughout the flight (this is related to the part above, where I show how the craft is flying forwards, backwards, and sideways and continuously varying).

Illustration 5.58, below, shows an example of the same flight day referred to above, in New Hanover. When you enter the Dataflash page and recall a particular flight (or series of flights) it shows an image such as this picture. Top right is a satellite image with the flights you have selected overlaid (the red and purple tracks). Top left is a graph which you can use to compare various forms of data, such as Illustration 5.57 above. You select this data from the drop-down menu on the right. Each parameter indicated with a '+' can be further expanded. Bottom left is the actual data itself, which you can further enter by clicking on one of the boxes to investigate further.

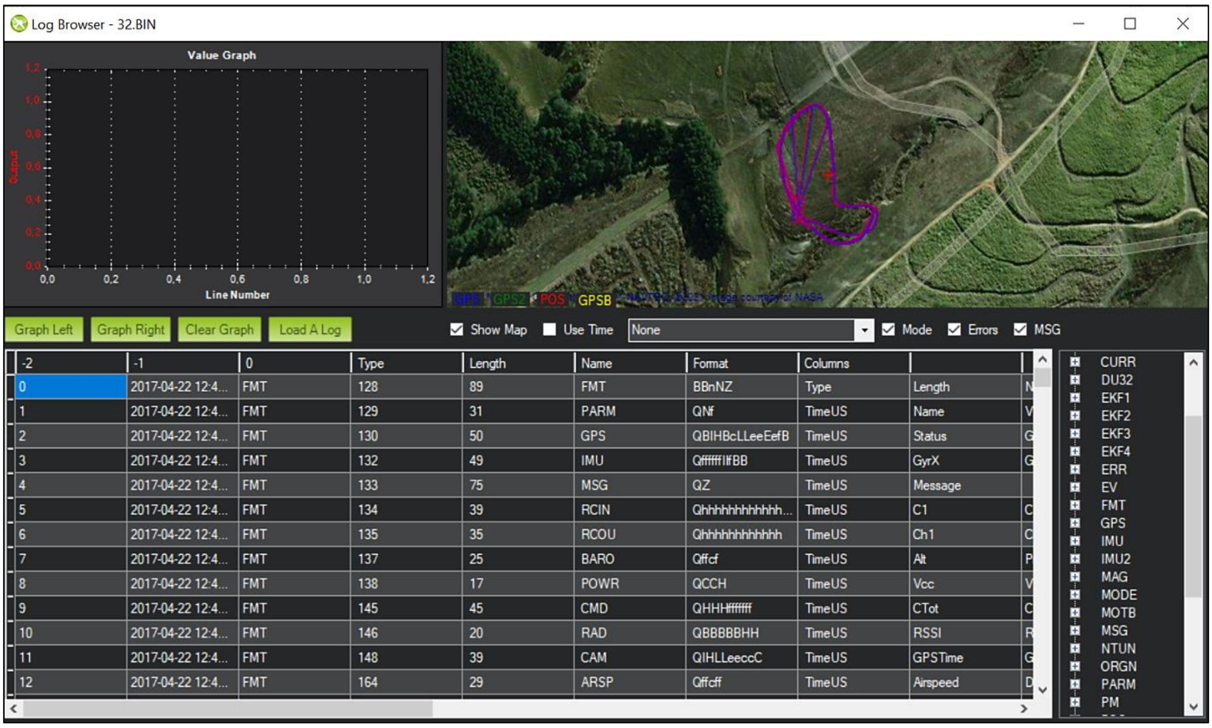


**Illustration 5.58:** **Dataflash download of a flight displayed**

Continuing on with the exploration of Mission Planner takes us to a page/tab known as 'Initial Setup', shown in Illustration 5.59, alongside. This is the tab you use for configuring and calibrating the drone you wish to fly. This page is the 'Frame Type' tab, and it is

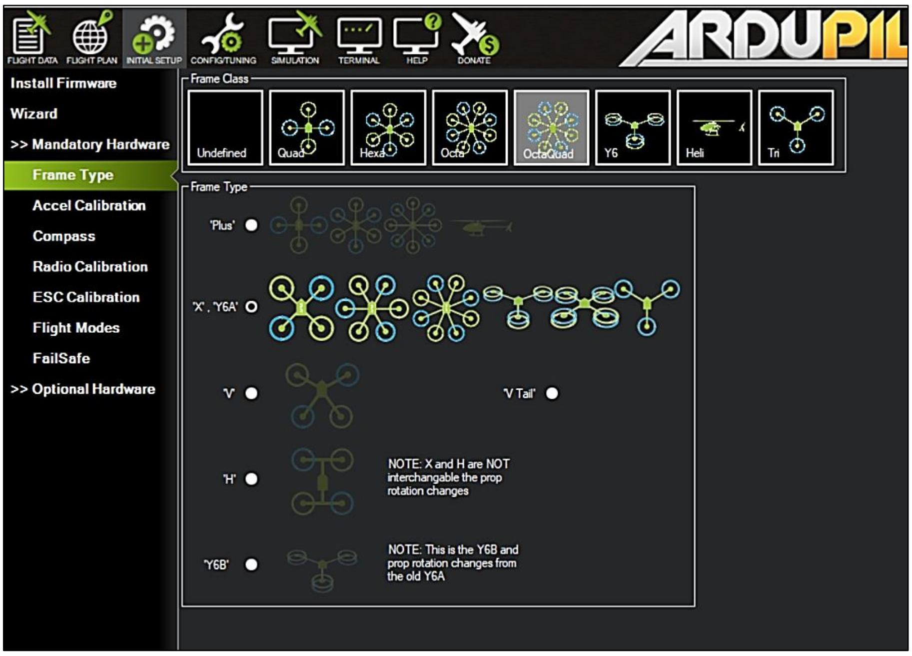


**Illustration 5.59:** **'Frame Type' tab in 'Initial Setup' of Mission Planner**

the initial stage of choosing what type of drone you are flying. You can see that Arducopter supports a wide range of frame types. I am not going to detail all of the available setup procedures; it would be far too long and there is documentation available online to do so.

What I will show is only a very few of the setup procedures as relevant to my needs for this research.


**Illustration 5.60**: **'Radio Calibration' page of 'Initial Setup' in Mission Planner**

Illustration 5.60, above, shows the 'Radio Calibration' tab where you interface your Radio Controller with Mission Planner and the drone. I have a 9-channel transmitter, but I only use 7 of those channels, as per these settings below (the green bars indicate where the setting was at the time of me capturing the image, and the changes as you adjust a certain parameter):

- Channel 1: Throttle
- Channel 2: Yaw
- Channel 3: Pitch
- Channel 4: Roll
- Channel 5: Flight Mode
- Channel 6: Camera Pitch/Tilt
- Channel 7: Not used (was previously setup for Camera Roll but became unnecessary with improved camera gimbal software)
- Channel 8: Waypoint setting
- Channel 9: Not used

Some of these are self-explanatory, but others I will elucidate on.

Channel 5 is the 'Flight Mode' channel, or switch. It is essentially a '6 position' switch, but it is actually a combination of 2 switches on the Radio Controller. The switches are located on the top right-hand side of the Radio Controller and are shown in Illustration 5.61, alongside. You will note that the left-hand switch is longer than the right hand one, and also has a different contour. This is important because when you have to operate them you have the video goggles/screen in front of your eyes, so you cannot visually see the switches, but have to feel for them. The left-hand switch has three positions, and the right-hand one has two; together they give six different options which are configured via Mission Planner to the drone. As you change the switch/s the drone enters a different flight mode.


**__Illustration 5.61:__ Flight Mode switches on Radio Controller**

Mission Planner allows and supports numerous flight modes. The ones I have chosen to use are shown in Illustration 5.62, below, and they are: Stabilize, Altitude Hold, Loiter, Auto and Return To Launch (also commonly called 'Return to Home'). I will briefly explain each in turn. However, it is worth noting before this that, although there is only one mode called 'Auto' (for fully autonomous flight), each mode contains a certain level of autonomy or intervention from the drone software. There is one mode I don't use known as 'Acro' (from 'Acrobatic') which has no intervention, but it is for pilots who are highly skilled and want to do flips, barrel rolls and such like; something I don't need and don't want to endanger my drone by attempting.


**Illustration 5.62:** **'Flight Mode' setup page in Mission Planner**

'Stabilize' does just that, it stabilises the drone during flight. You have full control of the Roll, Pitch and yaw of the drone, but the onboard sensors on the drone attempt to keep the flight 'stable'. So, they intervene if you put far too much control input into the drone (for example, by mistake, not intentionally) and will not allow the drone to do anything untoward which might be difficult in the heat of the moment to correct. It is the default mode for learning to fly and improving your skills. It must be noted that all these modes of operation have settings within the Mission Planner software where you can customize them to your own particular requirements, so you can specify the degree of automatic intervention of the software into the control you have over it. Stabilize is typically the mode you use for launching and landing the drone, or for 'free flying'.

Altitude Hold (Alt Hold in the picture) is a mode where the software controls the altitude of the drone and keeps it at that preset level. If you switch from Stabilize to Alt Hold, it will remember the altitude at which you switched and keep that same height all the time. It is one of the first tests you do on the drone as you set it up towards full autonomy, and you take a while calibrating it initially. It uses the on-board barometric altimeter as well as the inertial navigation software to maintain this height. Once correctly set you should be able to fly the drone forwards, backwards and sideways at full speed, or just hover it, and the height above the (level) ground should not change noticeably.

Loiter is a mode which keeps the drone in one place in the air, and includes maintaining Latitude, Longitude, Altitude and Compass Heading. Essentially when you enter Loiter mode the drone should stay exactly where it is and keep the same heading. If the wind blows it away from this place, or changes its orientation, it must return to the original place in the sky with its original heading. To the untrained eye Loiter doesn't seem like it's that difficult to achieve, because the drone is 'just staying in one place', but to the student of engineering it is a beauty to behold. It means that all the sensors, as well as the software, are working in perfect synchronism. Getting the drone to Loiter successfully (which often takes hours of setup and tracking down recalcitrant traits like vibrations) is a worthwhile exercise; and it is the last setup to get right before proceeding to full autonomous flight. Once again you can override the 'plain' Loiter by configuring the software, so for example you can manually move the craft while in Loiter mode using the throttle, yaw, pitch and roll controls, but only slightly or slowly.

Return To Launch (RTL) is a 'safety' mode generally. It is used if something untoward happens and you need the drone to come back to you. When you engage 'Return To Launch' the drone will immediately come back. Say, for example, it is quite far from you and you visually cannot see its orientation in the air, so you think it is facing away from you, but your control is reversed because it's facing towards you. Engage RTL, bring it home, and start again. Return to launch can also be initiated by 'Failsafes' (there are various ones), so for example, if the drone loses radio-control signal (maybe it is too far away, or a building or tree is masking the signal), the drone will sense this loss of signal, enter RTL, and 'come home'. You can configure these fail safes in the software. You can also configure how you want the drone to behave during the RTL phase; for example, I have set mine up to immediately gain altitude of 5 metres, fly home at that altitude, and then enter a loiter phase at 3 metres above from where it took off initially. I can then enter Stabilize and land the drone manually. I use the RTL mode as an 'emergency' mode; this is important to remember when I detail the layout of the switches, soon.

‘Auto’ (for ‘Autonomous’) is where the drone is programmed to follow a preset flight path. Essentially you set up a series of ‘Waypoints’ to which the drone will fly in a particular sequence, at a preset speed. Each Waypoint has a Latitude, Longitude and Altitude specified. I will spend more time on this aspect soon, but first I must explain how I have set up the Mode switch/s for my particular needs.

Illustration 5.63, below, shows the Mode switch combinations. The ‘long thin’ 3-position switch on the left, the ‘short fat’ 2-position switch on the right; and how they are configured for the various modes I want to employ as referenced to the Flight Modes tab in Mission Planner (Illustration 5.62, above). In the diagram it may seem that there is no reason as to why each mode has a particular configuration of the switches, but there is a great deal of logic involved as to why I set them up like this.

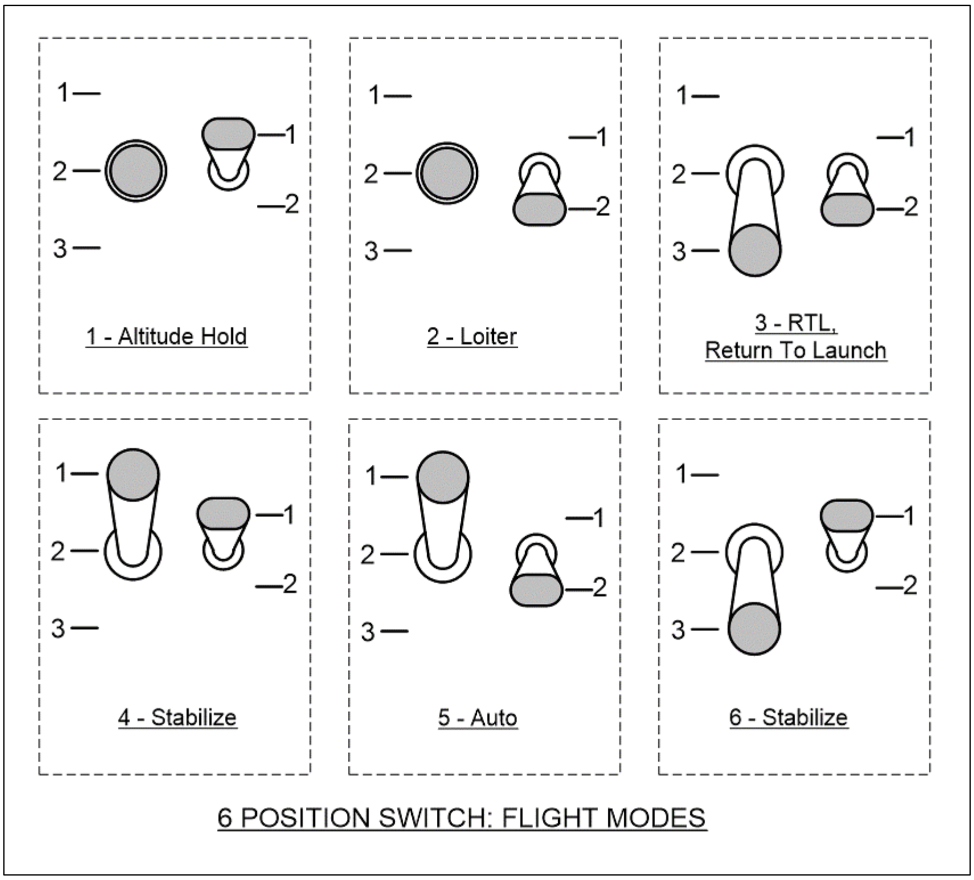



**Illustration 5.63:** **Flight Modes according to Switch Combinations**

Uppermost to bear in mind when applying the logic is that the switches must be operated unsighted, because you have a video screen strapped to your head over your eyes. This means that not only must everything be done by feel (typically using the thumb and/or forefinger of your right hand), but also the next mode you want to engage should only be ‘one click away’ from where you currently are. The modes are set up in such a way that they suit both testing the vehicle as well as autonomously flying it.

Illustration 5.64, below, shows the possibilities during testing. Of paramount importance are the two modes which must be most easily available, Stabilize for takeoff, landing and general testing; and Return to Launch (RTL) for emergency use. These modes have the switches either both ‘up’ (Stabilize), or both ‘down’ (for RTL). The switches are physically positioned quite close together on the Radio Controller, and you can flip them together quickly and immediately (thumb for up and forefinger for down).

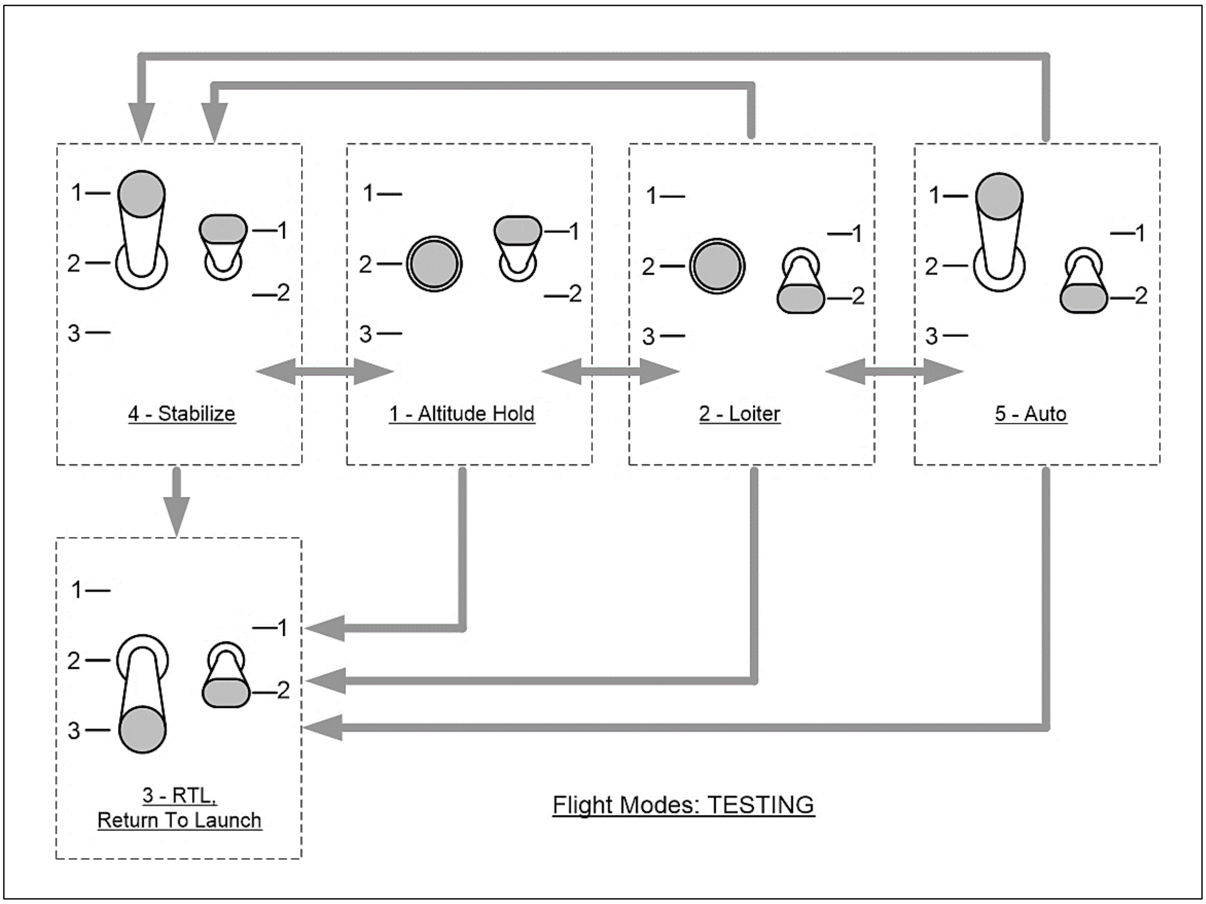



**Illustration 5.64: Flight mode switching during Testing phases**

During testing I want to progressively test more and more complex flight modes, in other words I want to transition from Stabilize, to Altitude Hold, to Loiter, and then finally to Auto (and the reverse order as well). I can do this using a sequence of switching which has only one switch transitioning one position change each time, as shown in the above diagram. If necessary, I can engage Stabilize or RTL with only one movement as well.

The same mode switch positions should also be applied to autonomous flights, and this scenario is shown in Illustration 5.65, below. Now, I can take off in Stabilize and get the craft at a comfortable height in the air, and then switch to Auto with one switch only changing one position for the drone to begin its autonomous flight. However, sometimes I may want to interrupt this Auto flight by transitioning to Loiter mode. There are numerous reasons for this, but I will give two examples. The first one concerns ‘waiting for riders to arrive at the pickup point’. The pickup point is when they arrive at a certain place, and I begin following them with the drone. So, I will fly the drone on Auto out to this pickup point (which can be quite far from where the drone is launched and could involve geographical features such as a valley in between the launch spot and where the riders first appear into view of the drone/camera), then once I’m there I switch into Loiter and wait in this mode for the riders to appear. I can Yaw the drone to frame up the opening shot or change the position slightly if necessary whilst in Loiter as explained previously. Once I’m ready to follow the riders, I switch back into Auto and the drone continues its flight whilst following them. This switching between Auto and Loiter once again only requires one switch changing one position each time.

Another reason to switch between Auto and Loiter is if the riders encounter a difficult obstacle which slows them down. For example, they may have to cross a rocky river. When they get to the river they slow down, often stop to gauge their best way of crossing, and then ride slowly through. What I will do is switch from Auto to Loiter as they get to the river, hold stationary above them watching their decision and progress (I will also tilt the camera down as well during this phase), and then once they get going again beyond the river, switch back to Auto flight. Once again switching between Auto and Loiter is only one switch one position at a time; and also RTL is only one movement away for emergencies.

It takes a bit of practice to learn the switching, getting a feel for it as well as memorizing the sequences, but on the whole, I have been pleased with the logic I have applied and its implementation in the real-world situation.

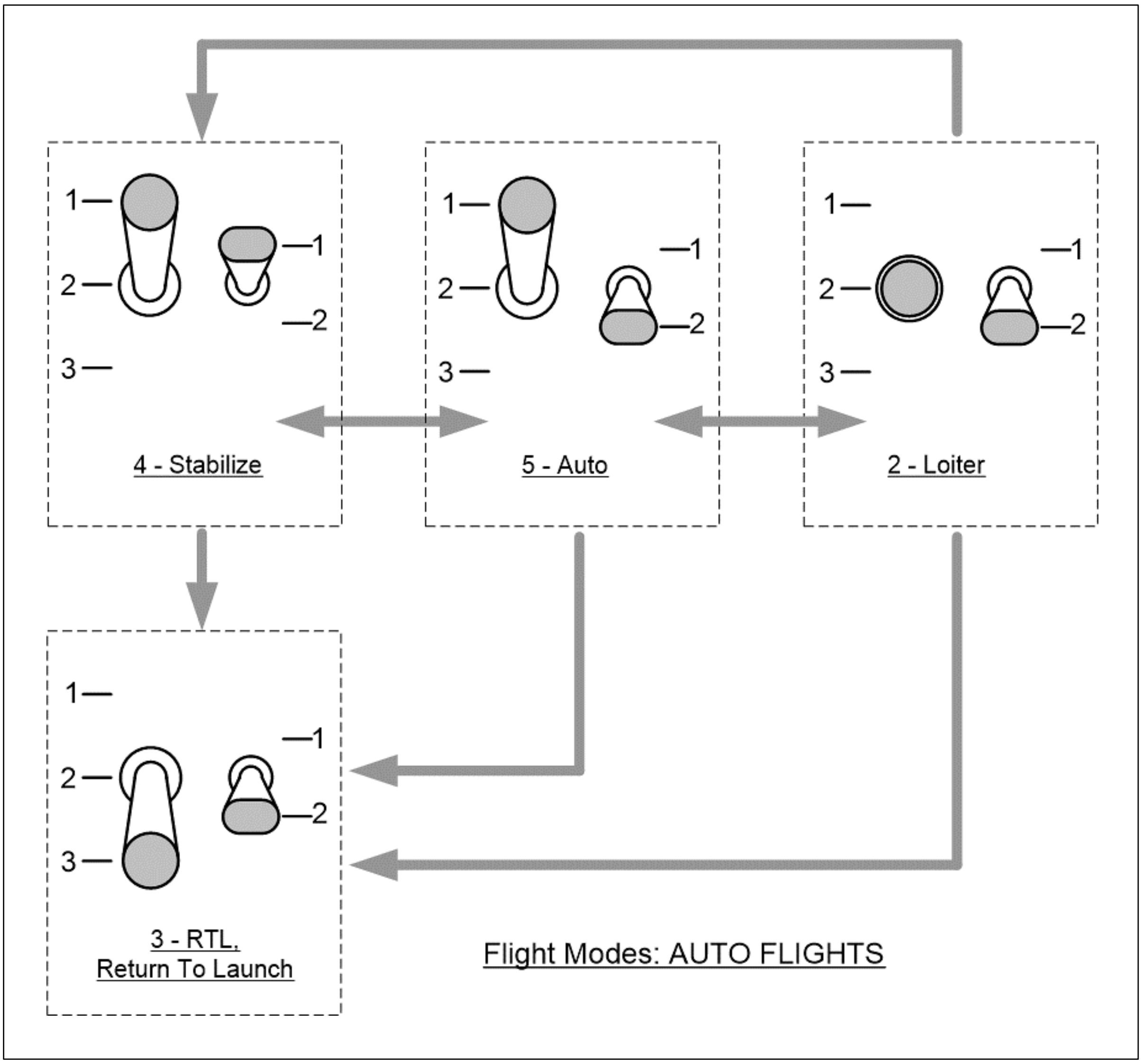



**Illustration 5.65:** **Flight mode switching during Auto flights**

Illustration 5.66, below, shows the 'Extended Tuning' page of the 'Configuration/Tuning' tab in Mission Planner. I have included this Illustration to show a few parameters I have set, or which can be changed. The first to notice is the 'Channel 8 Option: Save WP (Waypoint)' towards the bottom of the screen. As noted earlier I have assigned Channel 8 of the Radio Controller to saving waypoints. This is via a switch on the top right of the radio controller, shown in Illustration 5.67, below. You can fly the drone, and wherever you engage the switch it will remember it's position and record it as a waypoint. This is a very useful function, though limited in its practical application somewhat when the drone is quite far away, and you want to record a precise position. This drawback led to the development of a 'pseudo drone' which I will detail later, and then I used this switch extensively.

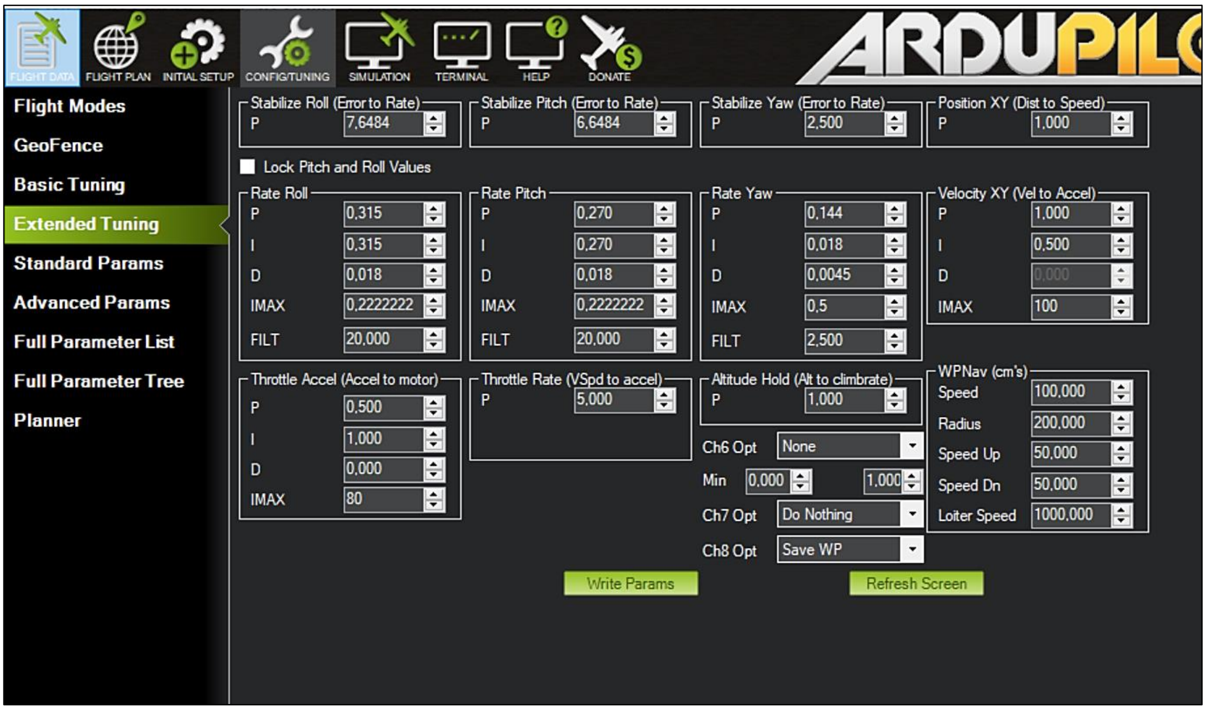



**Illustration 5.66**: **'Extended Tuning' page in Mission Planner**

Above the Ch 8 Opt choice is Channel 6 Option, and you will see it says 'None'. Whilst this is true for the Mission Planner software, I have actually configured the drone to bypass Mission Planner and go straight into the gimbal controller so that Channel 6 on the Radio Controller sets the pitch (or up/down tilt) of the camera. The control for this is the (unfortunately out of focus) black knob on the Radio Controller behind the 'Set WP' switch in Illustration 5.67, alongside.

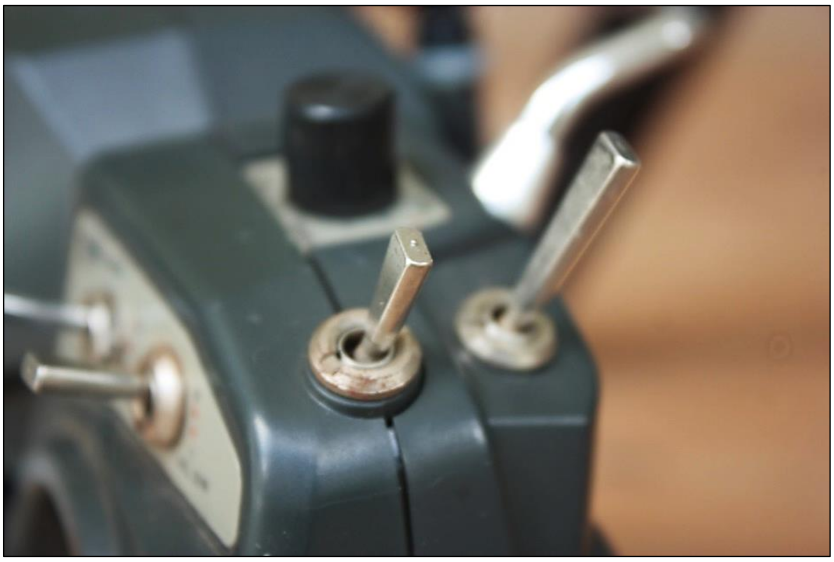
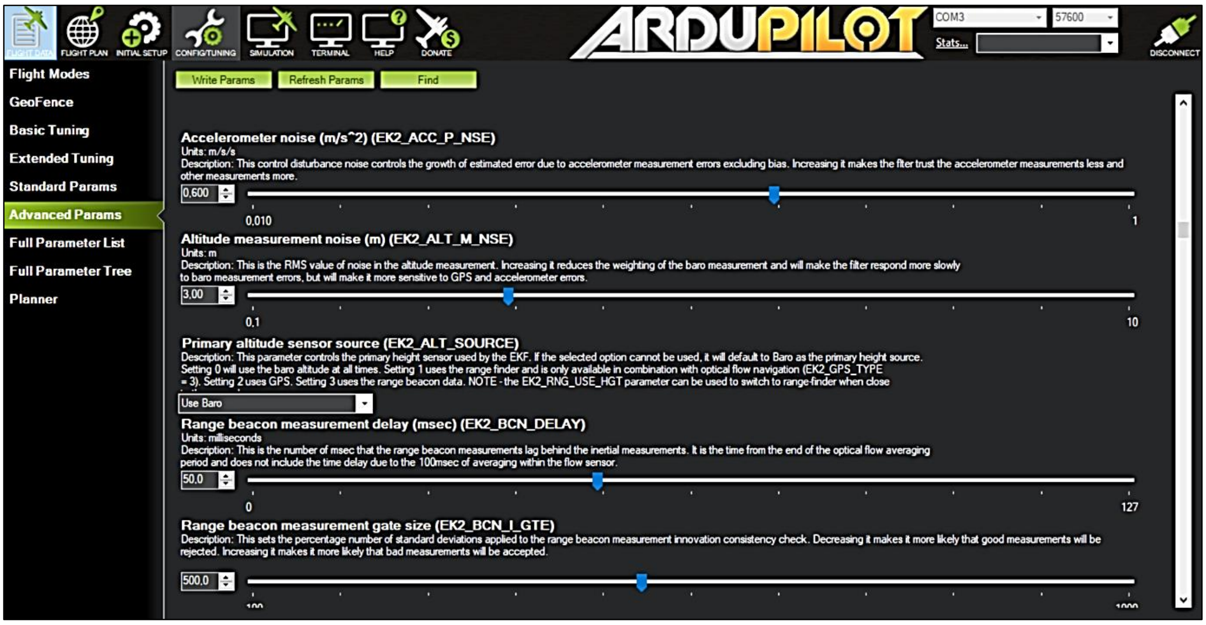


**Illustration 5.67: 'Ch 8 WP Set' switch (in front) and 'Ch 6 Camera Tilt' knob (behind)**

To the right of these options (in Illustration 5.66, above), are the Way Point Navigation (WPNav) settings. The top one is 'Speed', or the velocity that the drone will move at from one waypoint to the next. It is measured in 'centimetres per second' an in the Illustration it shows '100,00'; or 1 metre per second. This is actually quite slow (the last time I had changed it before I had captured this image was doing a small test in my garden), and I will typically set it at between 500,00 (i.e., 5 metres per second) and 1000,00 (i.e., 10 metres per second), depending on the terrain that the riders are navigating and how fast they can progress through it. I have taken this speed up to 1500,00 (i.e., 15 metres per second) during testing, but this has proved unnecessary during actual practice. Below this setting is 'Radius' (set to 200 or 2 metres): this shows how accurately you want the drone to intersect a particular waypoint before it progresses to the next. Although you can get higher accuracy than this, I keep the setting at 2 metres to avoid the drone 'hunting' for a waypoint if the GPS or other sensors lose accuracy at that moment. Two metre accuracy is fine for my purposes.

I have included two more pages from the 'Configuration/Tuning' tab in Mission Planner, shown in Illustrations 5.68 and 5.69, below. They are the 'Advanced Parameters' and 'Full Parameter List' pages. These are merely included to show the extent and ability of the Mission Planner/Arducopter software to be adapted to one's specific needs. Each page shows only a small portion of more than 200 parameters that you can set (the vertical scroll bar on the right-hand side allows you to scroll to which one you want to change). It is really powerful software, made all the more remarkable by the fact that it is open source. You would not have these options available to you with an 'off the shelf' drone running



<u>**Illustration 5.68:**</u> **'Advanced Parameters' page in Mission Planner**

proprietary software; you are left with how the factory configured it and you must work around that. When you install Arducopter on a drone it has ‘default’ settings which ‘work well under most circumstances’; but you can change the settings, save them, download previous settings for comparison, or return to default settings using the buttons on the right-hand side of the screen.

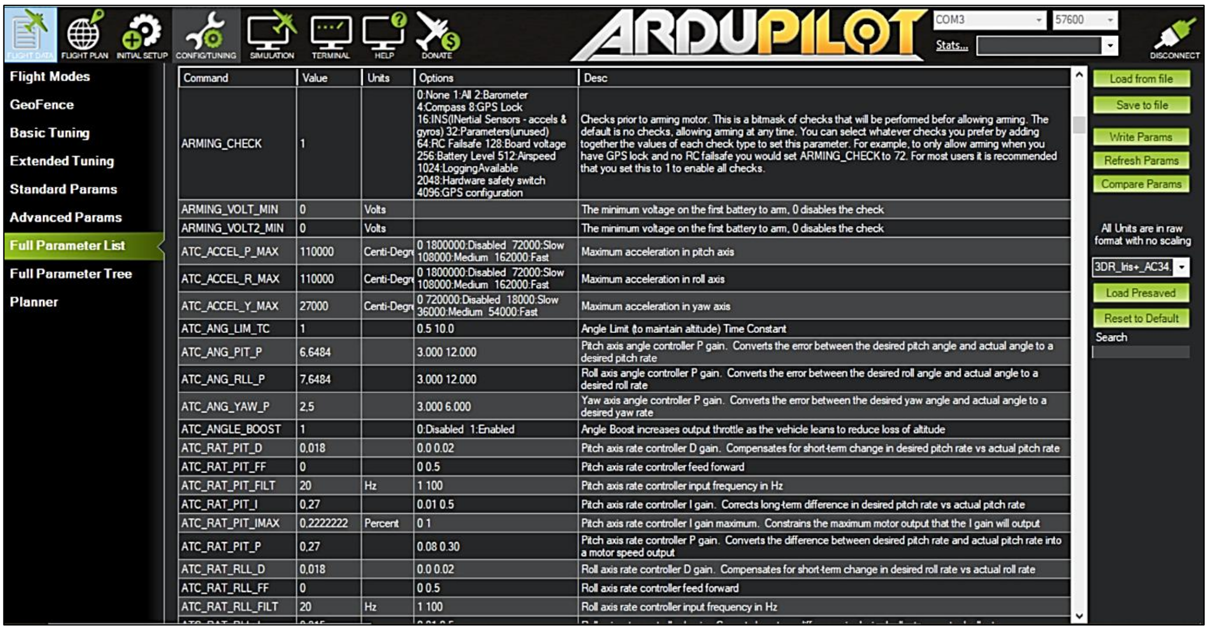


**Illustration 5.69:** **‘Full Parameter List’ page in Mission Planner**

Next I shall briefly explain the ‘Flight Plan’ tab in Mission Planner. This page is used to plan and execute autonomous missions. The opening page is shown in Illustration 5.70, below. Central to the page is a satellite image of the area you will be flying in. On the right are buttons for managing the waypoint information. ‘Read WPs’ allows you to download any waypoints that you have gathered by the drone, and ‘Write WPs’ allows you to upload waypoints to the Drone. ‘Load WP File’ lets you call up a waypoint file that you have previously stored, and ‘Save WP File’ lets you save a series of waypoints to the ground-control station computer for later use. At the bottom of the page is a grid which details the waypoints (none is shown yet in this image) which will be populated by the various waypoints later. The important information in this grid is the Latitude, Longitude, Altitude and the ‘Command’ column which will be used to specify how the drone will behave as it reaches each waypoint. The waypoints are arranged numerically on the left-hand column. Once you have populated the grid you can ‘click’ on any box with your computer mouse and alter the information within it. So, for example, you might want to lower the altitude of a particular waypoint: you enter its respective setting, delete the old altitude, enter a new one, and save it.


**Illustration 5.70: The 'Flight Plan' tab in Mission Planner**

On the right-hand side of the screen is a list of the different satellite imagery you have available. I have expanded this list and shown it in Illustration 5.71, alongside. The default satellite imagery for Mission Planner is 'Bing', but you can choose which one you would prefer. Note that although the list is comprehensive (there are further options by using the vertical scroll bar) most of them are not useful in South Africa because they don't cover this area. I mainly alternate between Bing and my 'old faithful' Google Earth, since both of them cover the whole planet and are regularly updated.

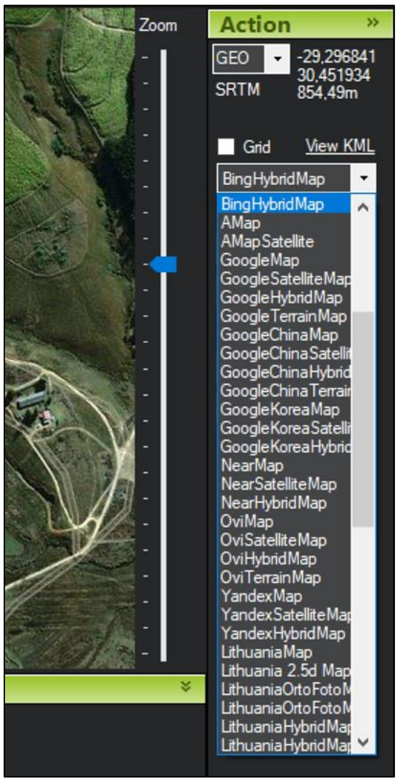
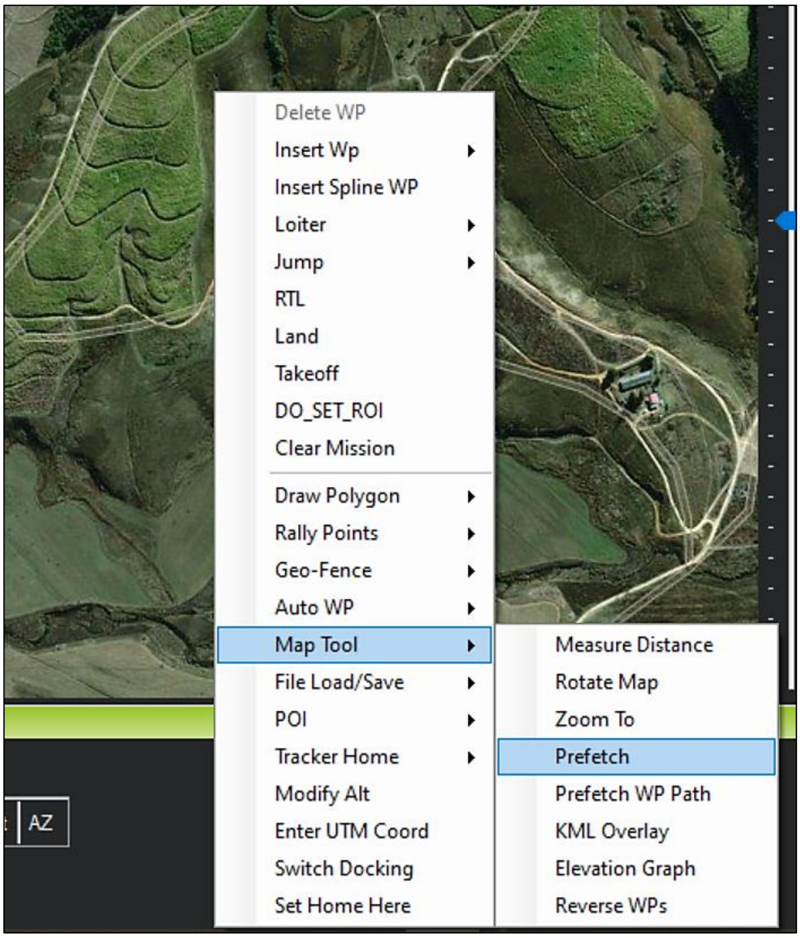



**Illustration 5.71: Mission Planner satellite imagery resources**

One of the biggest problems is, once again, working in remote areas for this research. Not only are the places I want to shoot remote geographically, but they are also remote from a connectivity perspective. In Lesotho, for example, there is very poor cellphone coverage, particularly in the mountains, and no internet connectivity out there either. I need to be self-sufficient notwithstanding the fact that I have no connectivity. At issue is the fact that Mission Planner wants to connect to the internet when you are in a particular area, and once it has verified your global position by satellite it then downloads the imagery for that area. No internet, no imagery, no visuals of the terrain you are flying over, and thus no way of accurately mapping your waypoints. (This is not strictly true, Mission Planner will allow you to set up waypoints without any imagery, but you really have no idea as an operator how these waypoints reference to ground details; they will just appear over a consistently grey background. So, you have no idea what the 'features' of the terrain are, you cannot see the course, you cannot see trees or rivers, etc. If you want to adjust the waypoints you have no idea what you are adjusting against. You could quite easily fly the drone into a tree. The satellite imagery is a critical aspect of setting up the flying pattern.)

Fortunately, Mission Planner allows you to 'prefetch' the imagery, as shown in Illustration 5.72, alongside. There is a menu available which includes 'Map Tool', and within this a submenu 'Prefetch'. The satellite imagery is made up of a multitude of individual 'tiles' which when pieced together form the overall image, much like a series of mosaics forming a pattern. It is possible to identify the area you want to fly in beforehand – for example, when you are still at home with internet connectivity – and then prefetch the tiles which make up that area, at which stage




**<u>Illustration 5.72:</u> Mission Planner satellite imagery 'Prefetch' tool**

Mission Planner stores them on your computer. Typically for the amount of detail I need for flying I need to prefetch about 2000 tiles of the area. Once you are at the flying zone Mission Planner recognises that there is no internet and regathers the tiles which have been stored, and then displays them.

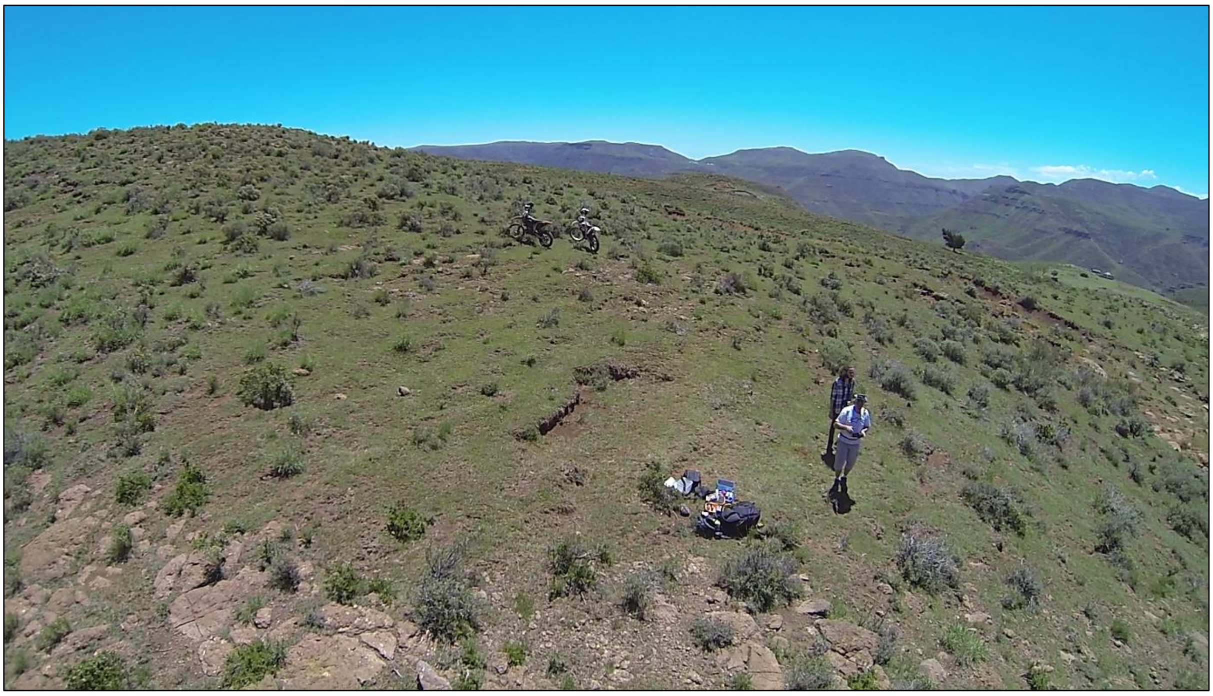
Although this solves the very real issue of not having satellite imagery in the remote area, it does have one problem. You have to choose your flying site before you leave home. You cannot go out to the course, have a look around, and then choose to fly in any place, because you  will not have the imagery for it. Typically, before a race I will scrutinize the course on Google Earth and choose 3 or 4 potential places to fly per day (in Lesotho there are 3 days of racing, so that means I have chosen about 12 different zones at this stage). I will then prefetch all the tiles for these areas whilst still at home. Once I get in the vicinity of the race, I will visit each zone beforehand and make a final decision as to where I will fly on each day. However, downloading 2000 tiles for each potential flying zone takes a fair amount of time, multiply this by 12 potential zones and it makes for long nights of downloading before the race, considering that the racecourse is only released a few days before the event. This is a small price to pay, though, for actually having the imagery at the flying zone.

There are many considerations to take into account when choosing the flying zone, and most of them I have 'learnt the hard way' through experience. I have previously referred to a few considerations such as staying off the course whilst accessing it, and the time of day which the riders will arrive, but I add a few more specifically to the zone I choose to fly in:

- The video link requires 'line of sight' for it to deliver consistent and good quality pictures. The transmission antenna is mounted below the craft, so that I get a good link when the craft is above my head. If it were mounted above the frame of the drone, it would be shadowed by the body of the craft. This means that I look for an area to operate from where the craft altitude will always be above me. This area is called 'Home', and it is where I take off and land the drone. The altitude of the waypoints in Mission Planner is relative to this 'Home', anything higher is a positive altitude, and lower a negative one. Mission Planner can actually deal with negative altitudes, so that is not the limiting factor; it is the video link. The only frame of reference you have when flying is the video pictures, so it is imperative that they are of good quality. This also means that you cannot fly behind a hill, or even with trees in between you and the drone.

- I need to find a place that has a big enough area to lay out all of our equipment without it being too close to the riders coming through. Normally we will park our bikes a bit away from where I commence flying, then walk to a place from where I can operate. It helps if this area can be trending towards level (real level doesn't truly exist!) to make life a bit easier to move around and lay out the equipment without it rolling away.
- I prefer to fly a 'triangle', so that the drone flies away from me, picks up the riders, and then the last two legs of the triangle are the course which develops back towards me. This is an ideal and doesn't always happen. I also prefer to have the furtherest the drone will be away from me early in the flight, so that it gets closer to me as the battery depletes in case of emergency.
- I need a place where I can see the riders appear in the distance, so that I can prepare, get the drone in the air, and get it out to the pickup point for filming before they arrive. This is a critical aspect, and one which I learnt the hard way. It is not easy to see on Google Earth planning beforehand just what you will be able to see of the course from ground level. It also helps to have a 'spotter', someone who can accompany you out into the field, walk along the course, and give hand signals as to when a rider is approaching. Many times, however, I was operating on my own.
- I need to find a place where I can stand and place my feet firmly on the ground, without any rocks or grass tufts nearby. When you are flying FPV your entire frame of reference is the video monitor, and you need to have good balance, particularly if you are standing on sloping ground. In fact, many FPV operators talk of motion sickness when flying because of this detachment from the world around you. You sometimes unintentionally move your feet slightly to maintain balance. If you move your foot onto a small rock (which might also roll) or a tuft of grass you can quite easily lose your balance. I speak from experience, and it isn't pleasant. Falling over when you cannot see the ground because you have a video monitor strapped to your head and discarding the radio controller as you inadvertently let it go because you instinctively put your hands out to stop the fall is in no way graceful.

Illustration 5.73, below, shows a typical area in Lesotho, where my son Scott and I have set up, taken from the drone as it flies by. I will explain later in some detail the 'Home' area as I discuss each day's flying.



**<u>Illustration 5.73:</u> 'Home' for the day**

When I arrive at the zone I have chosen I first identify the route of the course. Sometimes it is quite clear, because there may be a small track or footpath which you can identify from the satellite imagery. Sometimes though there is no obvious track, just virgin veld. In these cases, I have a handheld Garmin GPS on which I have previously loaded the race course. I will then follow this GPS track through the terrain, taking note of where it goes for mapping later. At the same time, I note anything which may become a problem, such as a tree alongside the track or in a potential flight path. Walking the course beforehand also gives me an idea of what sort of obstacles the riders might encounter, and thus the speed at which they will be traversing that particular part; this in turn informs me of the speed at which I should set the drone to fly its autonomous path. I then map the course using the 'pseudo drone'. I don't want to explain the term 'pseudo drone' (this is a term I invented, it doesn't actually occur in any documentation) and its necessity right now, neither how I developed or operated it, because it is worthy of a whole section on its own and I will write about it later.

Illustration 5.74, below, shows a flying area where I have mapped a course in Mission Planner (once again the same example from New Hanover for continuity) with initial waypoints that I have downloaded from the pseudo drone. Altogether in this example there are 16 waypoints which are shown in the satellite imagery, and which also populate the matrix below it (a scroll bar allows you to move between the waypoints). You can easily move a waypoint in Mission Planner by clicking on it and dragging it to a new location. Changing values in the matrix is described previously. The arrows indicate the direction of flight.

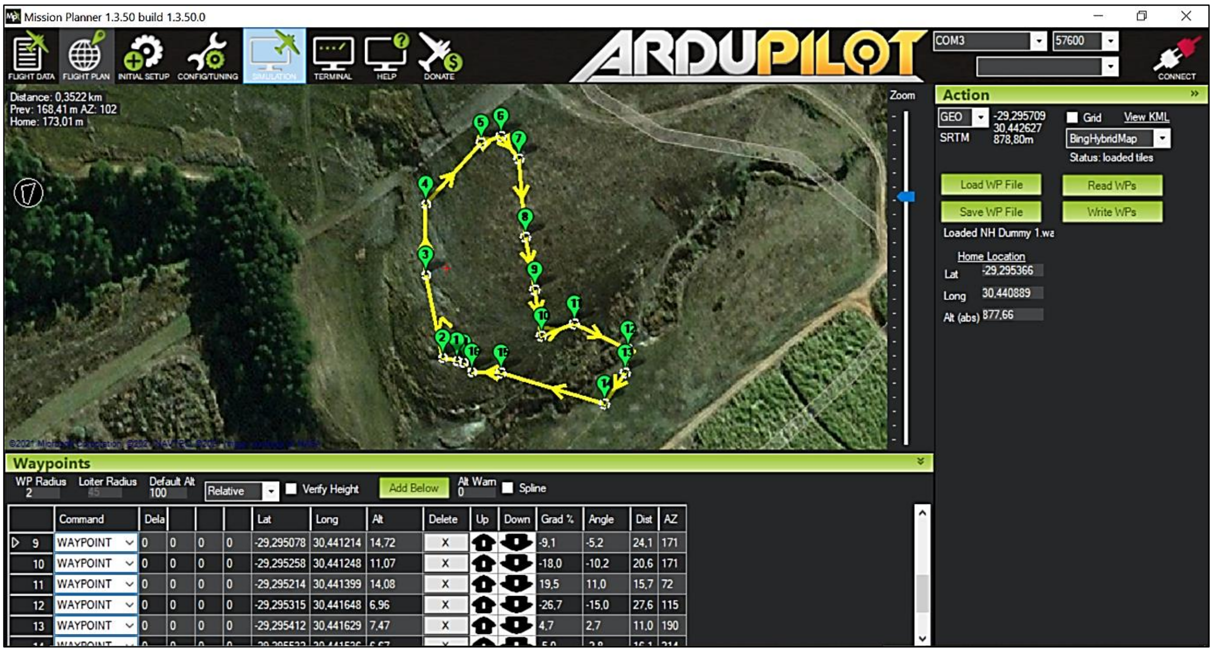
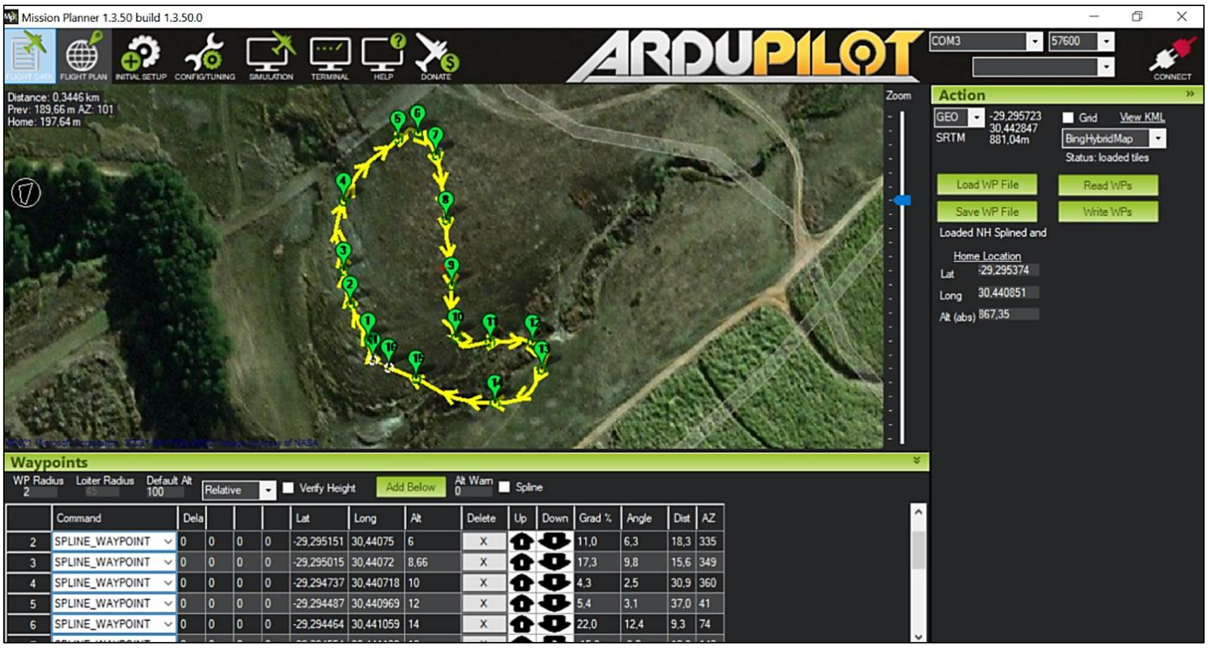



**Illustration 5.74:** **Prospective drone flight mapped and imported into Mission Planner**

I then start adjusting these waypoints. I might move a waypoint slightly according to my earlier observations during the ‘walk through’ of the course, or I might adjust altitudes over successive waypoints to ‘smooth’ the altitude changes the drone has to perform. The most important change I make is to create each waypoint as a ‘spline’ waypoint. Initially the waypoints are actual points with straight lines of flight connecting them (as seen in the Illustration5.74, above); splining involves the software making the drone curve along its course, intersecting the waypoints along the way. This splined course is shown in Illustration 5.75, below. I upload this new flight path to the drone.




**<u>Illustration 5.75:</u> Flight plan Waypoints adjusted and Splined**

Next I assemble the drone, do a visual inspection of it to make sure nothing is loose or become disconnected, and do a short test hop to test that it is performing as expected (Stabilize, Altitude Hold, Loiter and Return to Launch), before I do my first Auto test flight. I will do a few Auto test flights without any video link at first, just visually watching the drone as it progresses through its flight path. After each test flight I may adjust the flight path in some way or other, and then upload this new course on to the drone. Once I am happy with its flight path (and assuming it has not crashed and my testing has not been interrupted by repairs!) I will do a test flight with the camera, video link and screen to familiarize myself with the terrain and what it looks like from the drone's perspective. Testing done, I am finally ready to fly and record video, hopefully with enough time before the first rider comes through to enjoy a well-earned cup of tea! When I am flying following the riders I will often make more changes to the flight path, and upload these new versions each time. Illustration 5.76, below shows a day's flying, with the number of new flight paths I altered and saved each time.

As a matter of interest, and once again because of the nature of being far away from any support, I need to be very aware of battery consumption. This extends not only to the drone batteries (of which I carry about 14, each giving me between 5 and 8 minutes of flying time depending on conditions), but also extends to the video receiver and video monitor battery, the radio controller battery, and the laptop battery. I need to be careful and conserve these by switching off the relative piece of equipment if I am waiting for any length of time. From the laptop perspective I have to put it to 'sleep' each time I am doing a test flight or actually filming. This means disconnect the telemetry, put the laptop to sleep, then subsequently wake it up when I have finished the test flight, reconnect telemetry and wait for all the drone parameters to load, make changes to the flight path, upload to the drone, disconnect telemetry, put laptop to sleep, do test flight; repeat each time. It is a process which might seem tedious but it's absolutely necessary because if my laptop battery goes flat in the middle of nowhere that is the end of the day's flying; it is such a vital part of the setup.

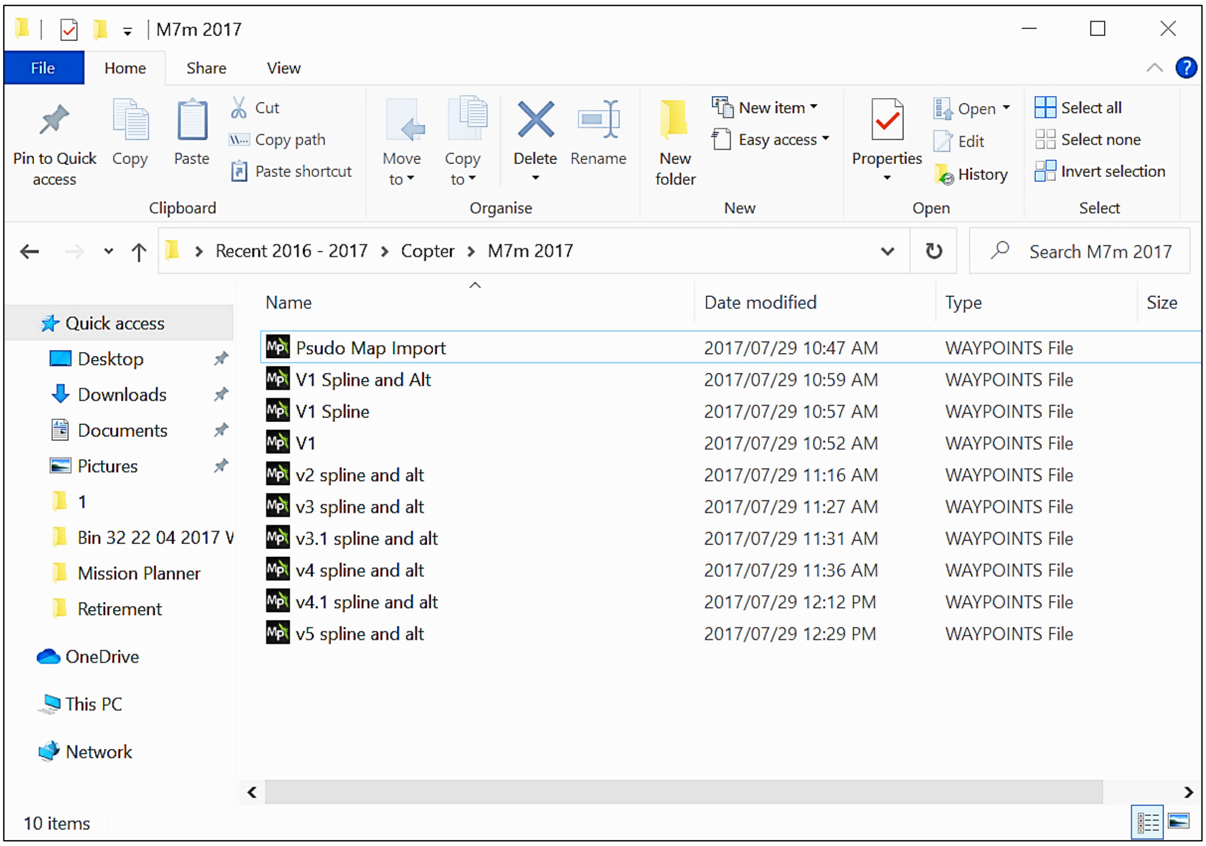


**Illustration 5.76:** **Adjusted Flight Plans for a day's shooting**

## 5.6 Enduro Motorcycle Racers

Motorcycling can be broadly classified under two main types of riding, street bikes and dirt bikes. Street bikes are those which are designed to be ridden on tarmac roads, and dirt bikes are designed to be used in places where tarmac doesn't exist. A popular international way of separating them are as 'on pavement' and 'off pavement'; although there is a type of motorcycle – the ‘Adventure’ motorcycle – which is designed to cross over between these two and provide a means to travel both on tarmac as well as gravel roads.

This research is focussing on the ‘off pavement’ or ‘Dirt Bike’ style of riding, and in particular Enduro riding. A brief explanation of the different kinds of off pavement riding is necessary, before a detailed explanation of enduros is explained. I will use the South African terminology, although this is often used internationally as well. It should be noted that there is also ‘racing’, where participants are competing against each other, and ‘social’ riding, where participants are out to enjoy a ride with their friends.

Dirt biking can be further broken down into more classifications, and it is generally typified by the speeds which a dirt bike would average during the course of a typical days riding and/or racing. Starting from the highest averages, we would typically get:

- Desert Racing/Rallying: Here the motorcyclist covers many hundreds of kilometres every day, across open expanses of desert or arid countryside. The average speeds for the day are very high, over 100 kilometres per hour (kmh). The bikes are normally limited to a top speed of around 180kph (for safety reasons) and the slowest speeds are probably about 40kph. The course (also called the ‘piste’) can be either on gravel roads or open terrain desert and dunes, sandy with rocks interspersed. An example of a desert rally is the Dakar Rally. The duration of any single race is over several days, and the riders accumulated time determines their placement in the race, with the lowest accumulated time being the winner.
- Off Road Racing: Here the average and top speeds are lower than desert rallying, and the event covers less open terrain with bush along the way. The course is staged over both open terrain and small gravel roads (‘tweespoor’ in South Africa). Top speeds are of the order of 120kmh, and average speeds about 80kmh. An example of a Southern African offroad race is the ‘Toyota 1000’ a 1000-kilometre race held over 2 days in Botswana. An annual championship in South Africa normally comprises 5 or 6 events over the course of the year, and the champion is given the title ‘SA National Off Road Champion’.

- Enduro Racing: The terrain which the riders traverse is more mixed, but seldom ‘open’, and only a few short sections might be on small tweespoor roads. The vast majority of the course is set on paths (known as ‘singletrack’) or where there are no paths whatsoever. The course covers bush, forests, hills, river valleys, river crossings and much ‘tighter’ riding. Average speeds are lower, around 50kmh, with top speeds about 80 kmh and there are times where the speed drops down to about 20kmh. The champion is crowned ‘SA National Enduro Champion’, and there are also regional/provincial championships.
- Extreme Enduro: A form of enduro where the riding is even tighter, and more technically difficult. Average speeds (for the winner) are around 30 kmh, top speeds about 60kmh, and there are sections where the best riders might only be averaging 5kmh. The course is characterised by sections which have extreme difficulty to traverse, because they are very steep, or very rocky, or very tricky to navigate. There is no formal SA championship, but there are individual races such as the ‘Roof of Africa’ held annually in Lesotho.
- Foot Up Trials: Technically not a race, but a test of a rider’s ability to traverse ‘sections’ (which may only be 50 metres long), which must be ridden without putting your foot down onto the ground to regain your balance. The sections comprise big rocks, ledges and other terrain over which a person would have great difficulty even walking, let alone riding. The winner of an event is the rider who puts their feet down the least whilst traversing the sections and is a real test of balance and motorcycle control. Whilst there is a South African championship every year, the sport does not have a big following locally. Internationally however, particularly in Europe, it has a large number of participants.
- Motocross (MX): This is an event held on a specially prepared dirt bike track which the racers ride laps around. Each race lasts for about 40 minutes (at a National level), and comprises big jumps, sections of very undulating terrain, corners, uphills and downhills. The riders line up on a ‘starting grid’, and unlike the races mentioned above where they ‘race against the clock for accumulated time’ the riders race against each other, the first person to get to the chequered flag is declared the winner. Motocross is a huge international sport, sometimes staged inside stadiums to massive audiences (at which stage it becomes known as ‘Supercross’), and the best rider in South Africa over the course of a year’s events is known as the ‘SA MX Champion’.

There are type specific motorcycles for each type of riding, and they vary considerably. A Rally bike is very different to an Off Road bike, which is close to but still different to an Enduro bike, which is close to an Extreme Enduro bike, which is very different to a Motocross bike; and all of them bare almost no similarity (other than 2 wheels, motor, and a set of handlebars) to a Foot Up Trials bike. Within each form of racing there are smaller subdivisions, which might be based on the cylinder capacity of the motor, or age groups, or some other form of differentiation.

For the purposes of this research I will be concentrating on Enduros and Extreme Enduros in the Southern African setting, and I will spend some time explaining them in more detail.

The term Enduro is derived from 'Endurance', and the name is fitting. Riding an enduro requires physical endurance, mental endurance and motorcycle endurance. Riders have to be physically very fit and be prepared to spend long hours in the saddle with high heart rates and sustained aerobic capacity. The motorcycles themselves have to be strong and durable, yet lightweight, and able to withstand many hours of constant manoeuvring over inhospitable terrain. However, the best attribute an enduro contestant can have is mental endurance, the ability to believe in ones capabilities over many hours of being alone far out in remote areas and to 'bring it home' at the end of a long day. Your average enduro rider is very different to the mainstream image of a 'biker'; that of machismo and bravado. Good enduro riders are typically quiet, inward-looking and mentally focused. They have to be able to make split second riding decisions hour after hour, continuously stretching the envelope of navigating at speed over terrain which they have never had sight of; able to conquer obstacle after obstacle, able to grit their teeth through difficult sections, and immediately once they are through that to put it behind them and attack the next one. They need to have the mental capabilities to 'pick themselves up' even when they are completely exhausted and drained. Extreme Enduro riders have to be even better at all these attributes.

South Africa has been the breeding ground for some of the world's best enduro and extreme enduro riders; we continually produce competitors who are at the pinnacle of the international scene, even though our riding population as a percentage of the total population is very low compared to most other countries where the sport is popular. This holds true for both our male and female competitors. And in South Africa KwaZulu-Natal heads the tables – by far – when one considers the number of champions we have produced. Names such as Alfie Cox, Travis Teasdale and Wade Young (to name just three from many more) all hail from KZN, and all of them have achieved international fame and recognition for their endeavours and the championships they have won overseas.

Why, one may ask? One of the reasons is that South Africans are naturally resilient, another is that we are blessed with a climate where we can ride all year round. But the overriding reason lies in our riding areas – vast regions of undeveloped open expanses – which are relatively close to urban infrastructure. This doesn't occur in most other developed countries; the land is farmed or 'out of bounds' for motorcycles, and only open to hikers or at the most bicyclists. Our riding places feature some of the best, most difficult and most varied terrain in which to practise and hone one's skills, whilst at the same time being close to an urban 'home' where one can hold down a job for financial reasons, and also get the bikes and spares necessary to maintain the equipment. KZN and its surrounds (such as the Eastern Cape, Swaziland and Lesotho) are recognised worldwide as 'dirt bike riding heaven' and draw riders (both social and competitive) from many parts of the world to come and experience the off-road riding we have. There are even fully professional international competitors who base themselves here for the practice they can get all year round, and they then travel to events to compete around the globe. We have built a reputation as the place to be to 'up' your riding skills and competitiveness.

In South Africa the sport is administered under the auspices of Motorsport South Africa (MSA), which in turn is governed by the Fédération Internationale de Motocyclisme (FIM), the international body for motorsport generally. We also have many regional clubs falling under MSA; in KZN the club convening regional enduro championships is the WFO Enduro Association. There are also many local 'social' clubs running their own events.

There are two main ways in which an enduro course is 'marked' for competitors to follow the track. They can either be delineated by placing brightly coloured stickers on trees or other landmarks at close intervals as an indication for the riders to follow, or it can be by following a GPS 'track' on a GPS device which the rider has on the motorcycle. The course route is provided by the organisers beforehand, the rider downloads it to their device, and then follows the 'breadcrumb' track as they race. This has become more prevalent for a variety of reasons because not only does it negate the problem of sticker markers being lost through rain, or a rider inadvertently brushing into a marker and removing it for all following riders, but it also removes the environmental impact and problem of the organisers having to remove all the stickers after the race. In addition, GPS devices have got smaller, more accurate and more reliable in recent years. The most commonly used GPS device worldwide for enduro and extreme enduro is the Garmin eTrex series. Faster riders often employ 2 side-by-side on their handlebars, one 'zoomed out' to give an overall view of the course, and one 'zoomed in' to a closer view to watch the actual 'turn by turn' of the racing track.

I have ridden and raced enduros in many areas of KZN and South Africa. I understand what you are faced with whilst riding, and I know that the parts of the course which are most typical are far from the 'beaten track'. I will use this knowledge to choose likely spots for me to experiment with my drone and filmmaking, and my riding experience to enable me to ride a dirt bike with all the necessary equipment to these parts of the course.

The heading to this section is 'Enduro Motorcycle Racers' and the operative word here is 'Racers'. The people I am trying to capture are competing in a race. This is not a social ride with your friends where it doesn't matter if something untoward happens along the way. This is not some marketing shoot where I am employed to get the best footage of someone, and they are at my beck and call such that I can ask them to go back and do it again (and again) until I get the shot just right. This is not something where I can intrude into their 'head space' just because I want to 'get a better shot'. Uppermost in my approach to this project must be that the riders must be 'left alone' in all ways, so that they can give their best performance; it must be as if I (and by extension my drone) 'were never there'. The riders have a lot on their plate. They are trying to maintain control of a motorcycle through unseen terrain as fast as possible for hour after hour. They are at the limits of both their physical and mental resources. Whilst some of them are just racing for fun, and with the overall goal to finish or beat their mates, most of them are racing to get as best a result as possible, with an eye to overall championship standings. Some of them are fully professional, this is what they do for a living, and their results define whether they will be employed the following season. Getting to the finish in the least possible time and being able to stand on the top step of the podium, is their only goal; and they will push themselves beyond their limits to achieve that.

I have raced, and whilst never championship-winner material, I know what it is like. When a friend who comes to the races with you asks afterwards, ‘Did you see me waving at you?’ I did not, particularly if you were amongst a group of fellow spectators. Sorry. Thank you for coming to support me, but spectators alongside the course are the least of my worries. I am so focused on that small track ahead, so in tune with my bike’s brakes, clutch, throttle, traction, attitude, suspension, speed, sound, and a host of other things. It is complete tunnel vision, and the tunnel is probably only about a 10-centimetre-wide piece of dirt coming at me at speed, with soft sand, or rocks, or roots, or mud, riding at times alongside the edge of a cliff where one very tiny mistake can have disastrous consequences, at other times flat out and on a different kind of edge; that of a high-speed crash if you make a mistake. Constantly, all day; and if I stray even slightly off where I want the bike to be on that small width of the track, I know that I am in trouble, and something has to give.

The first and foremost lesson to learn about racing enduros is ‘The only person you are racing is inside your head’. Enduro riders spend many hours in the saddle with only themselves for company; you can go for quite long periods of time where you never see another competitor. It is by definition a rider and their bike, trying their best to maintain a good pace hour by interminable hour. It is a great test of physical and riding ability, and a great test of making sure you ‘bring the bike home’; but above all it is a test of willpower, and for very large parts of every day you only have yourself to motivate you and get you through. There may be times when you catch another rider to lift your spirits, there are times when you have a fuel stop and your pit crew is there to encourage you, and there are times when you will come across a spectator point and the people cheering you on give you a bit more adrenalin. But the basic tenet of enduros, is it is largely up to you, whether you finish, and how well you do. This is the great attraction of the sport.

There is a caveat to the ‘sorry I did not see you waving in amongst the group of spectators as I rode by’ mentioned above. I have long had a passion for photographing and filming enduro races, probably since I got my first ‘real’ camera in the late 1970’s; and I still enjoy it to this day. During that era, I have avoided the ‘deck chair and cooler box brigade’, the spectators who crowd easily accessible parts of the course (for example where the riders might cross a road). I far prefer to get out into the countryside having planned beforehand and either walked or ridden my off-road bike to access a truly remote spot. I prefer the solitude of the wide-open spaces, and quite honestly the photo opportunities are far more aesthetic. So, it will be that I – and possibly one other friend - am in the middle of nowhere and along comes a rider, someone who possibly has not seen anyone for quite some time. I will always try and cheer them on in between taking photos. They are really appreciative of this presence and support ‘far from the madding crowd’ and will usually shout a ‘Hello’ or some greeting back (even the professional competitors). Often when I see them after a race they will recognise me and ask me ‘What were you doing out there’. They understand when I say that the real racing is ‘out there’, and it doesn’t matter if it takes a great deal of effort to get there, it is worth the time spent. As an aside I have earned a reputation from the riders for my photographs and have supplied many thousands of them to competitors over the years (as well as having them published, used on magazine covers and marketing purposes, and an exhibition), but I have never charged anyone for them. It is my passion, and first and foremost something I enjoy doing for myself.

Whilst a rider might see me and my drone ‘out there’, my object is to remain as inconspicuous as possible. To not intrude in their racing in any way. To make the most of opportunities which present themselves to me. The riders appear, and then they disappear. I must use the minute or so that I have in between to do the best I can. This requires making constant second by second decisions. What is the right framing? Is it a fast or slower rider? How will this affect the development of the shot? Are there two or more riders approaching? Which one should I follow? Should I begin with one, then transition to another? How will I do this? What other opportunities are being presented, and how best can I exploit these? Is everything with the drone going according to plan, or do I need to abort the mission? So many thought processes condensed into small slivers of time. Making choices, both literally and figuratively ‘on the fly’.

A question which must be asked is why are not I using a ‘follow me’ approach to the rider and the drone. To explain, it is possible to have a drone follow you, by installing software onto the drone and carrying a device (such as an Android phone with the correct app installed) on your body. Examples of such systems abound, and a few are compared in ‘What is the best follow me drone’, a DronesRush article (https://dronerush.com/follow-me-drones-14544). What happens is you ‘lock’ the drone to your device, and it will follow you at a distance behind you. Although still in their infancy of development such devices are getting better and better, and are very popular with recreational skiers, cyclists, skateboarders and the sort.

There are two reasons why I did not take this approach. The first is aesthetic, and the second cost and logistics. From an aesthetic point of view, the drone only gives a framing from behind the device wearer, and it always stays a set distance behind, so the frame size is consistent throughout the shot. I wanted to have a variety of frame sizes, from the wide shot to the close-up. In addition, I wanted to be able to shoot from the front, and side, and from behind the rider. The ‘follow me’ system cannot do that, because it cannot predict where the device-wearer is going to go to next. It can only follow from behind. The second reason is a cost and logistical one. I would have to equip every rider on the start line with a device they can wear, which the drone would recognise as they appear into view. This would be not only a very costly exercise, but also very difficult to get every rider (there are sometimes 400 of them starting a race) set up each day beforehand (aside from charging and programming all these devices before the start, or between each day’s racing). Then I have the added problem as to which rider the drone would follow if two of them appeared at the same time. It just was not feasible in the context of what I wanted to do in this research, and I don’t think it would have achieved the desired results.

Having said that I must look to the future. Right now, the ‘factory’ or professional racers are all required to ride with an on-board GoPro camera as part of their contracts in major events.

These cameras are set up, charged, and installed on the rider's helmet before each stage by a team from the event sponsor or the broadcaster. At each checkpoint or fuel stop there are broadcast personnel who clean the lens as the rider comes through, and at the end of the race the team once again collects the GoPro's from the riders and prepares them for the next day. I foresee a day, and not in the too distant future, where this GoPro becomes a personal drone. There will be a bank of drones situated somewhere out in the field, probably before an 'interesting' section of the course. Professional riders will be required as part of their contract to wear a 'follow me' device as part of their kit. (This is not unheard of; already large swathes of professional sportsman wear electronic devices as part of their kit, from cricket players to rugby to football and innumerable other sports. This monitors their performance for assessment after the game.) As the riders approach the 'zone' their individual drone will deploy, follow them through that section of the course, and then return to the launch point. It will take off, fly, and land completely autonomously. At the end of the day the broadcaster's team will arrive, collect all the drones, download the footage, prepare them for the next day, and install them on the subsequent stage. This concept is not far-fetched, and with enough resources could be done already.

## CHAPTER 6

## Designing and Constructing an Unmanned Aerial System for Specific Purposes

In this chapter I will detail the design choices I made and how I constructed the various components of the Unmanned Aerial System which are unique to my particular needs for this research.

### 6.1 Spoelstra's Influence

I knew that I would have to design and build a drone which could fold up and fit into a backpack. I researched various options. I have already written about the first 'folding' hexacopter which I purchased from jDrones, and how besides the problems I had encountered with materials quality the final 'folded' version still occupied quite a large 'footprint' and wouldn't be suitable for backpacking. The essence of the problem is how big the 'folded' version (for packing) would be compared to the 'unfolded' (for flying) version. The larger the flying version (with respect to how far apart the props are), the more inherently stable the platform is. Typically, 'racing' drones are very small and highly manoeuvrable, whereas drones used as camera platforms tend to be much larger with the props more spread out for stability. So, I wanted a fairly large drone, but one that would fold up as small as possible. If one thinks of the folded version as having to 'fit inside a box' (with length, breadth and height dimensions), how small could I make this box?

The limiting factors with the size of a drone are the length of the arms (with motors and props) and the length of the legs. There are essentially two ways to fold the arms of a drone. The first is where the arms fold downwards, in what is known as an 'Umbrella' or 'Tripod' style. An example of such a drone frame is shown in

**Illustration 6.1:** **'Umbrella' style folding drone**

Illustration 6.1, above. Now, although this does decrease the length and breadth of the drone, it still leaves the height similar to the unfolded model. In addition, it has various delicate parts of the frame, such as the legs, left exposed and vulnerable to damage during transport. It should be remembered that, although I was going to transport the drone in a backpack, it would still be susceptible to jarring and bumping as I rode the bike over bumpy terrain to get to the flying zone. I therefore discounted this umbrella style as an option.

The second way of folding a drone is for the arms to fold in the same plane as the body, but up against the body. There are two ways of doing this. The first is to fold individual arms up against their corresponding frame edge, as shown in Illustration 6.2, alongside. The problem with this is that the arm length is limited by the frame-edge size. If you want a longer arm, you have to have a larger square body. Once again, although the folded version is smaller than the unfolded one, it is not that much smaller; and if I wanted a drone with fairly wide prop-spacing for stability it would end up in a folded version that was still too large for easy transport.

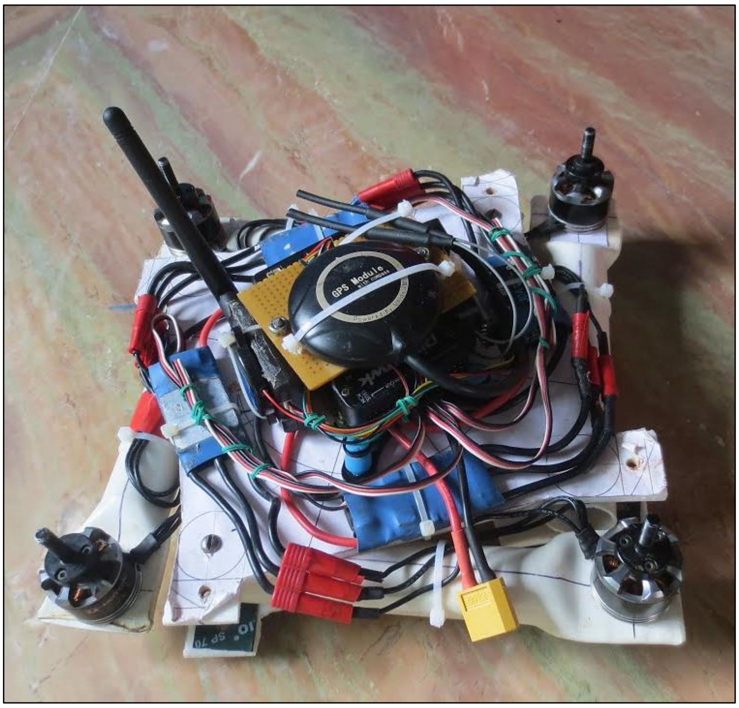


**Illustration 6.2:** **Square drone body with arms folding alongside**

The more I researched my options, the more I returned to the 'Spoelstra' design I have spoken of previously. As a reminder, Murray Spoelstra published his design on the DIYDrones forum in December of 2012; it was entitled 'Folding quadcopter for the holidays' (https://diydrones.com/profiles/blogs/folding-quadcopter-for-the-holidays). I have included images of his design in Illustrations 6.3 and 6.4, below. This design has an oblong-shaped body (as opposed to the square shape in the previous example) with arms which fold one inside the other longitudinally alongside the body. To me this fitted my initial ideas, that of a small 'box' in the folded position, but a much larger footprint with props spread well apart in the unfolded flying format. I decided to go with this essence of a design. The earliest drawings I have when I began the design process date back to March of 2014.

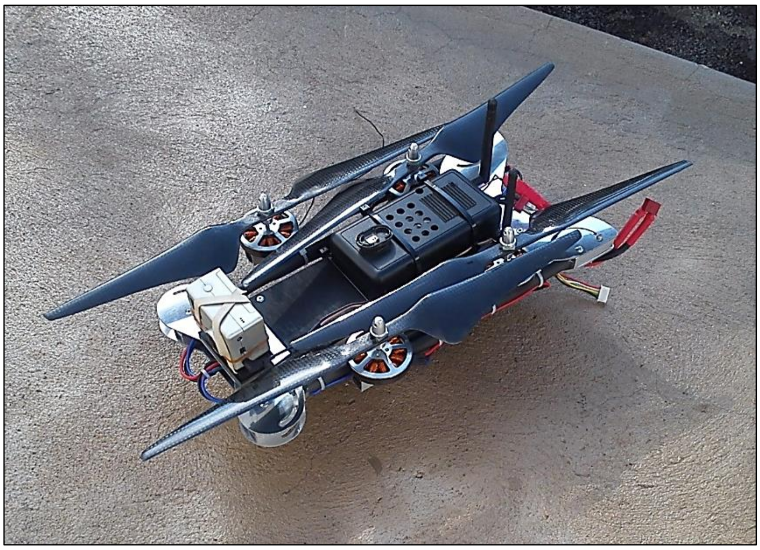


**Illustration 6.3:** **Spoelstra design folded for transport**

I mention this because there is a trend towards folding drones for easy transport, and what has become a worldwide standard of the way they fold, that of the arms folding in against an oblong shaped body. A Chinese manufacturer DJI released a drone (The DJI 'Mavic') in December of 2016 which used this principle. DJI sales are the largest of all commercially available drones globally, and they have earned a reputation for innovation and quality. Since then, many different drone manufacturers have followed their lead for folding drones and this method has become *de rigueur*. Spoelstra should be acknowledged not only for his innovative design, but also for his foresight towards a worldwide standard four years before it became common; and this also justified my choice in 2014 to adopt this design in essence.

**Illustration 6.4:** **Spoelstra design opened for flight**

Having said that there were still many elements of Spoelstra's design which did not suit my needs. The first was that his drone did not have any landing legs, merely a foam bumper underneath to support the drone when it was on the ground. This is quite common with various drones, particularly those which are launched and land on flat-level surfaces; the legs are short and ‘stumpy’, or non-existent at all as in the case of Spoelstra. However, I needed long legs, for landing and taking off in grass. If these legs had been fixed to the body or arms (as was the case with the first quadcopters and hexacopters I built) then once again the folded version of the craft would still take up a large envelope (and also the legs would be prone to damage during transport). So, not only would I need the arms of the drone to fold, I would also need long legs which folded into a smaller package for transport.

Uppermost in my mind during the design phase was this problem – how well protected during the transport stage would the various components of the drone be? This led to the second problem I foresaw with Spoelstra’s design. The delicate props still extended out way beyond the body of the folded craft. I envisaged a drone which would be placed horizontally in the backpack when the backpack was on the ground, and then once it was slung over your back the drone would be in a vertical orientation. Had Spoelstra’s drone been carried vertically (it was not, he had used a plastic toolbox to carry the drone around) then the weight of the drone would have been supported by the props. This was potentially too risky for me. The option was to remove the props for transport, and rig them out in the field, but I had always wanted everything to stay attached to the drone for transporting and then unfolding in the field. My design should have everything ‘in board’ of the basic frame, so that the rigid frame elements provided protection to the vulnerable components. This extended to the airframe ends of Spoelstra’s design as well; the drawings show that the folding mechanism of the main frame has ‘protrusions’ which extend beyond the basic frame, and were thus also susceptible to damage. I wanted the front and back frame plates to be ‘flat’ so that they spread the load of supporting the drone in a vertical position across their entirety. Note also that Spoelstra’s drone is solely set up for FPV flying and not filming. This means that his camera is fixed to the frame, and the drone flies forwards only; it has no gimbal for the camera. When I added a gimbal to the drone it would also need to be within the ‘protective envelope’ of the frame plates when folded. Lastly note that – allied to Spoelstra’s aims of only flying FPV and thus the drone only flying forwards – his drone is asymmetrical when unfolded for flight; the rear props are closer together than the front ones. I had always wanted a symmetrical drone to fulfil my needs of having to fly in any direction without any change to flight behaviour; in other words the prop-spacing needs to be exactly the same between all of them. If we are talking about a quadcopter, this means that the props should be positioned at the corners of a square.

I have spoken previously about the issue of redundancy. The basic premise of this is if one motor/prop/motor drive fails the drone should still be able to fly (and return to me). With an octocopter this is fairly straightforward. If a motor fails, the adjacent motors can 'take up the slack' and support that particular plane of the drone to continue flight. With a hexacopter this is also possible because there is still lift available in that plane, albeit less so. However, with a quadcopter (or tricopter for that matter) this becomes an impossible situation. If one motor fails there is no lift on that corner of the drone, and the adjacent motors cannot provide this lift because they are too far removed. The result is that if a motor (or corresponding hardware) fails on a quadcopter that corner of the drone is immediately unsupported, and the drone spirals down and into the ground. Speolstra's folding design only supported quadcopters, and I had not seen an efficient folding design for hexacopters and octocopters. I would need to modify Spoelstra's design but build in redundancy. (There was a further reason I did not want to build a hexacopter or octocopter, and that was one I mentioned previously which was the arms and legs of the drone intruding into shot. I realise that there are octocopters used for filming, but the camera is slung very far below the drone to avoid this intrusion into shot, which means a dramatically larger size of drone. With a quadcopter I could keep the camera forward of the drone rather than lower, to exclude the arm/leg intrusion into the video images.)

The solution is an 'X8' design, which I have touched on previously. X8 means that there are only four arms as in a quadcopter, but each arm has two motors. The motors are what is known as 'co-axial'. On each arm one motor is mounted above the arm as in a traditional drone configuration, and one motor is mounted directly below it in the same position on the arm. Whilst this is not as efficient as having eight 'separate' motors around the perimeter of the frame because the lower motor sits in disturbed air directly below the prop 'wash' of the upper motor, it does actually work. More importantly for me, though, was the fact that if one motor was to fail, the corresponding coaxial motor on that arm would still provide lift and be able to support that corner of the drone. In addition, the Arducopter software supports an X8 configuration, so I could still employ this open-source software with which by now I was familiar. Obviously though, having motors slung below the arms added to the complexity of how I was going to fold the drone, particularly if I were to keep everything with the frame envelope; this was just a design problem I had to overcome in some way.

Having motors slung below the arms began another problem; that of props spinning in the vicinity of where the legs are situated and mounted on the arms. If you look at the early drones I built you will see that if I mounted the legs in the same way, the underslung props would hit them. The solution may seem to be to move the legs close to the body of the frame, but this would mean that the feet of the drone would be close together, which is not good for landing on uneven ground. I wanted as wide a stance as possible. The end result was that I would need feet far apart, but the legs should be mounted close to the body of the drone. This set in motion a whole new way I had to approach the leg design – wide stance of the feet, close mounting of the leg to avoid props hitting the legs, folding legs for transport, and then not forgetting a previous design brief; that of having a suspension system for each leg. This was getting complicated, and I will devote an entire section to leg design and the modifications I made due to difficulties I encountered during testing.

As an aside, to that I will be presenting many drawings that show the design of the drone (or components thereof). These drawings are only the final version of the parts. I have over 150 different drawings that I have done along the way, most of them 'working drawings' where I contemplate the various options for each component before I settle on a final version for manufacture. I have not included all these working drawings (except in a couple of cases where I need to explain a problem in more detail). I am a firm believer in the 'measure twice cut once' principle, and so I try and visualize all the possible problems which may arise in the preplanning stage and find solutions to them on paper beforehand.

## 6.2 Power

As noted previously the quadcopter and hexacopters I had built were to a certain extent underpowered. These new designs would need more power. I used the eCalc software to try and envisage the power requirements for both the batteries of the craft the motors (and props). It should be noted that battery and motor explanations and calculations can develop into a whole treatise on their own, way beyond the need for this thesis. I will however touch on them.

Drones typically use what are known as ‘LiPo’ (from Lithium Polymer) batteries. They are far more efficient than traditional ‘NiCad’ (Nickel Cadmium), Lion (Lithium Ion) or Carbon batteries. LiPo batteries have the best delivery of power for their size and weight of all batteries (and they are rechargeable), and since these requirements are paramount in drone design they are the default type of battery to employ.

LiPo batteries generally have two ways of denoting their specifications: the voltage they produce and the current they are capable of delivering.

The voltage is a function of how many individual battery cells are connected in and is measured and specified as a multiple of ‘S’ (from ‘Series’). Each cell can nominally deliver 3,7 V (Volts) before it must be recharged. When fully charged this figure rises, but for the health of the battery it should not be discharged below 3,7V. So, a 1S battery can deliver 3,7V; a 2S 7,4V; a 3S 11,1V; a 4S 14,8 V, and so on. The first way to get more power is to go to a bigger ‘S’ rating of the battery (and obviously motors and electronics must be configured to suit this change). The original drones I built had used 3S batteries and motors. I made a choice in the quest for more power to go to 4S batteries, motors and corresponding electronics.

The next way to measure the power availability of a battery is how much current it can deliver. This is measured in mAH (from ‘milli Ampere Hours’). So, by way of example, a 1000 mAH battery would be able to deliver 1000 mA for one hour. (Ampere is a measure of current consumption, and 1000 mA is equal to 1 Ampere.)

Illustration 6.5, below, shows a typical battery that I have been using. They are rated at 5200 mAh, but also that they have a ‘25C’ rating next to that. The ‘C’ rating is a factor for how much amperage the battery can deliver. If you had a 1000 mAh battery with a ‘5C’ rating it can nominally deliver five times the 1000 mA, in other words 5000 mA (or 5 Amps). If it has a ‘20C’ rating it can deliver far more current, twenty times 1000 mA, or 20 000 Ma (20 Amps). The ‘25C’ rating on the battery shown indicates it can deliver 25 x 5200 = 130 000Ma or 130 Amps of current, albeit for only short periods of time.


**__Illustration 6.5:__ Typical LiPo battery**

LiPo batteries are cutting-edge technology and have a very small window of optimum operation. If you stress them too much, they can easily degrade to the point of not working. You have to exercise great care in how you deplete them, and how you charge them. They also don’t have a very long life and are quite expensive. The battery in the photograph above costs in the region of R2000.00, and I needed many of them. I have used and discarded many batteries during my testing; they can almost be considered as a ‘consumable’. Sometimes I have destroyed multiples in one day, through no fault of my own (see a trip to Lesotho, which I will write about later in the research). I have spent an inordinate amount of time trying to get the best out of my batteries, because they are so expensive. Illustration 6.6, alongside, shows an example of testing my batteries before going out to fly the next day, this is only one of innumerable tests I did over the course of this research making sure the batteries were flight worthy for the next day’s flying.

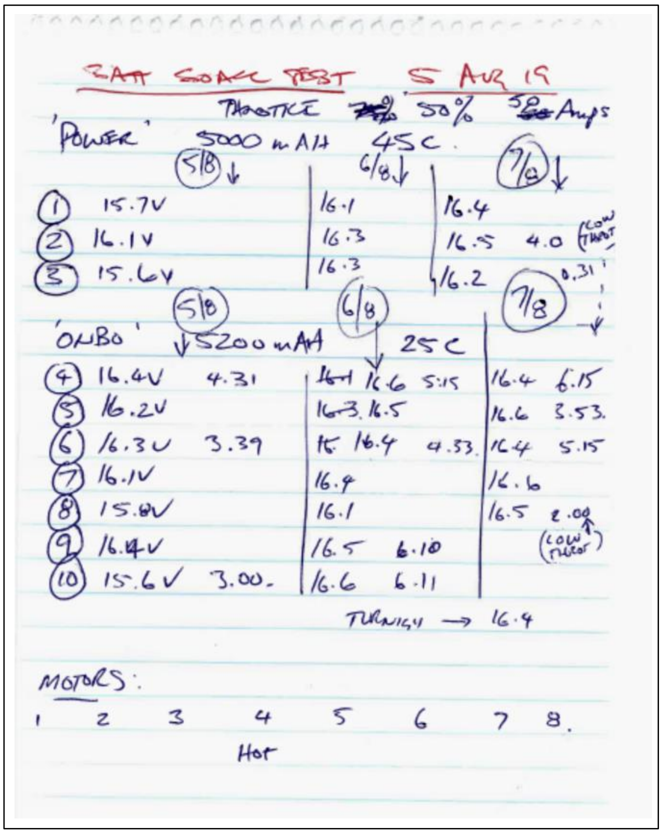


**__Illustration 6.6:__ Periodic Battery Test**

eCalc had suggested that I would need approximately 86 Amps during maximum throttle (i.e. climbing, or fighting a strong wind) for the 8 motors on the drone, so the 130 Amp batteries I chose should cope with a bit of leeway. It would be quite easy to just choose a higher Amp rating for the batteries ‘just in case’, but the problem is bigger batteries mean greater weight, which means that flight times are reduced; so you want to choose batteries which are rated slightly more than you will need. With these batteries I get between 5 and 8 minutes of flight time, depending on atmospheric conditions and the type of course I am flying.

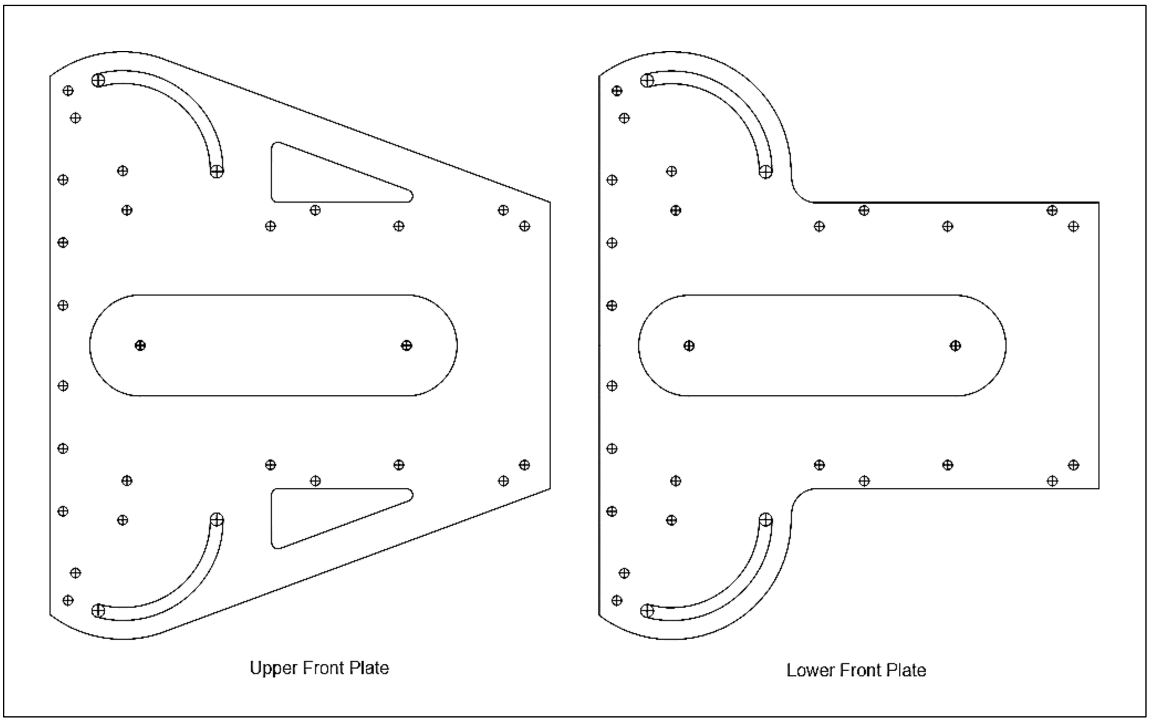
With the 4S motors I was able to incorporate 12-inch props, so the arms and legs of the drone were designed around these. Ultimately however, I ended up using 11-inch props with a higher pitch measurement than the 12-inch ones I originally intended. Experimentation with both suggested better performance from the 11-inch ones in combination with my motors. Nonetheless the arms and motors can accommodate 12-inch props, and there is enough clearance between the leg components and the spinning propellers.

So, with my power choices made, it was time to design and develop the first purpose-built drone, what I will simply call ‘X8 Version 1’.

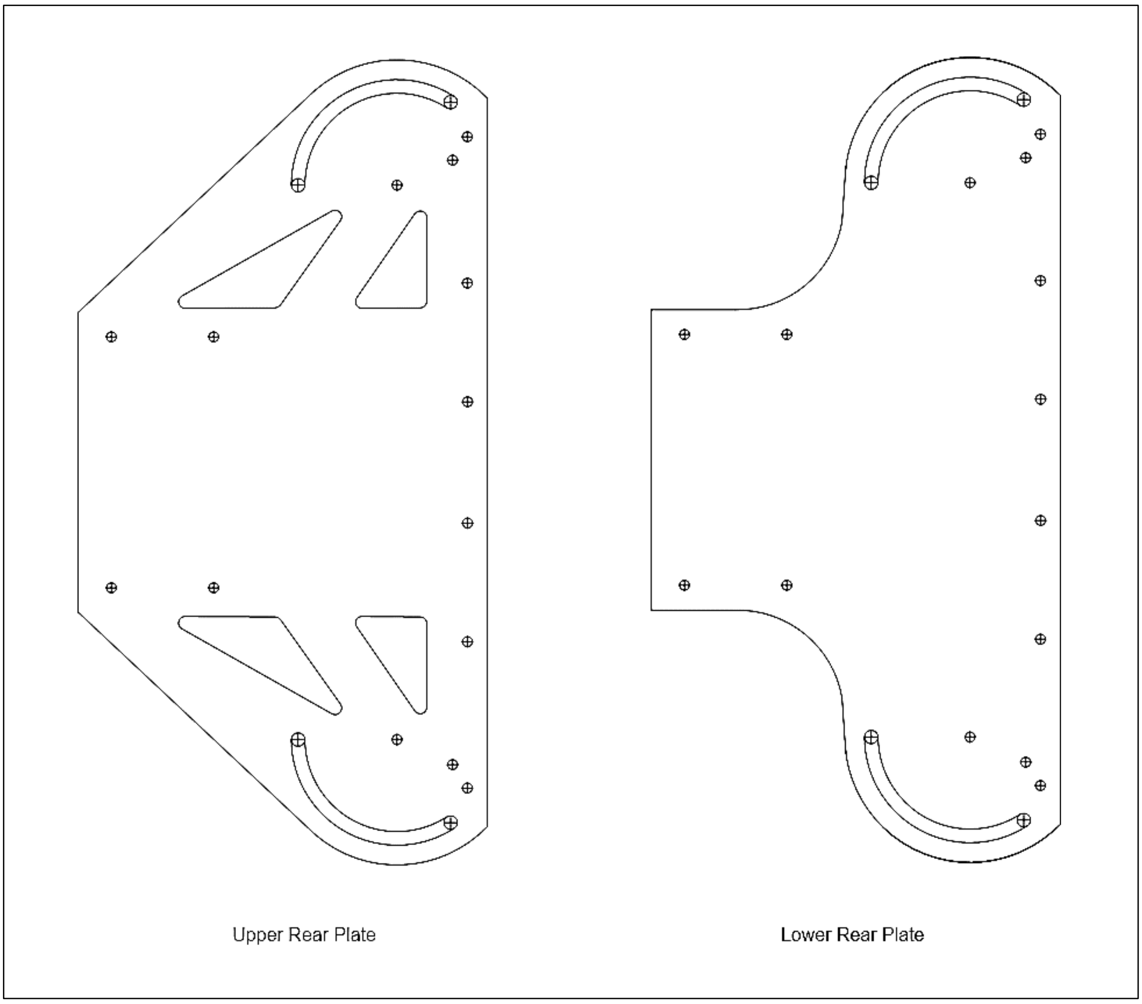
## 6.3 X8 Version 1

In terms of this project, I have experiences as a rider, a technician, a videographer, and a machinist, (amongst other attributes). All of these have engendered in me a ‘common sense’ which is relevant to this research, and greatly helped guide me in both my choices and my abilities. In her paper ‘Mapping the Meaning of Knowledge in Design Research’ Kristina Niedderer refers to this ‘common sense’ as ‘Tacit Knowledge’ and says that in the creative- and practice-led disciplines there are different kinds of knowledge such as ‘… practical knowledge, skills knowledge, process knowledge, personal knowledge, implicit knowledge, professional knowledge, situational knowledge, control knowledge, complex knowledge, conventional knowledge, cognitive knowledge, codified knowledge, public knowledge…’ ( 2007:7) and others, all of which contribute to how the practice-based researcher goes about making and executing decisions. I therefore present the following description based on this presumption.

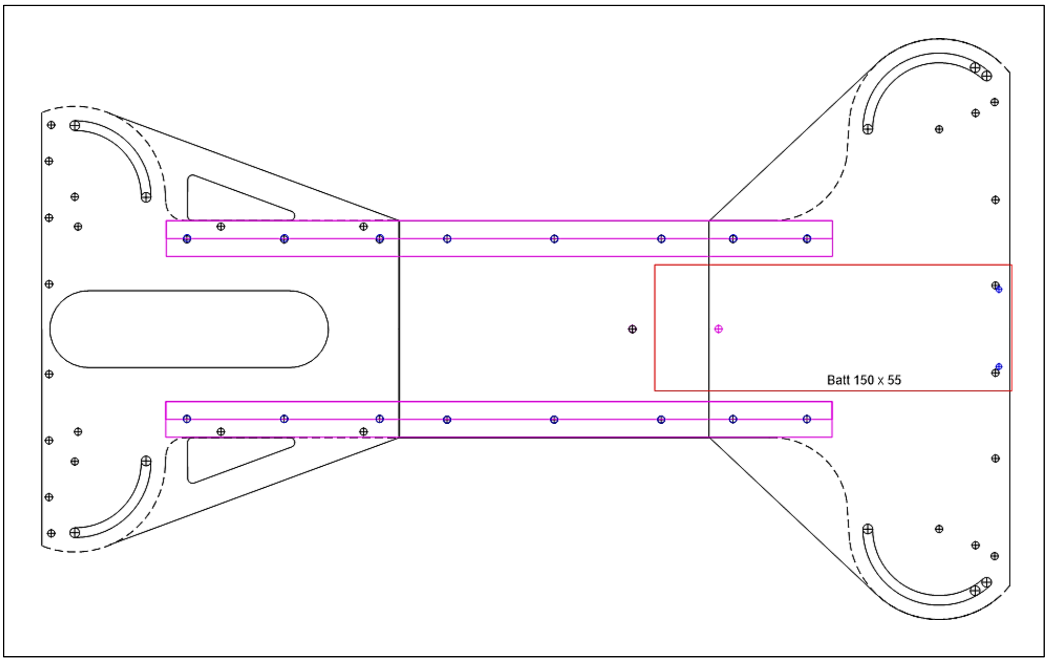
The body of the drone is configured around two longitudinal spars which tie the front and rear frame plates together. The spars are cut from lengths of 15mm square aluminium tubing, and the same tubing is used for the motor arms. This means a consistency of spacing between the frame plates and the spars and arms. The frame plates (and most other plates of the craft) are cut from flat carbon fibre plate, in a variety of thicknesses depending on the physical loading these plates will undergo. I used a variety of 1mm, 1.5mm and 2mm thick carbon fibre, sourced from an overseas supplier. Illustrations 6.7 – 6.10, below, show the various frame plates, front and rear; each with a corresponding upper and lower plate. There are also centre or 'mid' plates, the top one is carbon fibre, the bottom one aluminium for reasons which will be described later. The front and rear plates have a pivoting system for the motor arms, with cut-out, semi-circular slots for the bolts to move through when the arms are folded and unfolded. Having slots negates the necessity to have bolts removed and reinserted; they can merely be loosened and then retightened for folding and unfolding. The frame plates are bolted together through the aluminium spars, but the bottom frame plates are also glued to the spars. This means I can remove the upper-frame plates for making repairs if necessary, whilst the lower ones remain in place to preserve the integrity of the frame structure.



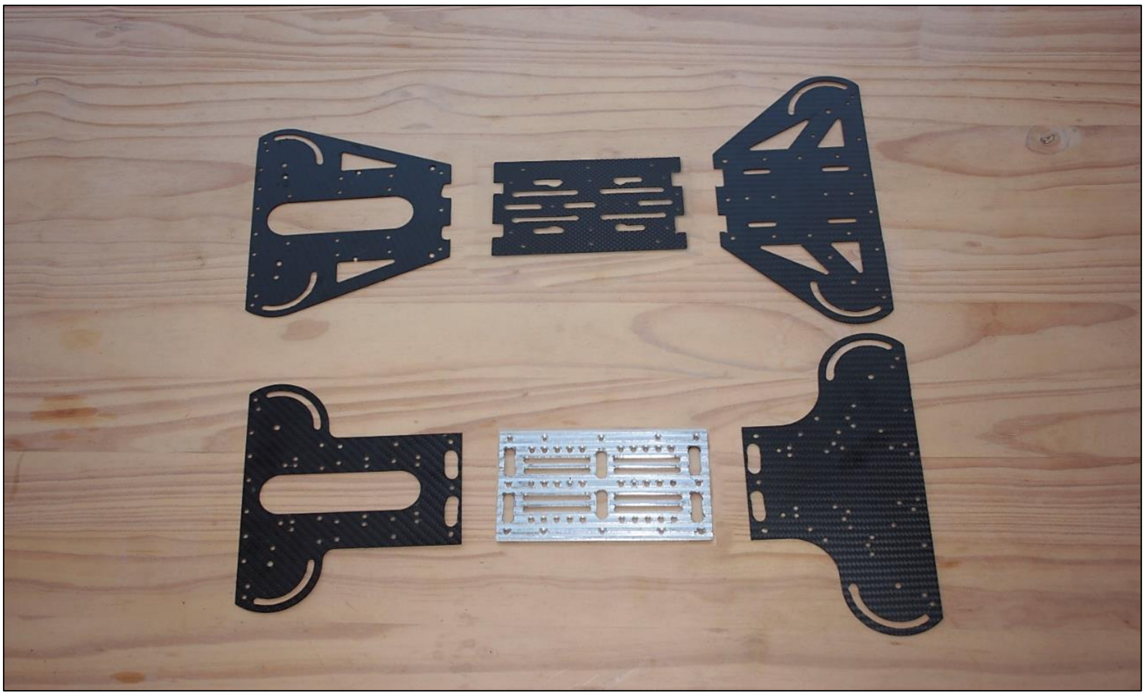

**<u>Illustration 6.7:</u> Upper and Lower Front plate templates**




**<u>Illustration 6.8:</u> Upper and Lower Rear plate templates**




**<u>Illustration 6.9:</u> Assembled Template showing Square Aluminium Spars (pink) and Battery location**



**<u>Illustration 6.10:</u> Frame plates cut from Carbon Fibre and Aluminium**

The size of the drone was largely determined by its folded state, ensuring that the props and all other delicate parts could be bounded by the parts which are strong, such as the bottom of the legs and the frame ends. The folded drone measures 245mm wide x 180mm high by 420mm long.


**<u>Illustration 6.11:</u> Flight Management Unit mounted to Upper Mid plate**

The upper and lower mid-plates are different. The upper mid-plate is cut from carbon fibre and is used to mount some of the electronic components, notably the flight controller which has a separate vibration isolated mounting on top of the mid-plate. The flight controller is housed within a plastic 'lunch box' affixed to this plate, as shown in Illustration 6.11, above.

The lower mid-plate is constructed from aluminium, which has good heat transfer and dissipation properties. This is needed because it will be used to mount the Electronic Speed Controllers (ESC's) which generate considerable heat. There are 8 of these in total, one for each motor, and they are held in place by zip ties. I also milled slots into the plate, to have a greater surface area of aluminium for heat transfer into the air. This is an accepted practice for all 'heat sinks' used in electronics and air-cooled engines and is common on older motorcycles and cars (such as a VW Beetle) which are air cooled. The 'fins' create a much larger surface area for the aluminium to dissipate heat through. Illustration 6.12, alongside, is a diagram of the mid-plate showing the holes drilled for zip tying the ESC's, as well as holes for cable routing, and the slots milled on the underside. Illustration 6.13, alongside, shows a portion of the plate with the ESC's installed. I also milled out a shoulder at either end of the aluminium lower plate to accommodate the bottom front and rear carbon fibre plates, as shown in Illustration 6.14, below. This provided a 'sandwich' joint with the overlapping carbon and aluminium plates and the aluminium

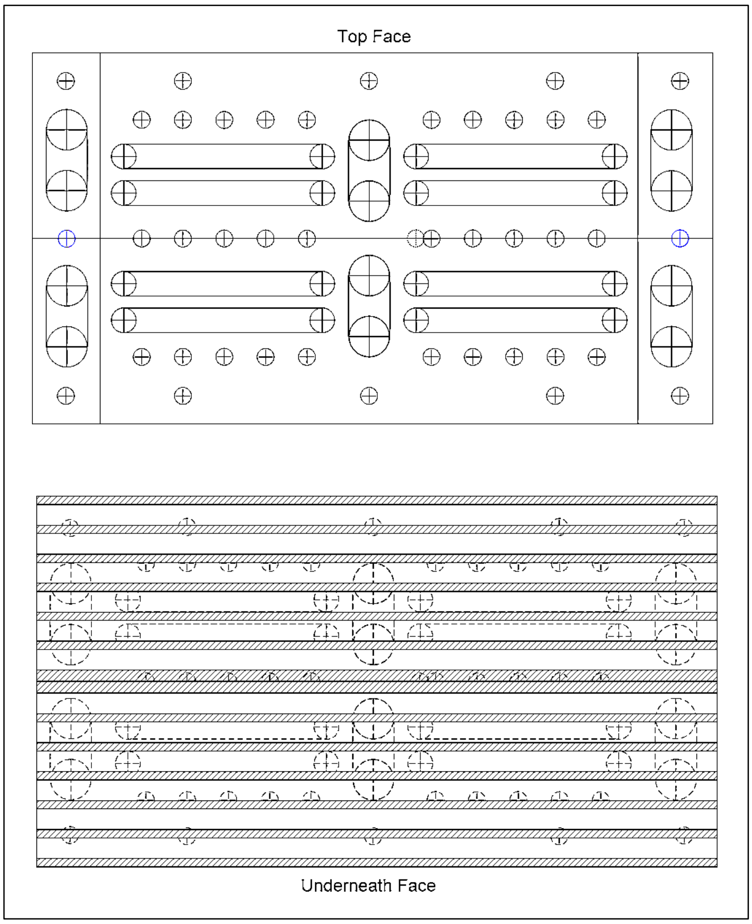



**Illustration 6.12: Lower Aluminium Mid plate template**

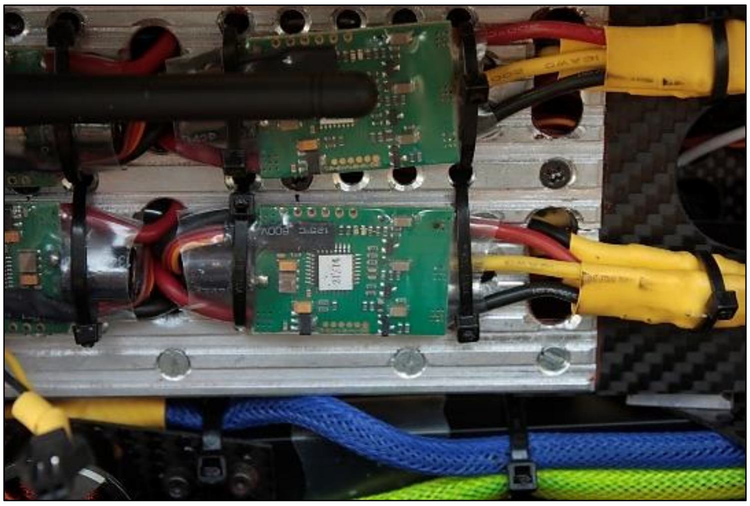


**Illustration 6.13: ESC's installed on lower mid plate**

spars, and when everything was glued together greatly increased the structural strength of the frame.

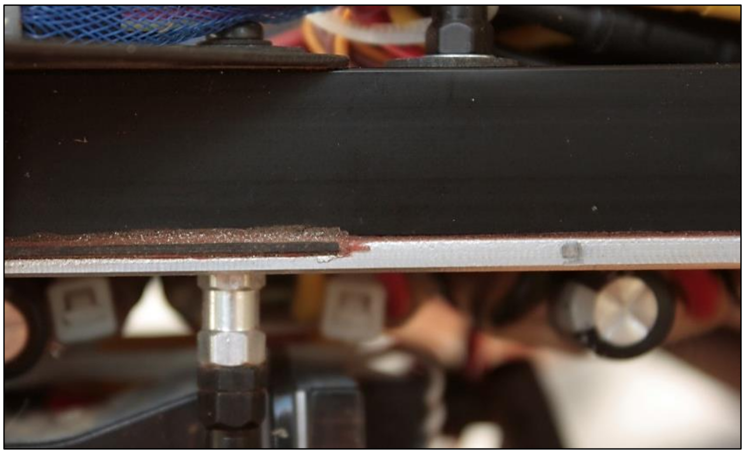


**Illustration 6.14:** **Milled shoulder on mid plate supports robust sandwich construction**

Portions of the front and rear plates which are not supported by the longitudinal spars are separated by 15mm spacers, so that they form a girder type of construction to improve torsional rigidity, as shown in Illustration 6.15, alongside. I used numerous lengths of these spacers in a variety of instances all over the craft.

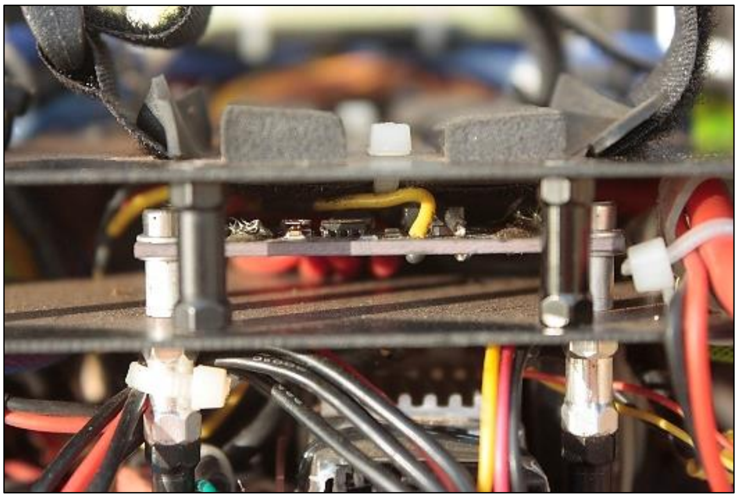


**Illustration 6.15: Spacers between frame plates, and Power Supply board mounted between rear frame plates**

Between the top and bottom rear plates the power supply for the craft is housed, as well the power monitoring board with associated wiring, which is also shown above in Illustration 6.15. The drone battery is fixed to the top of the rear plate and has Velcro fasteners to allow easy battery changes while still holding the battery very securely in flight, as shown in Illustration 6.16, alongside.

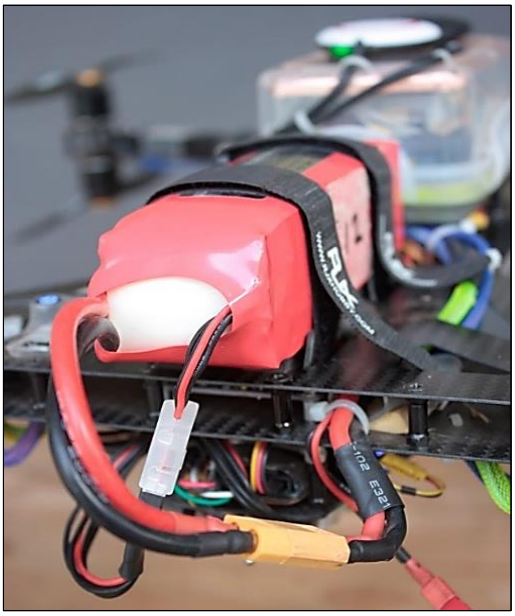
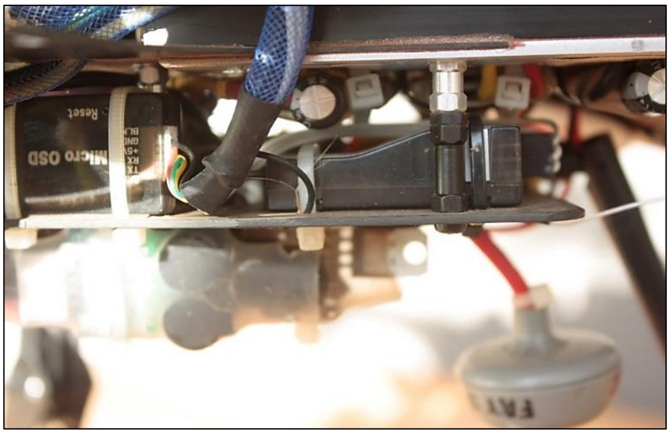
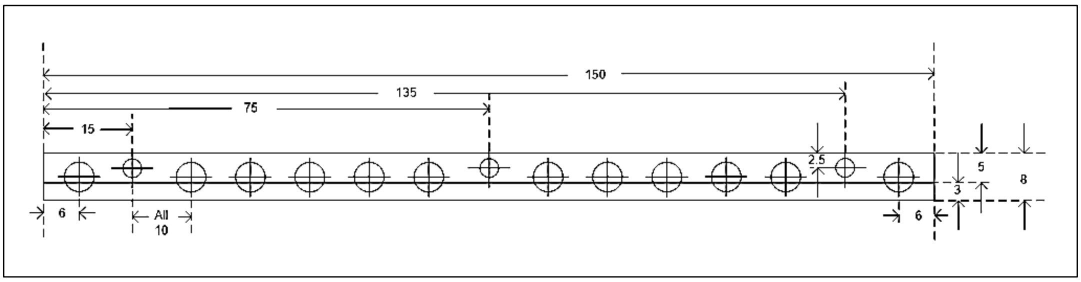


**Illustration 6.16:** **Battery Installation**

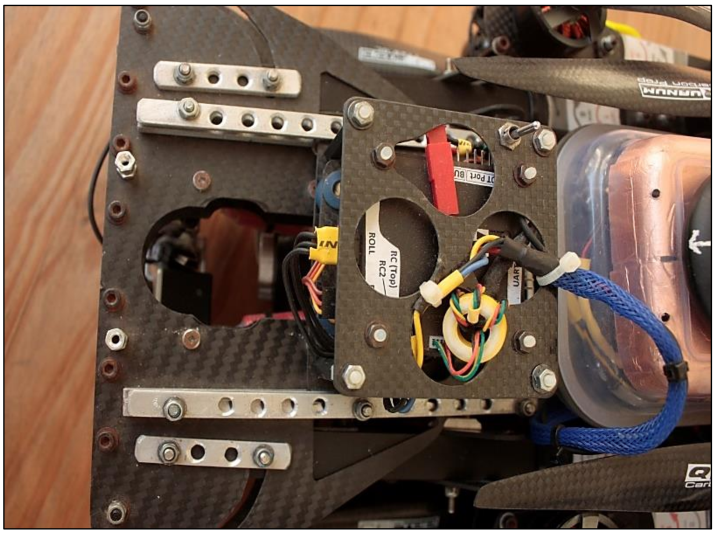
Below the bottom rear plate I mounted a separate ‘sub-frame’ on spacers for housing more electronics. Here you will find the Radio Control receiver, the Video Transmitter, the Telemetry module, the On Screen Display module and other small electronic components which I will write about later. Illustration 6.17, alongside, shows this sub-frame and some of the components. The antenna for the video transmitter and telemetry hang below this sub-frame. Note that neither the sub-frame nor the antenna hang below the lowest part of the drone in its folded state; this means that they are protected during transport.



**<u>Illustration 6.17:</u> Subframe with further electronics**




**<u>Illustration 6.18:</u> Gimbal Slider template**



**<u>Illustration 6.19:</u> Upper gimbal mount and slider**

**<u>Illustration 6.20:</u> Lower gimbal mount and cutout**

The front upper- and lower-frame plates have a large cutout running longitudinally. This is to accommodate the camera gimbal, which hangs off the upper front plate, and then protrudes through both plates for the camera hanging below. This cutout allows the gimbal to be pulled back within the confines of the frame plates for protection during transport, but then moved forward for flight so that the camera viewpoint clears the drone legs and rotating props. The assembly moves fore and aft on a sliding mechanism milled from aluminium which is bolted to the frame plates. The dimensions of this mechanism are shown in Illustration 6.18, above, and the entire upper gimbal mounting in Illustration 6.19, and lower mount in Illustration 6.20, also above. I will deal with the design and construction of the gimbals in a separate section later in this chapter, and there are more diagrams and explanations found there.

## 6.4 Motor Arms

The arms for the motors were also constructed from 15mm-square aluminium tubing. Unlike round tubing which creates problems with alignment of parts, square tubing is relatively easy to work with. It has faces which are parallel, meaning that any parts you mount to them remain in the same plane as other parts mounted further along the arm; and also it has faces which are perpendicular, which means that you can easily fit parts which need to have a vertical and horizontal orientation to each other. However, although I largely had success with this type of material during my exploits with the early drones, I still had to address the two issues which had cropped up (and I have previously written about). The first was that any mounting holes which were drilled through the arms would ‘oval’ over time with repeated jarring, and the second was that if I tried to tighten the bolts through the holes too much (to try and overcome the first problem) the thin walls of the tubing would collapse.

I used a multi-pronged approach to this problem. The first part of the solution was to use small tubing which went right through the arms and protruded beyond the face of the tubing on either side. This tubing had an Outside Diameter (OD) of 4mm, and an Inside Diameter (ID) of 3mm. This meant that a 3mm bolt would nest snugly inside the thin tubing and was supported along the entire length of the tubing rather than only by the thin walls of the square aluminium arms. This was only part of the solution however, because this small thin tubing would still oval the holes and also the square tubing could still be crushed with over tightening. So, the next part of the solution was to inject ‘expanding foam’ into the arms.

Expanding (also known as ‘Spray’ or ‘Builders’) foam is a chemical product created by two materials, isocyanate and polyol resin, which react when mixed with each other and expand up to 30-60 times its liquid volume after it is sprayed in place. As it comes into contact with air, it dries and hardens into a solid state. The result is a very light, but quite rigid, matrix of millions of air-filled pockets surrounded by a labyrinth of hardened polyurethane foam. The foam in its liquid state is quite tacky, and it retains this bond when it hardens to glue together anything it comes into contact with. When I injected the foam into the arms (with the small thin tubing in place) it bonded to the both the inside of the square arms as well as the thin tubing, holding them in place.

Once the foam hardened it solved both problems. Firstly, it supported the round tubing (and the bolts inside it) along its entire length, rather than the bolts only being supported by the thin walling of the square arms. Secondly, it filled the cavity inside and became a structural platform so that I could tighten the bolts without them crushing the thin walls of the square tubing. Illustration 6.21, alongside, shows a close-up of the final arrangement, where you can see the thin tubing protruding beyond the walls of the square tubing, as well as the hardened foam inside the arms.

**Illustration 6.21:** **Motor Arm details**

It is worth noting that from this picture the thin tubing seems to extend in different amounts beyond the square tubing. This is intentional because I was attaching different thicknesses of carbon fibre plate to various parts of the arm. The thin tubing is merely to locate the plate and prevent moving or ovaling from shock; but it should not interfere with the plate being tightened down onto the arm with bolts. If it extended beyond the thickness of the plate being attached, it would prevent the plate being properly tightened. So, the thin tubing should extend less beyond the wall of the square tubing than the thickness of the plate being attached. I was using both 1mm thick plate (for the leg mounting) and 2mm plate (for the motor mounts, the leg strut and the attachment to the main drone frame plates). I could have cut the thin tubing to the correct length after the foam had hardened, but this would have been difficult to do accurately so close to the arms. Instead, what I did was use washers I sourced with a thickness of 0,75mm. These washers had an ID of 4mm and were put over the thin tubing (which had been cut to 16,5 mm and 18mm exactly depending on where they were needed, before inserting into the square arms) and then held in place with a bolt going through the entire arrangement. If they were for a 1mm thickness of plate to be attached, I would use only one 0,75mm thick washer. If they were for a 2mm thick plate I would stack two washers together, giving a total height or protrusion of 1,5mm. Once I had everything in place, I injected the foam; and on hardening and removal of the bolts and washers I had the correct protrusion of the thin tubing. The nett result was that the thin tubing located the plates to be attached in the exact position, supported the bolt throughout its length, but did not interfere with the tightening of the bolts and thus the plates that were being secured.

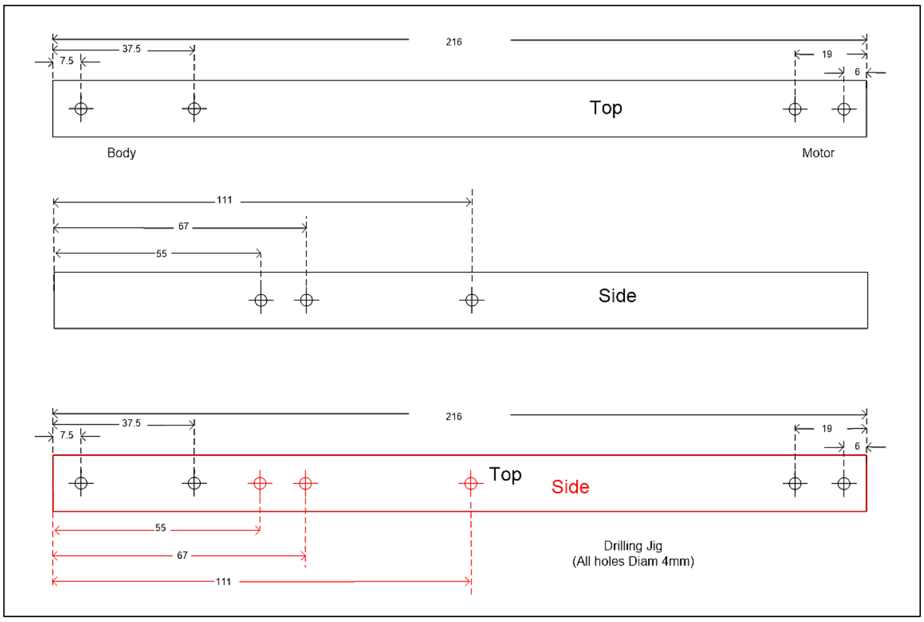



**Illustration 6.22: Motor Arm dimensions and Drilling Jig**

The arms had a variety of plates installed on them. The horizontal faces had the main drone frame plates attached at one end, and at the other the motor mounting plates. The vertical faces had the leg mounting and leg struts attached. Illustration 6.22, above, is a diagram showing the size of the arms and the spacing of the mounting holes; while Illustration 6.23, below, shows one arm completed ready for assembly. Note that in order to satisfy my design requirement of ‘one size fits all’ in order to carry a minimum of spares into the field all the arms must have exactly the same dimensions and construction. It thus becomes important that during construction all the arms are exactly the same. If I were to manually measure the arms and drill each individually there could be tolerance issues because the arms would not all be quite the same. The solution – and this is common engineering practice when multiple parts all exactly the same are manufactured – is to use a 'jig'. In Illustration 6.22, above, the bottom image is the jig I manufactured. I took a thick piece of aluminium and milled out two faces, one along it for the length of the arm to rest against; and one for the end of the arm. Then I carefully measured and drilled out the holes in this jig. Since all the holes were to end up in the centre (longitudinally) of the arms I could drill the horizontal faces first, then flip the arm over through 90 degrees, and drill the vertical faces. Although it took a while to make this jig in the end it saved me time measuring individually; more importantly it ensured that all the arms I manufactured were exactly the same dimensions. (There were not just 4 for one drone because I made multiple 'spares' knowing I would crash and need to replace them.)

**Illustration 6.23: Common Motor Arm**

The motor mounts are cut from 2mm carbon fibre and are bolted back-to-back on the end of the arms. The mounts also have 15mm spacers between the two of them at their extremity to further enhance rigidity. The motor mounts are all identical, no matter which arm they are on or whether they are the upper or lower mount. The motors mount individually to the respective mount. This system has proved to be reliable, strong, and easy to swop a motor out should the

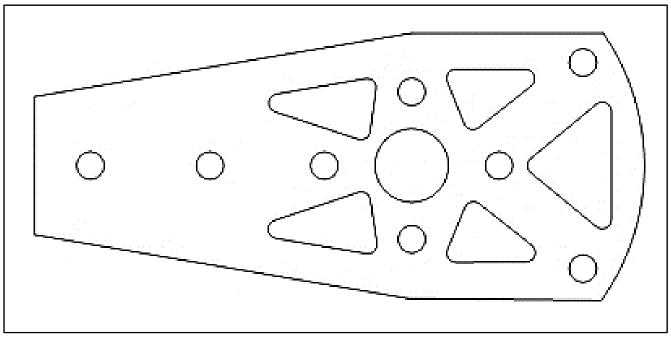


**Illustration 6.24: Motor Mount template**

need arise. Illustration 6.24, above, shows the cut-out of the motor mount, and Illustration 6.25, below, shows the coaxial mounting of the motors.


**<u>Illustration 6.25:</u> Coaxial mounted motors**

Swopping out a motor or prop in the field can be confusing. The motors spin clockwise or counter-clockwise depending on their position. Similarly, the props also spin clockwise (CW) or counter-clockwise (CCW) depending on their position. Some props are mounted 'upside down' on their motors, but 'right way up' when viewed from above the craft. If you break a prop out in the field, often the blade which breaks flies off into the distance never to be seen again (so you cannot identify whether the prop was CW or CCW); sometimes several props break and it's difficult to remember which goes where. To this end I have put a small sticker (covered in clear heat shrink for protection) on each arm which specifies each motor and prop, customised for each arm. Illustration 6.26, alongside, shows an


**<u>Illustration 6.26:</u> Motor and Prop information on arms**

example of this. It shows ‘LFT’ – Left Front Top motor; ‘2’ – the motor number according to Arducopter software, a ‘Red arrow’ - showing the spin direction of this top motor; and then ‘LFB’ – Left Front Bottom motor, ‘5’ – motor number 5, and a ‘Black arrow’ showing the spin direction for the prop on this bottom motor. From the spin direction you can work out whether a prop is CW or CCW. This system has proved invaluable, time-saving, and most importantly reliable when swopping broken props or damaged motors in the field.

The arms are connected to the main frame via a swivelling arrangement which allows them to be opened for flight or pivoted back against the body and stowed for transport. The carbon-fibre frame plates have a pivot point, as well as a semi-circular slot cut into them so that the bolts on the arms can merely be loosened and repositioned, rather than removing the bolt (and nut and washer) and then having to reinsert it into the new hole. This left a rather thin piece of carbon fibre running around the outside of the slot, and I was worried about this breaking in a crash. If the arm went into the ground first (in most crashes extremely likely) it would transfer a high leverage onto this thin arc of carbon fibre, and in all likelihood this would break. In turn, this would mean that I would have to repair the main frame plates; and such a case would mean removing the entire frame plate, with all of its attached wiring and electronics, in order to replace it with a new one. Out in the field this would be an impossible job, and even to do so in the confines of a well-equipped workshop would have taken many hours of labour. I simply had to avoid this possibility at all costs.

The solution was to create two braces or stiffeners attached to the arm, located at the pivot point; one above and one below the carbon-fibre plates. These stiffeners can be seen in Illustrations 6.27, alongside, and 6.28, below. They extend beyond the perimeter of the carbon-fibre plate and provide the necessary support in the case of a crash. In

**Illustration 6.27: Upper frame plate stiffener**

all my testing this worked extremely well; I never had to replace a frame plate after a crash, although I replaced quite a few arms along the way. The arms typically bent right at the point where the stiffener ends (as can be seen from Illustrations 6.29 and 6.30, below, of several crashed bent arms) and became a sort of crumple zone absorbing

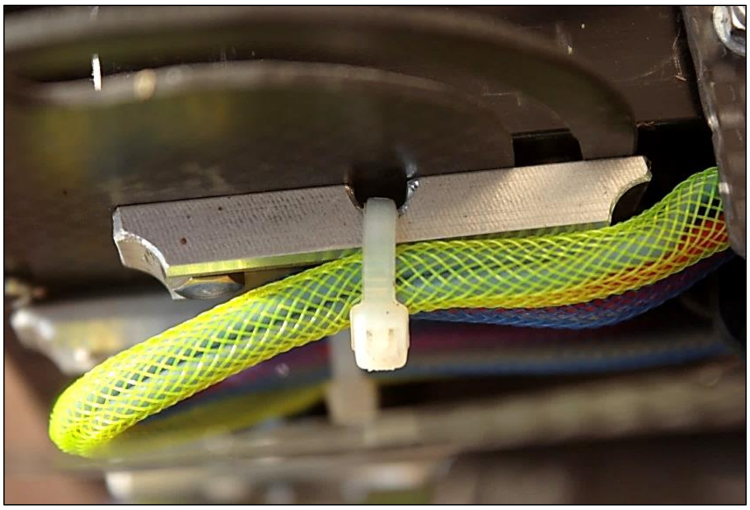


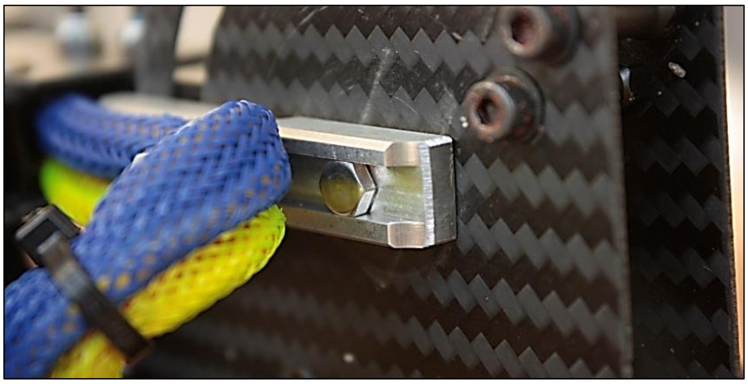
**Illustration 6.28:** Lower frame plate stiffener

**Illustration 6.29: Bent and Broken arms from crashes**

**Illustration 6.30: Arms bend/break at edge of stiffener, and protects integrity of frame plates**

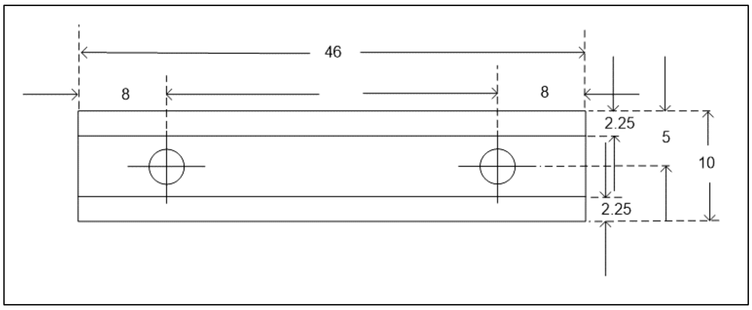
the shock of crashing within the arm and not allowing components beyond it to be affected by the crash. Noting how the arms had bent at the point where they entered the frame entirely vindicated my decision to employ the stiffeners; without them I would surely have broken the thin curved ribs of the main frame plates and ended up replacing these plates with frequency.

The stiffeners were multipurpose. In order to need only one tool for folding and unfolding the arms I would need some way of holding the bolts when they were loosened and tightened. The tool (a 5.5mm nut driver which I will show a picture of in a later chapter) would be used on the nut, but the bolt head had to be secured in place and prevented from turning as I loosened or tightened the nut. The solution was to use bolts with a 'hex' head. I then milled the bottom stiffener with a slot which was very slightly wider than the distance across the 'flats' of the hex head. The head fitted snugly into the slot and was prevented from turning by the walls of the stiffener. This setup can be seen in Illustration 6.31, above, and the dimensions of the lower stiffener for machining purposes in Illustration 6.32, below.



**<u>Illustration 6.31</u>: Stiffener prevents bolt head from rotating**

As an aside, it is very difficult to source small bolts (actually they are called 'machine screws' when they are small) with hex heads. Machine screws come in a variety of head shapes; you get Rounded head, Cheese head, Countersunk head, Slotted head and Phillips head to name just a few; but all of them have a circular peripheral shape which would not work in my case. Hex-head machine screws are not very common at all; even searching internationally I only found a few vendors. Strangely enough after much searching and many phone calls I found a small specialist company in




**<u>Illustration 6.32</u>: Lower stiffener dimensions**

Durban which had a few of the correct length in stock; I immediately purchased their entire inventory!

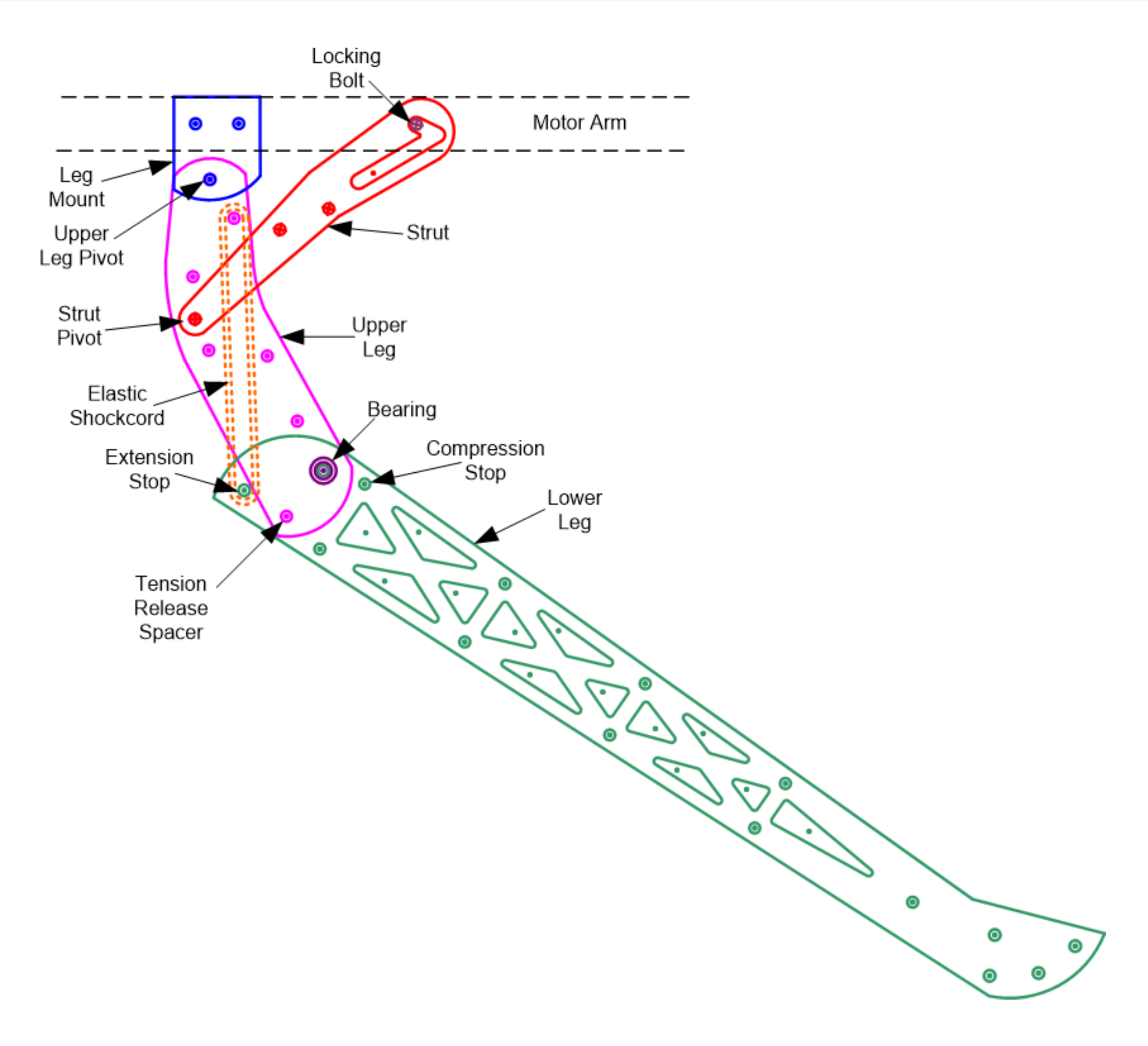
The other function of the stiffeners was to keep the motor-wiring secure and safe from damage. Typically, wiring on any electronic part should be kept immobile, because when it starts moving it can get twisted or snagged on adjacent parts, and the constant bending of the wires leads to them breaking. I foresaw that the pivot points of the arms were going to be a typical place where the wiring would be subjected to constant movement and risk of snagging or breaking as the arms were repeatedly opened and closed. To this end, I machined a small half-moon cutout into the lower stiffeners, which can be seen in Illustration 6.28, above. This allowed me to zip-tie the motor wiring securely to the stiffener in the orientation that it would always need to be and so prevent the need to have a loop of wiring which could get snagged and damaged. Note also that the wires to the motors (there are 3 for each motor, thus a total of 6 for each arm) are encased within sheathing, to further limit the possibility of twisting and snagging. The wiring is colour-coded so that I can easily trace back the cabling for a particular motor during fault finding.

## 6.5 The Legs

The legs were to prove to be one of my greatest challenges from a design and construction perspective. I progressed through many working-drawing design iterations and mock-ups on the workbench before I settled on a final version. I will not explain these earlier versions but simply the last one.

As per the design brief explained in an earlier chapter, the legs had to fulfil five requirements. Firstly, they should mount closely to the frame so as not to impede the prop rotation of the lower props, whilst at the same time having a wide stance of the feet for stability. Secondly they should be tall legs for launching and landing in long grass, whilst also able to fold up against the arms for transport (and not impede the folding of the arms in towards the frame). Thirdly, they should have an independent suspension system for each leg so that the legs can accommodate landing and launching off sloping or rocky terrain. Fourthly, the feet should not get caught in grass when landing or taking off; and finally, the system of folding and unfolding the legs must be done easily with one tool, and when the legs are unfolded they must remain locked in place as a safety precaution.

The legs are made from ‘mirror images’ of four main components which are tied together with spacers of the necessary sizes. The four main components are shown in Illustration 6.33, below, and I have colour-coded the various components to be able to see them in the drawing clearly. They are The Leg Mounting (Blue), the Upper Leg (Pink), the Leg Strut (Red) and the Lower leg (Green). The parts are manufactured from various thicknesses of carbon-fibre plate depending on the strength I needed from each part considering both the stresses each part would undergo as well as the need for having ‘crumple zones’ in the case of a shock

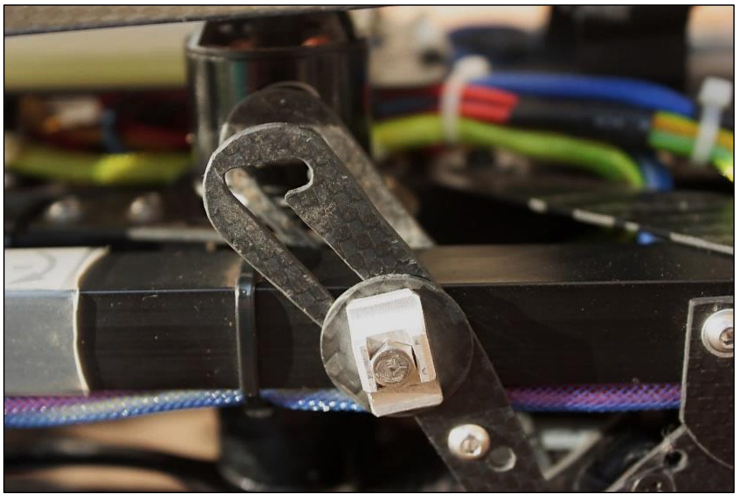



**<u>Illustration 6.33:</u> Leg Components and Assembly**

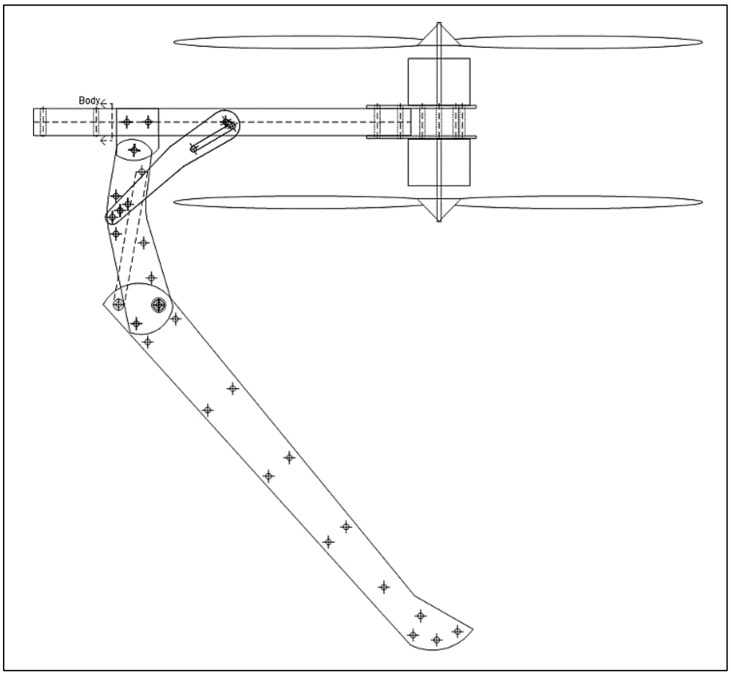
from a crash. The finalised leg components (for one side of the mirror image) are shown in Illustration 6.34, alongside.

**<u>Illustration 6.34:</u> Leg Components cut from Carbon fibre**

The Upper Leg is connected to the Leg Mounting by means of a cylindrical post which passes through it and is bolted on either side to the leg mounting. This allows the upper leg to pivot around the cylinder, relative to the leg mounting. Similarly, the Strut is bolted to the upper leg with the same cylindrical post system; which also allows it to pivot respective to the upper leg. The strut has a slot machined into it; when the locking bolt on the motor arm is loose the strut can move freely along the slot, but when the bolt is tightened the strut is held firm. The bottom of the slot corresponds to the folded position of the leg and is carefully cut so that when the legs are folded their back face is perfectly horizontal to support the drone. The top of the slot 'kicks back'. When the leg is extended the locking bolt moves into the position of the kick back and the bolt is tightened to lock the leg into the extended position



**<u>Illustration 6.35:</u> Finger hold for Strut bolt**




**<u>Illustration 6.36:</u> Diagram of Leg in Flight position**

for launching, landing and flying the drone. The kick-back section of the slot is utilised as a safety precaution so that even if the locking bolt were to work its way loose, the leg would remain firmly in the extended position. The combination of leg mounting, strut and motor arm forms a triangle, which is a very strong and stable engineering shape. To fold or unfold the legs merely requires the same 5.5mm nut driver on the nut of the locking bolt. To hold the bolt during the tightening and loosening of this nut, I once again machined up a small aluminium slotted piece similar to the arm stiffeners I explained earlier; you can easily hold this with your fingers while you use the nut driver. Illustration 6.35, above, shows this small piece.

**Illustration 6.37: Leg Unfolded for Flight**

Illustrations 6.36 and 6.37, (both above), show the leg in the extended or unfolded position for landing, launching and flight. Illustrations 6.38 and 6.39, alongside shows it in the folded position for transport (the photograph is just for illustrative purposes; the arm would still be folded against the body). Note how the ‘bottom’ of the leg is horizontal now, and forms a firm base to put the drone down in its folded position when transporting. Illustration

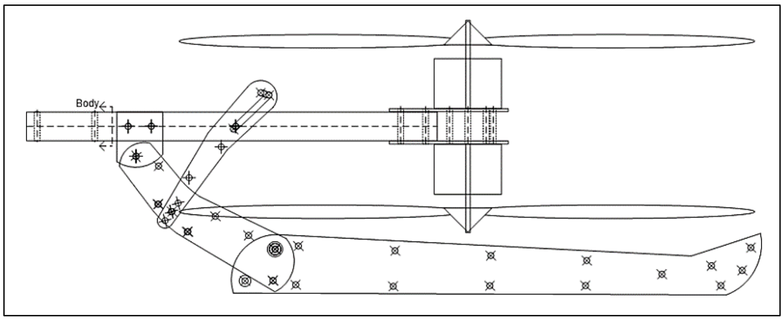



**Illustration 6.38: Diagram of Leg Folded for Transport**

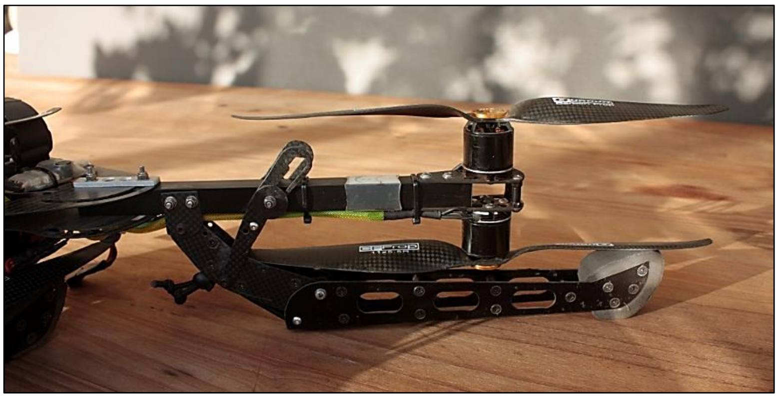


**Illustration 6.39: Illustrative photograph of Leg in Folded position**

6.40, alongside, gives a better idea of this, it shows a side view of the drone with both legs in the folded position.

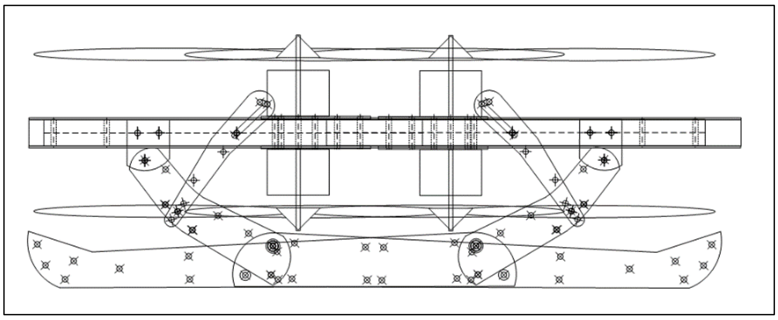


**Illustration 6.40:** **Diagram of both legs folded for transport**

Illustration 6.41, below, gives a side-by-side comparison, on the left the unfolded drone ready for flight, and the right folded ready for transporting. Note that technically these two drones are slightly different. I will write about the second one later; but they both use the same arm/leg folding and unfolding principles. What can also be seen clearly in this picture is the wide stance of the feet of the legs.

**Illustration 6.41:** **Folded and Unfolded drones side by side for comparison**

**Illustration 6.42**: **Lower leg pivot bearings**

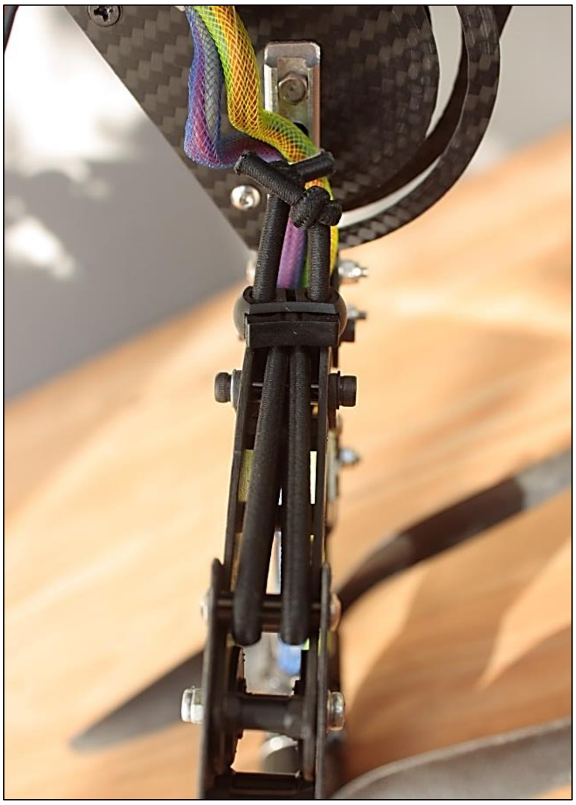
The Lower Leg forms the suspension component of the system. It must be able to rotate smoothly and easily, up and down, relative to the Upper Leg. To this end I used small, sealed bearings, examples of which are shown in Illustration 6.42, alongside. I drilled the upper arms so that the bearings were a press fit into them. Then, via a combination of washers, threaded spacer, and bolt and nut I attached the lower leg. This arrangement can be seen in close up in Illustration 6.43, alongside.

**Illustration 6.43: Lower leg pivot construction**

Suspension works in two directions and is used on all kinds of vehicles. For example, when a car wheel hits a bump in the road the wheel moves upwards (relative to the car) to absorb the impact. This upwards movement is known as 'compression'. Once the wheel is beyond the bump it moves down again, this movement is known as 'rebound' or 'extension' of the suspension components. This is controlled by a spring mechanism which is carefully chosen not only for the amount of mass the spring must support (i.e., the weight of the car) but also for how far it must allow the suspension system to 'travel'. A typical car travelling along a tar road which doesn't encounter big bumps in the tar needs far less travel than, for example, a dirt bike which is encountering big bumps off road. On the other hand, the spring for the car will need to be much stronger than the dirt bike because it is supporting much more weight.

Most suspension systems utilize a spring to support the vehicle, and it does so by providing a compressive force. I researched drone leg suspension systems for quite some time. Firstly, there are hardly any, there never seems to have been a need for them; almost everyone is content with rigid legs because they are launching and landing on smooth level surfaces. The few I found would not suit my needs at all. They utilised small springs or elasto polymer 'bumpers' between the body of the craft and the legs. There were two main issues I foresaw with using such systems. The first is that I would need to experiment with many different 'spring rates' before I found the one which would suit my needs. Spring rate is a measure of how much force the spring needs to compress it and is tied to the weight of the vehicle. For a start, there are not a wide variety of small springs available, and they don't have their spring rates easily specified. I would need to buy one, test it, buy another, test it; until I found one 'just right'. A bigger problem, though, was the amount of 'travel' I needed from the system; I wanted it to have quite a big movement at the foot. There are two ways to achieve this; either have a long spring, or otherwise place the spring at a part of the lever close to the pivot where a small spring deflection leads to a large deflection at the end of the leg. Both ideas presented the same problem, which is that springs are made of steel, which is heavy. A long spring has more ‘windings’ or ‘coils’ which makes it heavy, a small spring which has a high spring rate has thicker steel coils which again make it heavy. I was just not happy with the use of springs for my application.

My thoughts turned to nature, and how it solves the problem. Springs work under compression, in other words they are ahead of the pivot and the lever they are supporting. What if I were to suspend something under tension? This is how muscles have evolved in nature. A muscle doesn’t ‘push’, it ‘pulls’. Imagine your elbow joint. If you lift something the force of lifting comes from the bicep working in front of the elbow pulling up the forearm. But at the same time, you have an ‘antagonistic’ muscle working behind the elbow joint – the tricep – controlling this movement by also pulling. When you bend your arm, the bicep is pulling, when you straighten your arm the tricep is pulling. If you were to do a ‘push up’ off the floor, it is the tricep which is lifting your weight (as well as chest muscles) by straightening the elbow joint. Muscles work like elastic under tension, and this was my solution. Use an elastic system behind the joint to provide support for the suspended leg. I have not seen elastic used anywhere in drones for this purpose, in all of my research. Please refer to Illustration 6.33, above, which shows the positioning of the elastic on the leg, and Illustration 6.44, alongside, with it installed on the leg. Elastic ‘shock cord’ is freely available in a variety of lengths and thicknesses. The thicker it is the more force it requires to stretch it. By using shock cord I solved both my problems. It allowed me the necessary suspension



**<u>Illustration 6.44:</u> Shock cord installation**

travel, because it can stretch a lot. This gave me the large foot movement I required. As importantly, it allowed me to 'tune' the support it gave to the weight of the drone, by means of 'cord locks'. A cord lock is a small spring-loaded mechanism through which the shock cord passes; when you push in the button you can pull the shock cord through, but release the button and it locks into place. The use of this button is shown in Illustration 6.44, above. Now I could easily adjust the tension on the shock cord by experimentation. I adjusted the four sets

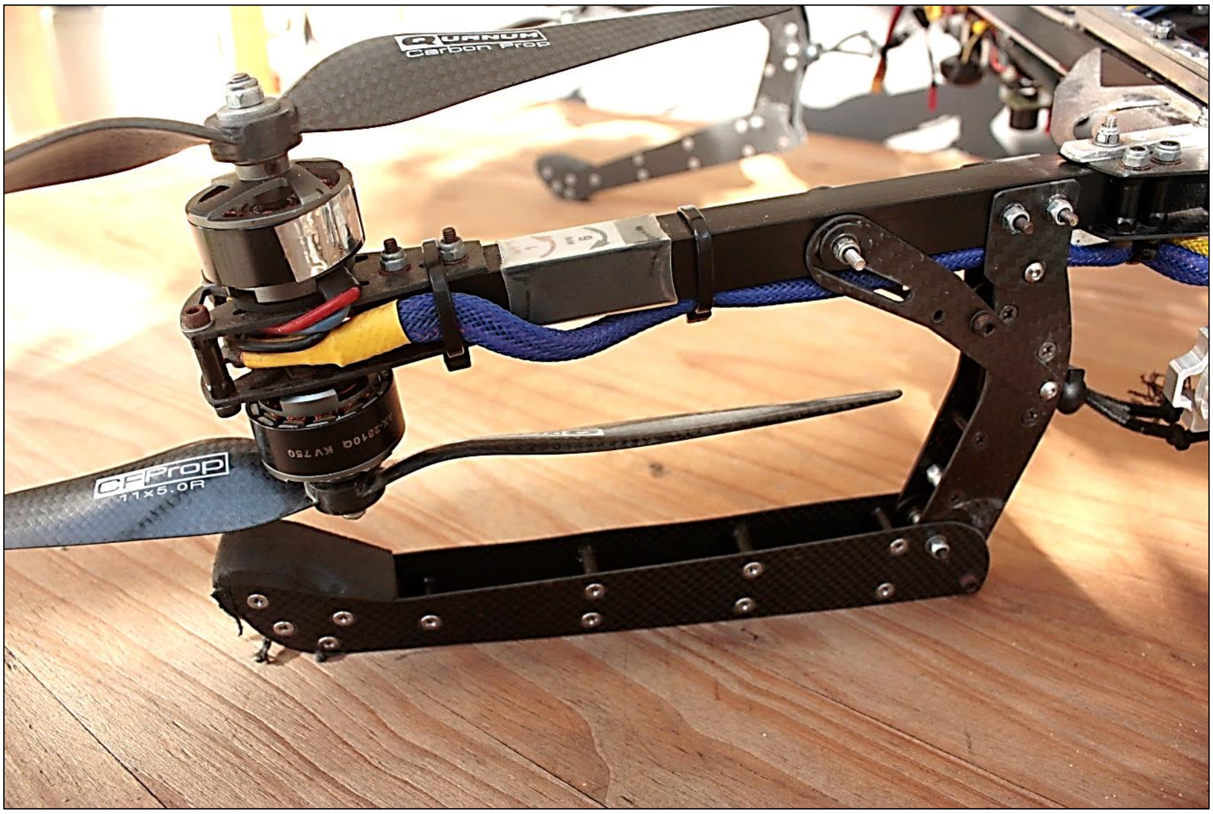
**<u>Illustration 6.45:</u> Suspension legs facilitate take off and landing on sloping ground**

**<u>Illustration 6.46:</u> Suspension legs allow landing on rocky ground**

of shock cord so that they barely supported the weight of the craft; this meant that each leg would require minimal force to activate the suspension on landing.

I was pleased with the solution; it worked very well. No longer the problem of working in areas which were not level, the legs could accommodate the differences in height. More importantly, no longer the problem of landing amongst rocky areas with the craft flipping over on landing. The individual leg which touched down on a rock would just compress until all the other legs touched down. Illustration 6.45, above, shows the craft on a sloping surface, whilst Illustration 6.46, also above, below gives an indication of all the legs at different heights with ‘rocks’ below them.

The last issue to be addressed with regards to the suspension was the limits of the leg under full compression and extension. When extended, the legs should all be at the same length, so that the drone sat level on a level surface. I solved this by using a spacer on the lower leg that butted up against the upper leg when the lower leg was at full extension. Of greater importance, though, was the amount of compression which the leg could undergo on landing.




**<u>Illustration 6.47:</u> Fully compressed lower leg does not interfere with prop rotation**

I did not want the leg to compress so much that the foot intruded into the spinning propeller, so I used a similar spacer system to limit the upper travel of the leg. The position of these extension/compression ‘stops’ can be seen in a prior Illustration 6.33, above, whilst Illustration 6.47, above, shows the lower leg under simulated full compression. Note how the leg or foot is not allowed to travel up into the prop rotation area.

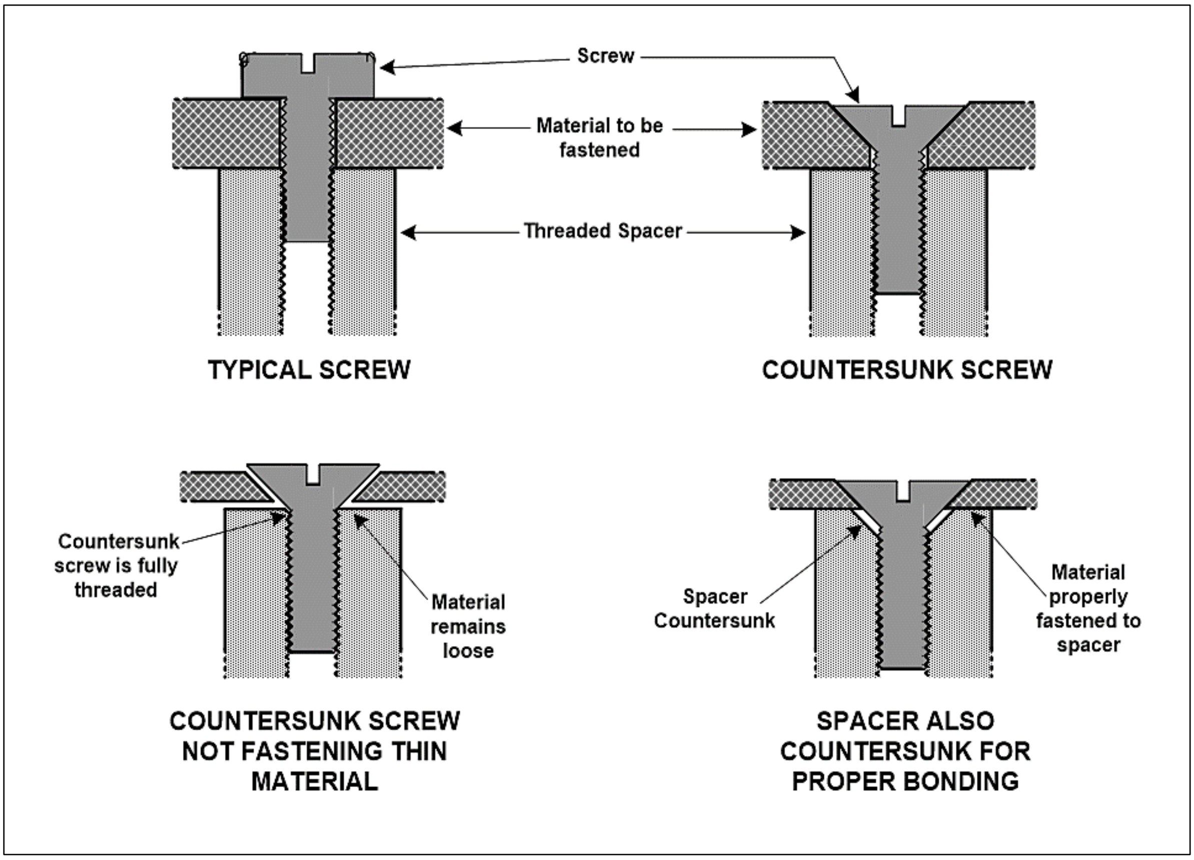
I discovered a very useful property of the suspension system – how it could assist with landing in long grass. I have spoken previously about the problem of the grass being caught and tightly wound around the motor shafts (and the subsequent time it took to disentangle it). The issue is exacerbated by the motors still being under power as you come in to land; the powering of them tangles the grass very tightly around the shaft. But – what if I just cut the power to the motors (by closing the throttle quickly) when the drone was still above the grass? It worked! I could bring the drone down until it was just above the grass, then cut the throttle. The drone would drop down through the grass; the suspension of the legs absorbed the shock of its fall; and the drone remained safe. There was still grass caught up around the shafts because the props still had inertia and were still spinning; but they were not under power, so they did not catch the grass and tighten it. In fact, the blades of grass (you need to remember this is really tough ‘veld’ grass) slowed the props down immediately. The nett result: although there was still grass around the motor shafts, it was much looser and very easy to remove; it certainly never required removing the props to disentangle the grass as it had previously. Without the suspension I could not have employed this technique of ‘dropping the drone into the grass’ because it would have damaged the sensitive on-board components. I saved myself much time out in the field by using this new way of landing in long grass.

The next problem to be addressed regarding the legs was that of the feet snagging on grass when taking off, or landing at anything other than perfectly vertically, such as when the wind is blowing, and the craft comes down at an angle. The problem was caused by small feet with sharp or protruding edges, that almost every drone which has legs seem to have. The solution was larger, rounded feet with flat surfaces. I fashioned these feet from closed-cell foam which was slightly thicker than the spacing between the adjacent plates of the lower leg. The feet had spacers the same length as between the leg plates which went through the foam. When I tightened the screws into the spacers, they compressed the foam and held the foam securely in place. This arrangement, and the foot itself, can be seen in Illustration 6.48 alongside; and I completely solved the grass-snagging problem using feet like this.

**<u>Illustration 6.48</u>: Rounded closed cell foam foot**

The last issue to address was the aerodynamics of the lower leg. Since the leg was extended directly below the props, I wanted the airflow to be as smooth and efficient as possible. One way to alleviate disturbed airflow was to have the outside of the legs as flat as possible. In aircraft this is a much researched and implemented principle, where special rivets are utilised in those craft which are constructed using rivets to hold external sheet metal panels to interior framework. A ‘normal’ rivet has a head which protrudes above the sheet metal. If there were only one this wouldn’t really be a problem, but where you have hundreds and very often thousands of these small heads protruding above the sheet metal surface into the airflow it can cause severe disruption of the air over the panels, leading to very poor aerodynamics and performance of the aeroplane. The solution in the aircraft industry is to use specialised so called ‘flush’ rivets, whose heads are ‘countersunk’ into the sheet metal and thus end up level with the surface of the metal, resulting in smooth airflow and good efficiency. This method is considered so crucial that it is the singular way of building aircraft of this type of construction.

In my case, I was not using rivets between the two sides of the legs, but rather small machine screws, which screwed into spacers between the legs. If I had used machine screws with a raised head, these heads would have been in the prop wash and have led to poor aerodynamics and thus poor efficiency of the prop. The solution was to use countersunk head screws where the head would end up flush with the carbon fibre leg and not impede the airflow over the surface of the leg. Now, this may seem like an obvious solution, and it was, but it became quite a headache when I wanted to implement it during construction. The problem, and solution, is shown in Illustration 6.49, below. It would not have been a problem had I used thicker carbon fibre material for the leg plates, but I wanted to use as thin as possible to save weight, because the legs are quite large components, and using thicker material would have added considerable weight to the craft.




**<u>Illustration 6.49:</u> Fastening thin materials with countersunk screws**

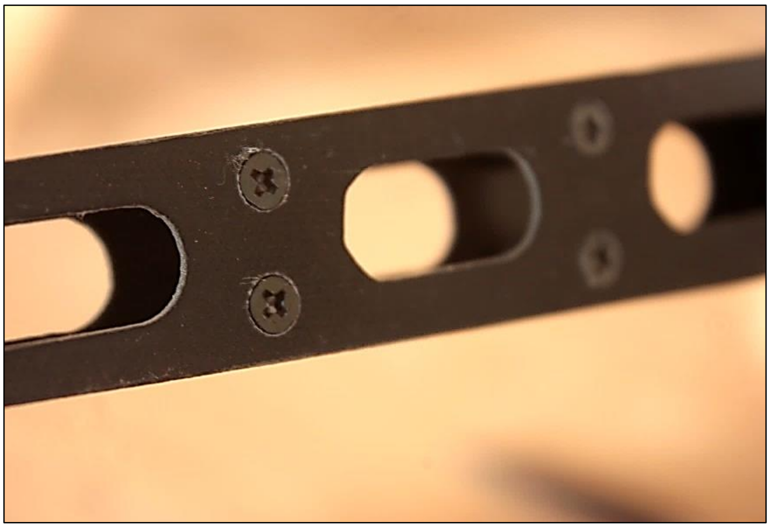
So, I chose to go with 1mm thick carbon fibre for the lower legs. (The upper legs were 1,5mm because they had to be strong in the triangular structure of upper leg, strut and arm mount.) The issue with using 1mm for the lower legs is that the countersunk portion of a 3mm machine screw is about 3mm before the thread of the screw starts. The upper face of the spacer it was screwing in to was flat. So, as can be seen from the illustration, if I screwed through the 1mm plate, the screw would 'bed down' at the beginning of its thread before it tightened the plate to the spacer, and the joint would remain loose. This is obviously totally unacceptable.

The only way of overcoming this (other than going to thicker plate which was not an option) was to countersink each spacer by a small amount. This meant that the screw would tighten down on the plate before it bedded down into the spacer as shown in Illustration 6.49, above. Easy solution? Yes. But implementing this solution was time consuming.

Every thread (whether outside such as a screw, or inside such as in the spacers I was using) has a section at the very beginning of the thread known as a 'lead in' to the thread. This easily enables the screw to 'start' the thread. Without this lead-in, the thread is more difficult to engage, and (especially in materials such as the spacers which are made of soft aluminium) can lead to 'cross threading' and destroying the thread as you begin engaging it. So, this lead in is manufactured into the initial part of the thread. The problem was that as I countersunk into the spacer, I removed this lead in, because the start of the thread was now lower down in the spacer. So, I had to recut this lead in on every thread I countersunk.

The problem was not only limited to the lower legs where aerodynamics were an issue, and I was using 1mm thick material. I also had to countersink the spacers between the upper legs; even though they were composed of thicker material, it was still less than the countersunk portion of the screw head. At issue here was not aerodynamics (the upper legs are out of the prop wash), but rather clearance between the upper-leg plates and adjacent plates. If you look at the drawings and photos of the leg components you will notice that the struts fit snugly over the upper-leg plates with only a small clearance between the two. Had I used screws with 'normal' raised heads the heads would have interfered with the movement of the struts as I folded and unfolded the legs. To avoid this the screws had to be countersunk flush with the upper-leg plates (in fact, I recessed them slightly more below the surface of the plates). A similar issue occurred at the bottom of the upper leg; there is a screw and spacer which sits inside the lower legs, and if these heads had protruded they would also have interfered with the lower-leg suspension movement. So, I had to countersink the beginning of each thread on each spacer of all the leg components.

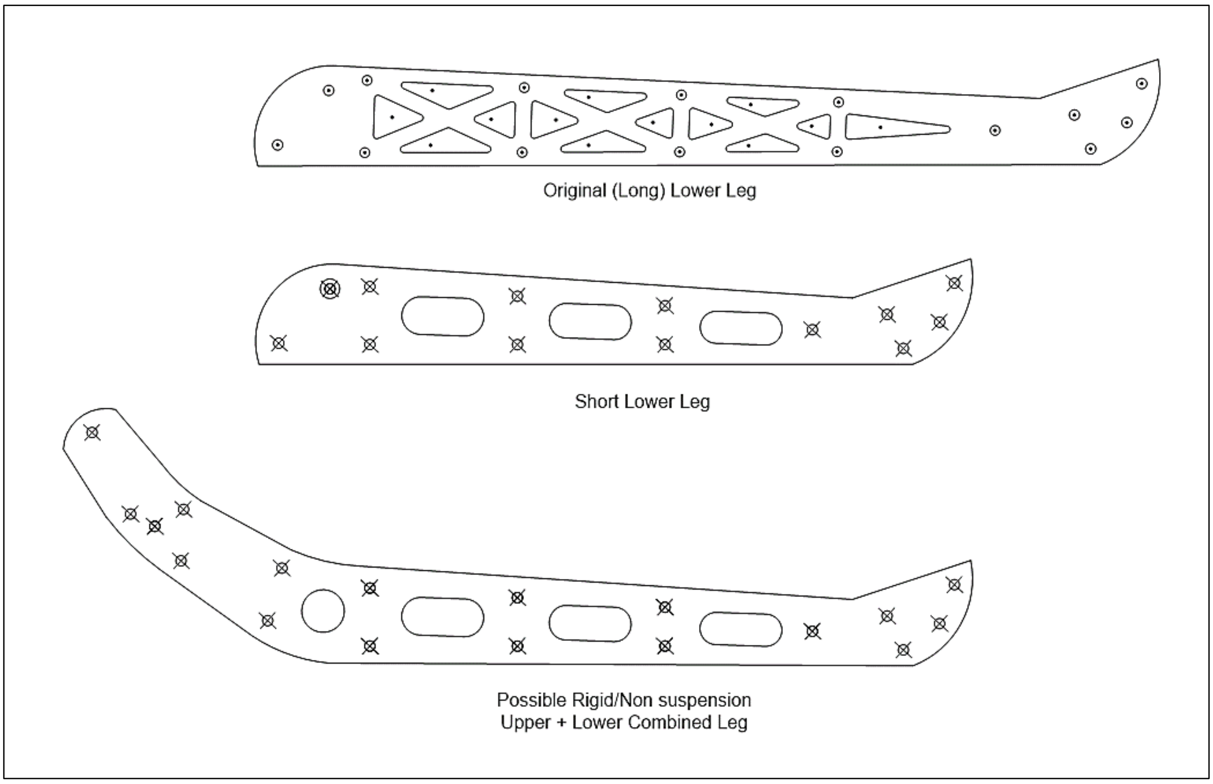
Consider the procedure for countersinking each end of each spacer. Set the drill press (with countersink bit installed) to exactly the right height to drill down/countersink to the correct depth. Clamp the spacer in a clamp so that the bottom of it is flush with the bed surface of the drill press (I used a pair of 'vice grips' for holding the spacer), and ensure it is perfectly vertical so that you drill straight down onto it and not at an angle. Centre the spacer below the drill, and countersink to the correct depth. Now, because you have ruined the lead-in to the thread and possibly created a bur on the thread, you have to recut it using a thread tap. Then thread in a screw to make sure it 'takes' properly. Now repeat the process again for the other side of the spacer. Then repeat this on both sides of the spacer for each of the other nineteen spacers on the leg. Now repeat that for four legs (and then another four on the next drone I built), and you have many long - somewhat tedious – nights in the workshop.  A close-up of this countersinking on the legs can be seen in Illustration 6.50, above; interestingly enough, it was one of the few times where 'Form integrated with Function' on the drone because the nett result was not only better aerodynamics but also pleasing on the eye.



**<u>Illustration 6.50:</u> Countersunk aerodynamic screw heads**

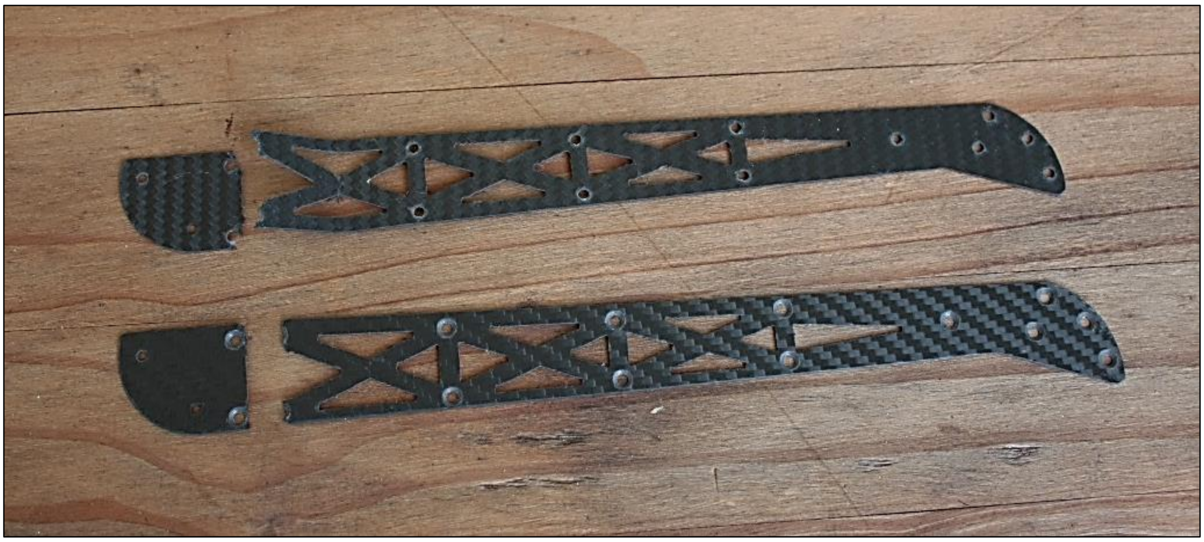
Illustration 6.51, below, shows three versions of the leg. The top one (the 'Long lower Leg') is the original version that I designed and used initially. I encountered two problems with it. The first was that it would break quite easily if the craft crashed; normally this would happen right at the top of the leg and where the leverage was greatest, across the small 'ribs' and the triangular cut-outs. I replaced a few where this happened, some examples of the breaks are shown in Illustration 6.52, below. I could have overcome this in a later version of the leg by making the ribs thicker, and the cut-outs less pronounced (I had initially designed the cut-outs as quite large to rid the leg of weight). However, a bigger problem with this long leg became apparent in flight. The feet would appear in shot when the drone rolled or pitched dramatically, particularly if the camera was pointed down at quite a steep angle.

So, the next leg design was shorter, in an effort to keep the feet out of shot. This was a compromise with how high the drone would be off the ground (particularly in longish grass),




**<u>Illustration 6.51:</u> Various iterations of the Leg**

and the amount of suspension travel at the foot end. But I decided this compromise was necessary and since the suspension had worked so well, I rationalised that this shorter leg would still work adequately. At the same time, I designed this shorter leg to have less extreme cut-outs of the carbon fibre, and greater size ribs surrounding them. This leg worked well; I had very few breakages from crashes (in fact I recall only one), and the feet no longer intruded into shot. This version is shown in the middle of Illustration 6.51 above.



**<u>Illustration 6.52:</u> Common leg breakages**

There was a third option I manufactured, and that was the bottom version shown in Illustration 6.51, above, what I termed the 'Solid Leg'. I wanted to see if I really needed the suspension element on the drone, or if the wide stance of the feet would be enough for working in sloping or undulating remote surfaces. So, this leg replicated the two part 'Upper/Lower/Suspension' leg in all facets; it folded the same, it was the same height and had the same wide stance of the feet. I fitted these legs to the drone and did some test landings. The results were back to where I had begun, the drone would touch down one foot first on the undulating surface, send the shock through the frame, and either tilt or flip it over. Experiment done, and unsuccessful; the 'Solid Leg' was consigned to the ever-increasing rubbish bin of broken or discarded parts never to be used again. The best version was the 'Short Suspension Leg'.

Out of interest I have included two photos which show the drone as a 'top view' and a 'bottom view' (please note that the drone is resting on its side to take these photographs). These Illustrations 6.53 and 6.54 below give an idea of how the drone's legs and arms fold up against the body, and how the props are positioned during this process. I will detail further on in this chapter the actual process of unfolding and folding.

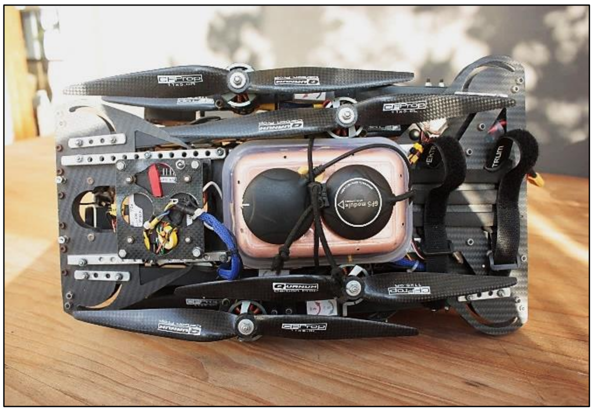


**Illustration 6.53: Drone folded top view**

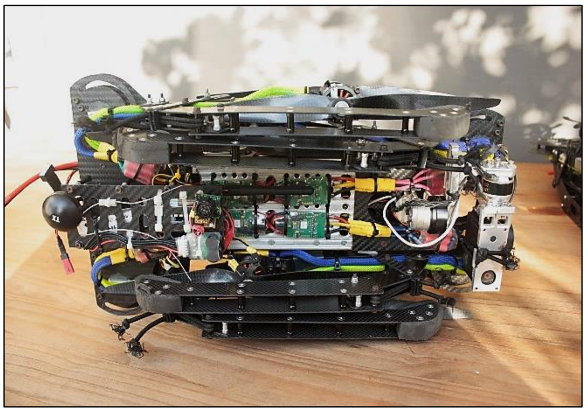


**Illustration 6.54: Drone folded bottom view**

## 6.6 Symmetry

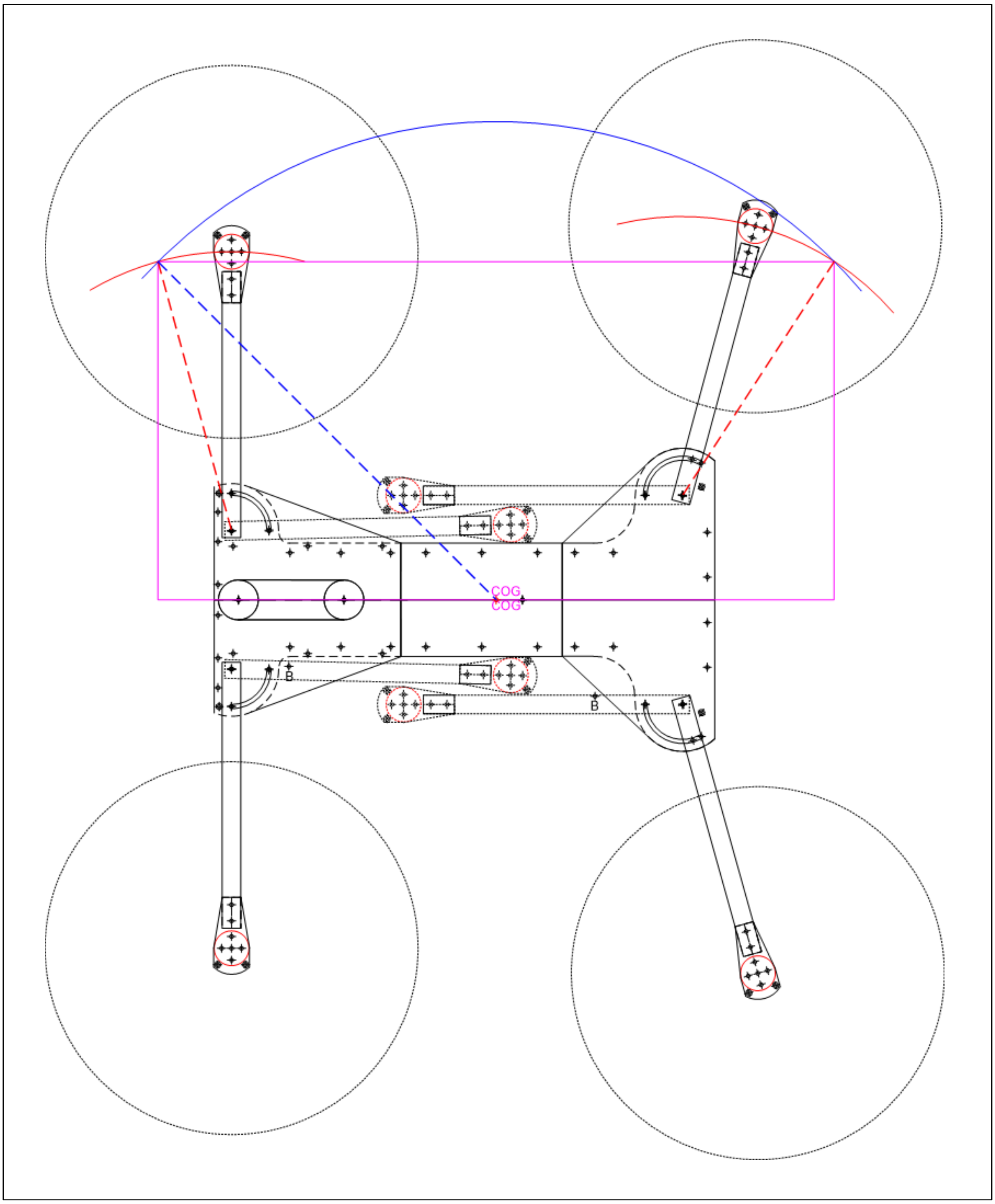
The next part of the design brief to address was the issue of symmetry; that of wanting the four motor axes to form a square when the arms were unfolded and readied for flight. (Not to be confused with the fact that there are eight motors, the two on each arm are co axial and so there are only four axes.) This would seem a simple problem to overcome, and it would have been had I employed arms of different lengths; but I wanted a ‘one size fits all’ approach to the arms and so this was not an option.

At issue is the fact that the arms fold one inside the other (with respect to the front and rear pair of arms on each side of the drone). This means that the pivot points of the arms are displaced a different amount from the centre line of the drone; the rear arm which folds outside of the front arm has its pivot further from the centre line of the drone.

I knew beforehand that this was going to be difficult to solve, but I did not realise just how difficult with the knowledge I had at my disposal. I envisaged solving it by using multiple drawings testing out various options (actually it was only one drawing where I continuously changed variables and tested them until I arrived at a solution). I also knew that there had to be a mathematical way of solving the problem, but the maths was beyond my capabilities whereas I was quite fluent with the technical drawing software. As an aside much later on in my research (after I had done a similar exercise for the second drone) I asked a friend, Professor Hugh Murrell, if it were possible to solve it mathematically, and how. Prof Murrell is a retired professor from the Department of Mathematics at UKZN, and he developed a model as to how it could be done. I will present his model later in the thesis; but in the meantime, I was stuck with solving it diagrammatically.

Please refer to Illustration 6.55, below, which shows the working drawing for half of the drone. Since the drone is a mirror image across its longitudinal centreline, I only needed to work with half of it. Please note that in this drawing the arms are in the incorrect unfolded position; I have done this for clarity of the explanation. The pink oblong is such that its height is half its width, in other words if I stacked two of them above each other they would form the square I was looking for. The problem up front was that I did not know the dimensions of this square; I would need to arrive at that through experimentation.

The red dotted lines are from the centre of the arm pivot to the centre of the motor axis, and the red arcs are the arcs of the motor axes as the arms are folded in and out. They have the same radius; this replicates the equal length of the arms. I was trying to find out how far I should fold out each arm so that it intersected with a pink oblong in such a way that the arms would form the final square. This may seem straightforward; it is anything but.




**<u>Illustration 6.55:</u> Diagram showing how the final position of the arms (red dotted lines) was arrived at for symmetry**

My way of solving the problem was to create another imaginary arc, shown here in blue with its corresponding blue-dotted line radius. I would alter this radius, as well as its centre point (which by definition had to remain somewhere on the centre line of the craft to uphold the mirror image status and integrity of the solution). I would then check where this arc intersected with the red motor arm arcs and test these intersections with the pink oblong. Did it form an oblong; in other words, was the left-hand height equal to the right-hand height (or was it a rhomboid)? More importantly, if it was an oblong, was the height half of the length?

There are an infinite number of incorrect possibilities, and only one correct one (for a set arm length, set distance apart, and set distances from the centre line of the arm pivots). The various components have a complex relationship which varies continuously. I was astounded by how little a change of either the radius of the blue arc or the position if its centre could have a dramatic change in the outcome. I was having to work in increments (or decrements) of 0.01mm to home in on the solution. Many, many changes were tested, until I finally arrived at the solution shown; the position of the red dotted lines and thus the position of the arms. The oblong ended up at 544mm X 272mm; when 'mirrored' a square of 544mm on all sides.

I have included this drawing (Illustration 6.55, above) to show how I had to go back and modify my original design for the front and rear plates of the drone. You can see from the above drawing that the final position of the arms takes them beyond the frame plates, and also the slotted arcs of the arm bolts. I had to go back and lengthen both before manufacturing these parts. Illustration 6.56, alongside

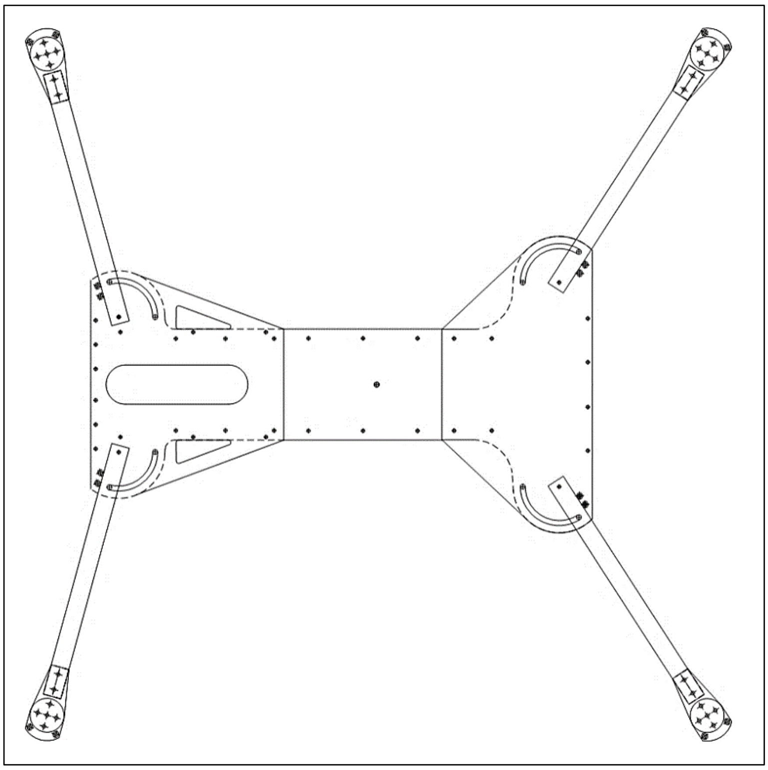


**Illustration 6.56: Final Square configuration**

shows the final arrangement, with the extended front and rear plates. It is clear in this picture how the arm ends form a square.

The other significant information in Illustration 6.55, above, is shown as ‘CoG’ (Centre of Gravity). It is the centre of the blue radius. The CoG is actually a misnomer; it should actually be ‘CoR’ for Centre of Rotation. This is the point which is exactly in the middle of the four motor axes and is the point around which the drone rotates when it rolls, pitches and yaws. It is best when designing a drone to position the IMU’s and accelerometers to coincide with the centre of rotation since then their measurements will be most accurate and without anomalies. This then informed me as to where I needed to place the flight computer (which includes the IMU and accelerometer) on the final drone body.

It is preferable to try and get the Centre of Gravity (or the centre of the mass of the drone) to coincide with this point as well, but this is not always possible and is secondary to the position of the IMU. I tried to achieve this by keeping the mass centralised laterally, and longitudinally by placing the battery at the rear of the drone to counteract the camera and gimbal at the front. The battery is very heavy compared to the camera/gimbal, but it is much closer to the middle of the drone. This somewhat replicates the solution of putting a large person on a see-saw closer to the centre than a small person further away, to balance the see-saw.

Now that I had determined the arm positions (and redesigned the front and rear plates to accommodate them) I could find the correct place for the arm ‘end stops’. The end stops are small spacers between the upper and lower frame plates which define the place at which the arms open out to; when unfolding the drone, you hold the arms against these stops and tighten the arms in place. The end stops provide a quick and simple way to correctly and consistently open the arms to the proper position. The spacers for these stops have a hexagonal cross-section, and this is the same size as the 5.5mm nuts I had been using throughout the craft. The ‘flats’ of the hex are thus 2,75mm away from the centre of the spacer. I wanted the flat side of the arm to coincide with the flat part of the hex for both accuracy and to have a large contact area rather than the corner of the hexagonal spacer engaging first and possibly ‘dimpling’ the arm when it was opened. This meant that the holes for the spacer stop had to be accurately drilled. The arm was 15mm square so the centre of it was 7.5mm from the face, and I had worked out the centre line of this with my drawing above. I therefore had to drill the holes in the top and bottom plates 7,5 + 2,75 = 10,25mm away from this centre line. This accuracy was difficult to achieve (I will explain how I achieved accuracy for all the holes in the frame plates later) but it was imperative. Just a small deviation would have meant a large change in the position of the motor at the end of the arm. The end-stop spacers and how they engage with the arms are shown in Illustration 6.57, above. I used two end stops per arm for greater contact area in the initial drone but found that one was actually enough and so the second drone only had one per arm.

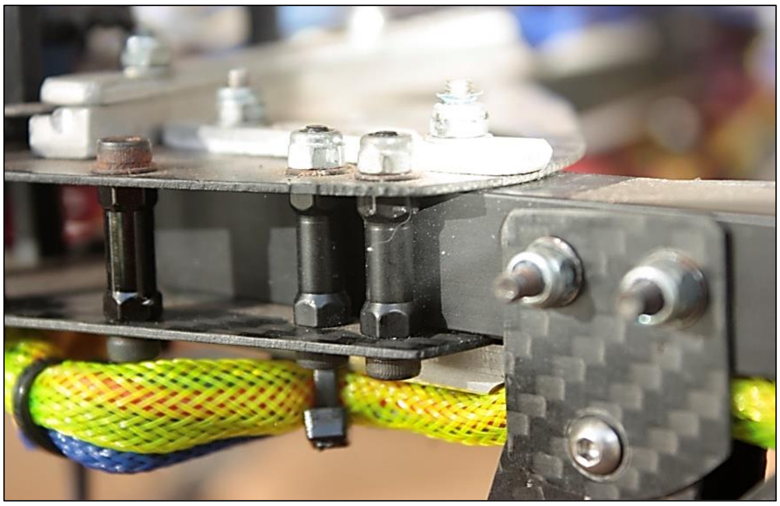


**Illustration 6.57:** **Arm folding Ends Stops**

When I finished the drone I measured the distances between the various motor axes, and the results were:

Left – Right Front: 546mm

Left –Right Rear: 547mm

Front – Rear Left: 545mm

Front – Rear Right: 545mm

All of them were very close to the 544mm square at which I was aiming, and in fact a tolerance of +- 5 mm was probably close enough for my needs. The final constructed drone is less than 0,6 % difference to the original drawings.

It is also interesting to compare the folded size of the drone to the unfolded size. The folded dimensions are 245 mm (W) x 180 mm (H) x 420 mm (L); in other words, it would need a 'box' with a volume of 18,522 litres to house it. The unfolded dimensions (using the prop tips as the outer extremities) are approximately 760 mm (W) x 340 mm (H) x 760 mm (L); now the box needs to have a volume of 196,38 litres to house it. Thus, the folded drone is 9,4 % in volume of the unfolded version; put another way it folds down for transporting to less than 1/10 of its flying state. The measurements were taken with the final version employing the 'short' lower leg, with the original longer leg these differences would have been greater. This is a significant decrease and satisfies my original design idea.

## 6.7 Cutting the plates

I purchased the flat carbon plates from an international vendor. You can get them in different thicknesses, sizes and weaves. Carbon fibre is layers of the fabric laminated together by an epoxy (much like the more common 'fibreglass') and is extremely strong for its mass. It is used extensively in all sorts of high-tech applications from fighter jets to parts of racing cars. Manufacturing carbon fibre – particularly if it is contoured or moulded - is difficult, and normally requires expensive tooling and equipment such as an autoclave to do it successfully; so this was out of the realms of me doing it personally. It isn't a cheap product to buy either, so you have to be mindful of using the plate efficiently, and also the plate is completely flat, so you have to design and build within this limiting factor.

I cut some of the plates myself, such as the underneath sub-frame plates and the gimbal-mounting plates. These have straight edges around their perimeter, and I could use my band saw to remove them from the stock sheet of carbon fibre. If there were any straight slots, I could carve them out using the milling machine, and any holes I could drill and countersink with the drill press. Were I to need to dress any of the surfaces, I would have to use my miniature die grinder. It should be noted that, as the fibres in carbon fibre are extremely hard, shaping quickly blunts the tools you are using. My budget for band-saw blades, milling cutters, drill bits and such like was very high. The problem is that if a blade or bit gets blunt it 'wanders' and tolerances and accuracy are easily compromised. The other issue is the carbon fibre dust and shards produced in the machining process are very light, they float in the air, you can easily breathe them in, and they are a known carcinogenic. So, you have to wear proper filtering masks and use a vacuum when working with carbon-fibre, and even this isn't ideal.

All this made me realise that cutting the complex shapes of the plates was not only beyond my capabilities but would have been extremely time consuming and the costs of replacement cutters quite high. So, I looked for a solution where cutting could be done industrially. There were three options to consider – Laser cutting, CNC (Computer Numerical Control) machining, and Water Jetting. All of them use a computer programme to guide the cutting process. Essentially you provide a CAD (Computer Aided Design) drawing of the part/s to the company, and they use that to control the machine.

Research led me to discover that 'normal' laser-cutting was not an option; you need specialised equipment not found in Durban for laser-cutting carbon fibre. There are businesses which do this, but the lasers they use don't have the power to successfully cut carbon fibre. What happens is that the resin epoxy in the carbon fibre is a different hardness to the carbon fabric itself. The amount of time needed with these low-power lasers to cut the carbon fibres is such that it melts the epoxy for too long, and the fabric starts delaminating. The other problem with laser-cutting of carbon fibre is it releases noxious gasses such as chlorine into the air, and specialised ventilation and filtration are important. This was not an option.

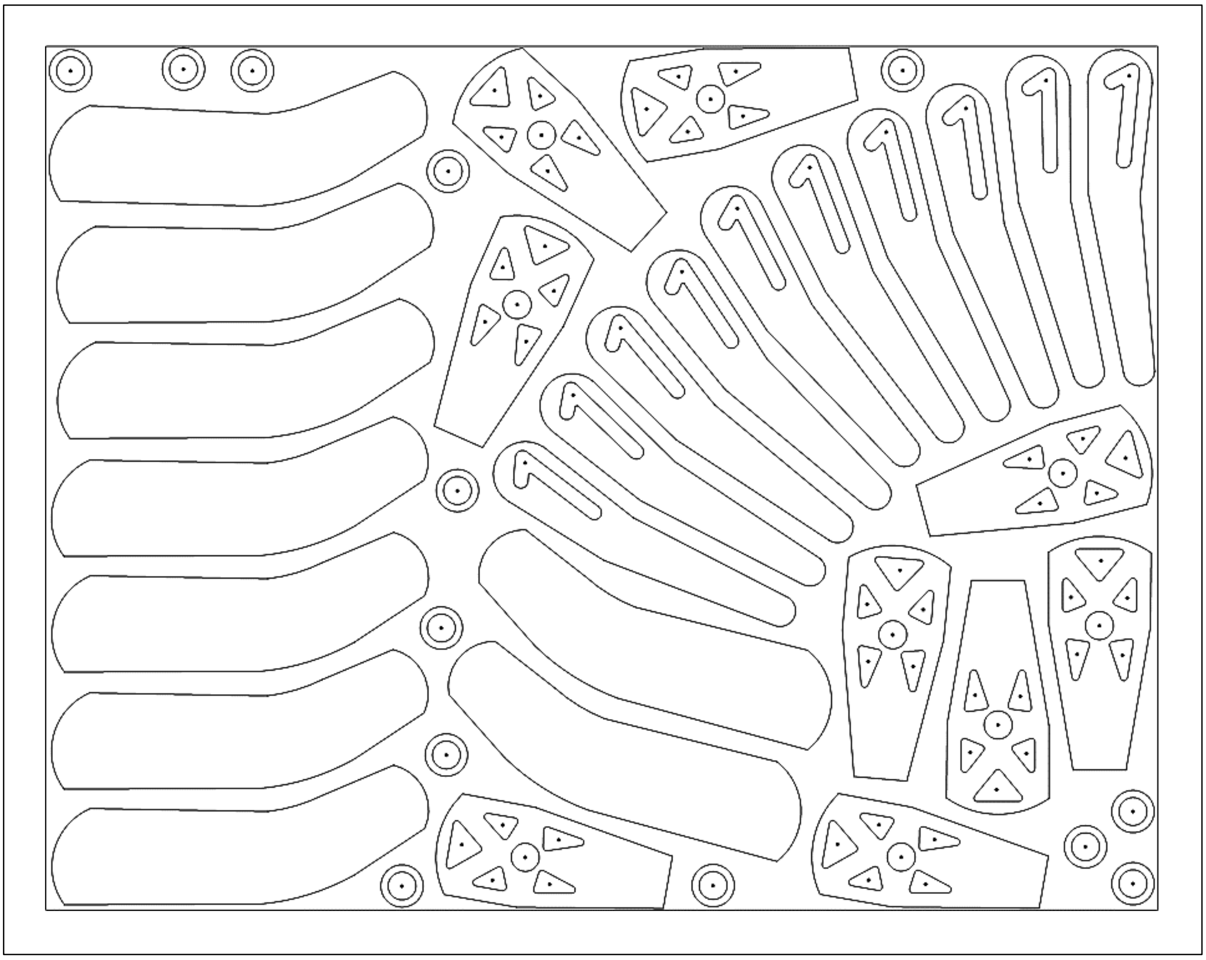
The next option was CNC machining. This is much like I could do at home; except on an industrial scale, a much quicker process, and able to cut complex curves. I started calling CNC machiners. None of them (in Durban) was prepared to take on the task. They all cited the problem of dust extraction and filtration, as well of the cost of their tooling going blunt. This meant I had to scrap that option as well.

The final option was water-jetting. This procedure uses high pressure water 'squirted' through a jet to cut through materials. The hole in the jet through which the water is thrust is very small, typically around 0,0025mm, and it is delivered at a pressure of approximately 3500 Bar. (When you consider that your car tyres can support a corner of your car with only 2 Bar of pneumatic pressure this is a very high figure.) The process is also computer-controlled and because there is water involved the carbon fibre dust doesn't go into the air and create ventilation problems. I found two companies in Durban which specialised in water-jetting, both of them in the business of cutting ceramic tiles. When I called them only one was prepared to take on my task. So, water jetting it was.

Further research revealed that water-jetting can also cause delamination of the carbon fibre, particularly if the jet has to 'punch' a hole through the plate. It is better when it starts off 'in clean air' and then moves to an adjacent edge of the plate to begin the cut. This meant that anywhere that I had 'cut outs' of the plate (such as the curved slots where the arms pivot, or the multiple triangular shapes in the lower legs) I would need to drill a hole at home first to give the water jet an unobstructed place to start. Then the jet would proceed to cut the shape. The jet cuts out a shape, switches off and jumps to the next position, switches on again and cuts the next shape. This meant that in all of my drawings I had to create the position of these sacrificial holes, and reference them on the CAD drawings so the jet knew where to 'jump' to and begin the next cut. Illustration 6.58, below, shows how I prepared one of the carbon-fibre sheets for cutting, and the small references for the start of each cut-out on the plates where the jet should jump are visible. I overlaid a sheet of contact paper with the outlines of the individual parts on the carbon-fibre sheets, and then used this to drill all of these datum points at home before I went to the water-jetting company. The company specified that each part had to have a minimum of 5mm clear surrounding it, so it was a bit of a jigsaw puzzle to get all the parts to fit.

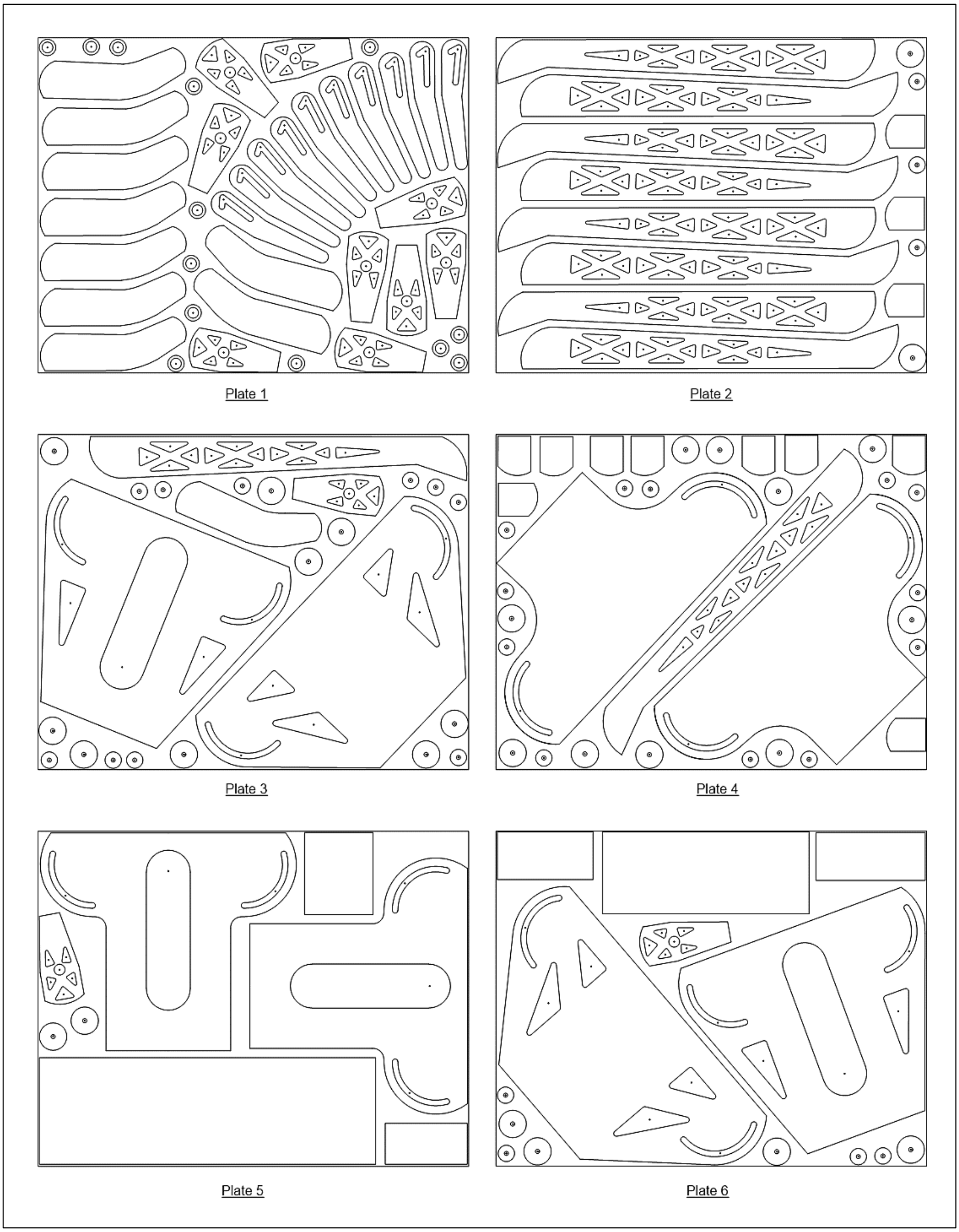
You will notice in the diagram that there are none of the numerous holes I would need for the many nuts, bolts, spacers, zip ties, etc. that would constitute the final assembly of the drone. This is because I was concerned about the water jet delaminating if it was used to cut these small holes. I decided, therefore, to drill these holes once I had the individual parts cut out.

This turned out to be a wise decision, not only from a delamination perspective but for another reason that I will explain soon.



**<u>Illustration 6.58:</u> Template for Water Jetting a single plate**

What you also cannot see in this diagram are the small 'ribs' connecting the various parts because these were put in for me by the company technician, who has experience with the practice. Each individual part has a small 2mm-wide rib on either side connecting it to the adjacent parts. This is done so that the jet doesn't cut out one part, stop, then move on to the next part, and start again. The outside perimeter of all the parts is cut with one long continuous cut, and the ribs are arranged in a logical but still complex way to achieve this. Essentially what happens is that the jet starts cutting one part, and progresses around its perimeter, but when it gets to the rib (which might be halfway round the part) it transitions across the rib to the adjacent part, which it then starts cutting; half way round this one it crosses the rib to the next part, and so on. Slowly it works around each part, and only returns to the 'other half' of the original part at the end of the cut, before it stops. You (theoretically) end up with a plate of parts all interconnected by these thin ribs, which you break off and dress before using the part.




**<u>Illustration 6.59:</u> Templates for water jetting all 6 plates**

Illustration 6.59, above, shows how I arranged all the parts I needed onto six plates. The parts are grouped together according to the thickness of the plate I was cutting. If you count the parts, you will see that there are more than needed to complete the drone; that is because I cut spares not knowing what I might need for repairs in the future.

Next, the water-jetting process. The company had assured me that they could achieve a tolerance of 0,5mm consistently. I asked them if I could watch the process, and – surprisingly – they agreed. It was not what I had expected.

It should be noted that the company specialises almost exclusively in ceramic floor tiles. These are large and heavy, and normally only have simple 'wavy' cuts going through individual tiles. They are used where architects want to create a pattern amongst different tiles on a floor. The material size, and the type of cuts, are very different to what I was asking the company to do. I expected that each sheet would be clamped down and referenced, but this was not to be. I was amazed – actually aghast – to see that the machine operator merely held it in place. As the jet progressed through the cut, he simply moved his fingers from one part of the carbon fibre sheet to the next, to avoid the jet slicing off his fingers! There is a massive amount of 'chattering' of the plate as the process happens; the jet of water is forcing its way through the carbon fibre and creates a lot of vibration doing this. The result was that the operator couldn't hold the sheet perfectly in one place, it began moving around. The consequences of this on my final parts was dramatic.

The process starts with the jet carving out all the 'cut outs' of the parts. But while this is happening the sheet of carbon fibre shifts slightly because of the chattering. It then starts to do the 'long' cut around the perimeter of the parts. The problem is that the sheet has moved (and continues to move thought the process) from its original datum point. The operator might think he is holding it steady, but it is shifting slightly, millimetre by millimetre. The result is that the outline of the part is no longer congruous with the cut-out sections. Similarly, a half a perimeter of a part is cut, the jet transitions across the rib to the next part, then starts cutting that, sequentially through all the parts on the sheet. It only returns to the initial part much later, to finish cutting the ‘other half’ of it. By this time the sheet has shifted, so it doesn’t end up in line with the original perimeter.

What compounded the problem was the fact that the bed of the machine isn’t solid, it is a grate or grid structure. If it were solid the water jet would rebound off the base after it had cut through the carbon fibre (and eventually cut through the base as well). The grate allows the jet to pass through to a ‘tub’ of water below it, which absorbs the pressure. However, as the jet released a piece of carbon-fibre sheet (for example, from one of the cut outs) this piece would drop into the grate, and wedge there, often between the sheet and the grid. This lifted that area of the sheet off the grid, and the vibration and chattering – and subsequent movement of the sheet – became worse. At other times, as the jet reached a side of an interconnecting rib it was misaligned, and would cut the small rib off, leaving the part loose and it too would drop below the sheet. When the operator realised this was a problem, he casually started using his fingers to remove the wayward piece, often within millimetres of the jet. I could not believe what I was seeing; and to top it all he even let me make a video of it!

By the time the first plate was finished I was very concerned. I offered some advice on how we could approach the subsequent plates, but all I got was a ‘I know what I’m doing’ look. I resigned myself to making do best with what I would finally be delivered. I haven’t yet discussed the construction of the second drone other than in passing, but I will say now that when I got those parts water jetted, I tried a different approach. I fixed the carbon-fibre sheets to aluminium sheets with multiple small nuts and screws placed at strategic places where they wouldn’t interfere with the final parts or the ribs between them. I countersunk these screws from the bottom of the plate so that it was flat and would sit properly on the grated base of the cutter. The screws and aluminium plate held the sheet more rigidly as the jetting process continued. I also included additional ribs into each of the parts which were cut-outs, so that the sections removed would not be freed and jam under the sheet. I asked, and was granted permission, to include two square aluminium ‘fences’ which I took with me and clamped at right angles to the bed of the machine. This provided a corner reference against which the operator could hold the sheets. All of this meant that the final products were more accurate and better in many ways. Such is the nature of action research.

To return to the original set of parts, I knew that I was going to have problems. The tolerances were far beyond the original promised 0,5mm; in fact some parts were more than 5mm out. The nett result of the shifting during cutting was that parts which were cut early in each sheet – such as the cut-out sections – were not finally aligned with the perimeter of the part which was cut near the end. An example of this can be seen in Illustration 6.60, above, which shows the original intended design of a motor mounting in dotted yellow, overlaid on the delivered part (after I had drilled the motor-mounting holes). You can see that some parts of the carbon fibre are very thin, almost non-existent in places. Also, because I had to drill the holes relative to the outside of the template, they have 'broken through' into the cut-out sections, and I was having to elongate holes for fit. In many of the previous close-up photos of the drone, you can see these anomalies.

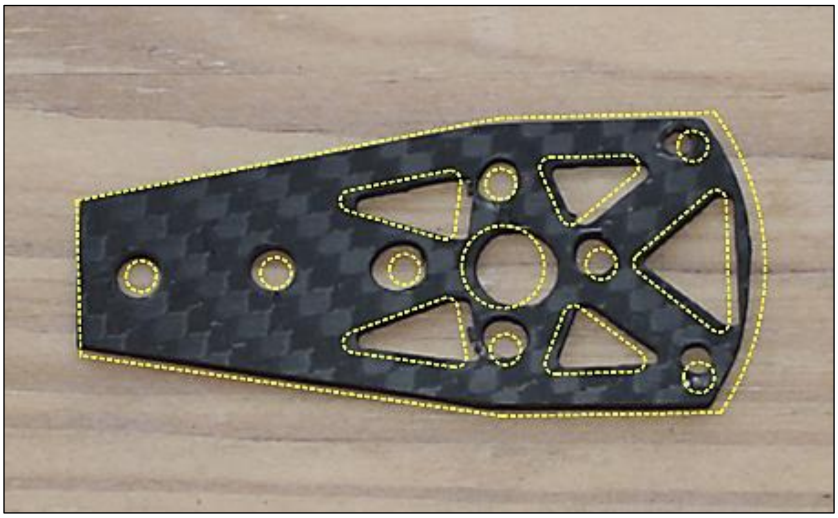


**Illustration 6.60: Delivered part versus expected template**

I have purposefully not named the company which did the water-jetting for me, not least because of what I perceived to be gross workplace safety irregularities. Having said that I must defend the company on two counts. The first is that the company, and particularly the machine operator, were used to cutting large, heavy ceramic tiles with 'simple' cuts; and what I was requesting was beyond their experience. Having said that, I also have to give them credit for actually taking on the task of cutting my small, intricate carbon fibre; they could quite easily have refused, and I would have been stuck with the arduous task of cutting all the pieces by hand.

Back at home I spent considerable time correcting what I could, in certain cases modifying my original designs to compensate for the cut inaccuracies. Now began the job of drilling the innumerable holes I would need in the plate for all the mounting screws and similar attachments.

I knew that accuracy was paramount in drilling these holes; in particular, in position sensitive places like the arm pivots and end stops. I wanted to achieve a tolerance of less than 0,1mm wherever possible.

I already had the technical drawings to work from. I calibrated my printer both laterally and longitudinally by doing test prints, until the sizes it printed exactly matched my drawings. Then I printed out the drawings on contact paper. I carefully cut out these paper templates, aligned them as best I could with the various plate components, and stuck them to the plates. In my drawings I had used a line thickness which was as thin as the printer could print. On every hole I had positioned a 'cross hair' which gave the exact centre of the hole. Using a very sharp pin I pricked the exact centre of the cross hair. I then used a sharpened dental pick to make this prick into a slightly larger piercing of the contact paper and a small indentation of the carbon fibre below. This piercing and indentation was enough to give a very small 0,7mm drill bit enough of a reference to start the hole. I drilled every hole using this method with the small drill bit. Once I had all the holes in a particular plate drilled to this small size, I used that plate as a template for any adjacent plates. I would line up the adjacent plate with the first, clamp the plates together, and drill the 0,7mm holes through the new plate. Where I had multiple plates all exactly the same, such as the motor mounts or the legs, I would use the first plate to drill all of the others. I then opened up all the holes to what would eventually be mounted to them. In most cases this was 3mm for the majority of the screws, but sometimes I would use progressively larger drill bits until I arrived at the necessary size (for example, the 8mm outside diameter of the leg bearings). Where necessary I would finish off by countersinking the relevant holes. This entire process was time-consuming, and I went through a lot of drill bits, because the carbon fibre dulls the cutting face quite quickly. As soon as it dulls it starts wandering, and the needed accuracy is not achievable.

Having completed this drone, I tested and flew it many times, both in simulated and real conditions following races. These flights and tests are detailed in Chapter 7. I realised that I had worked my way through Cherry's ten stages of Action Research several times over and over from the earliest drones and flights up to and including this latest design. As a reminder these stages are given as Action Planning - Action – Experience – Observing - Evaluating – Concluding – Attending – Noticing - Diagnosing and finally Refocusing; before the cycle begins again (Cherry, 2002). Even short test flights or hops in my front garden involved these stages, or most of them. Each flight - or each modification or change to the drone or system - minimally needed planning, observing, evaluation and conclusions for further testing. It was a constant evolution. McIntosh (2010: 37) expands on this when he writes that Action Researchers see knowledge in what they do and says:

> 'It is never complete and it is constantly shifting and developing as new and different understandings emerge. It becomes a way of being that is full of potential, surprises and unpredictability, so absolute answers to questions become meaningless, because whatever is found becomes a new question. Learning is therefore rooted firmly in experience: the experiences are reflected upon in the light of the researcher's values and then future actions can be decided upon.'

One of the major improvements was based upon the fact that I had identified a significant shortfall with this first version of drone, which I will explain in the next section. Essentially, I needed to design and build a new gimbal system for the camera. Since this current version of the drone could not be modified to accommodate this gimbal, it required a whole new drone body to be designed and manufactured. This new drone would also incorporate several other minor modifications. However, because it was centred around the change in gimbal, I will first describe the construction of these before dealing with this new drone (which I have called 'X8 Version 2').

## 6.8 The Gimbals

As stated previously there are two types of gimbal, the servo gimbal and the brushless (electric) motor gimbal. Servo gimbals have virtually fallen by the wayside, though, because brushless gimbals are better in every facet of what is needed from a gimbal.

Brushless motors have been developed more and more in recent times, primarily because the electronic control they require has got better and better. They produce high power for their size/weight, and exhibit very good torque characteristics. They are widely used in RC applications, and are the motors which drones employ. This is because they can be very finely controlled by the flight computer via their Electronic Speed Controllers (ESCs). I will refer to this again when I discuss the motors I have chosen for my drones.

Brushless motors can also be configured and utilised in another way, and that is to position something quickly and accurately. This 'positioning' of a part via a motor has been led by the advent of robotics, where robots are required, quickly and with high power, to position or place a part accurately over and over again: for example, in a car manufacturing facility. It did not take long for camera enthusiasts to realise that this technology could be applied to gimbals, where the camera has to be positioned – and repositioned – quickly and accurately.

A brushless gimbal has three major components: the motor (or motors) itself, a control board, and an Inertial Measurement Unit (IMU). The IMU is mounted to the same plate or assembly which the camera occupies. It thus mirrors any movement which the camera undergoes. IMU's are typically '6 axis', in other words they can measure in all three dimensions. They measure movement or position change; not only how much something has changed position, but the rate of change as well. This IMU is refreshed thousands of times every second and has a very fine sensitivity to change. Once it detects a change it informs the control board of this – the axis, the rate of change, and the degree of change (reflective of what is happening to the aircraft the camera is attached to). The control board has software which interprets the deflection, and then sends a control signal via motor drivers to the respective motor to correct and return the camera to its initial or former position. The motors thus keep the camera pointed at the original starting position, irrespective of the attitude of the aircraft frame. The software can be configured to control the camera in a variety of ways. (I will deal with these later.) Suffice to say that before you launch the drone the gimbal is 'initialised' to the position you want it to hold, typically level in a roll orientation, and pointing slightly down (for my application) in a pitch orientation.

The motor specifications are related closely to the size and weight of the camera and gimbal you want to control. Larger cameras – and thus bigger gimbals – require motors which have bigger size and torque, and vice versa for smaller cameras. However, whatever the size of the motors one principle remains universal to all gimbals. The mass which any particular motor is supporting must be centred exactly in line with the motor's centre axis. If this is not the case then this mass changes as the motor rotates, which leads to the motor straining unnecessarily or erratically. This setup, which involves the balancing of gimbal components in line with their respective motor axis, is the most critical phase of initial setup. It typically takes a while and requires that the gimbal be designed in such a way that the various components can be moved back and forth in different planes to compensate. Once setup, these are then locked in place for a particular camera/lens combination. If you change the camera or lens you have to rebalance the entire system.

The procedure for balancing a 3-axis gimbal is described below and also in the Illustration 6.61, below. It can also be used for a 2-axis version, but without the final 'Yaw' stage:

- The camera, together with any other components which are attached to the camera supporting plate (such as the IMU), is assembled. This assembly is then attached to the pitch motor. Since the camera is asymmetrical from a mass perspective it will need to be adjusted in two planes, up and down and fore and aft; relative to the pitch motor. These adjustments are made whilst observing the pitch motor. The camera should be able to be placed in any orientation – level, pitched forward, pitched backward, upside down – without any subsequent movement or change in orientation. Essentially you are adjusting the centre of gravity of the camera/supporting assembly to be exactly in line with the axis of the pitch motor. This adjustment typically takes the form of slots along which the components can be moved, and then tightened with small bolts once the adjustment is correct.
- The next stage is to attach the pitch-motor carrier assembly to the roll motor and balance this entire assembly around the roll motor axis. If – as I have done – you design and manufacture the entire pitch motor assembly symmetrically (from a mass perspective) with the pitch motor axis, you will only need to balance this in one plane relative to the roll motor.

- Finally, the entire pitch and roll assembly (with roll motor carrier plate/s) is attached to the yaw motor and this is balanced to the axis of the yaw motor. This assumes a 3-axis gimbal, in the case of a 2-axis gimbal this stage is non-existent. Once again, if you keep the mass of the roll carrier assembly symmetrical, you only have to balance in one plane.

Balancing these various parts is difficult and time consuming, however. If it can be done accurately it greatly aids setting up the gimbal later on (using the software) and has a positive effect on the final performance. One of the problems is that while you try to balance ever more complex assemblies (such as pitch + roll onto the yaw axis) the motors move, and the

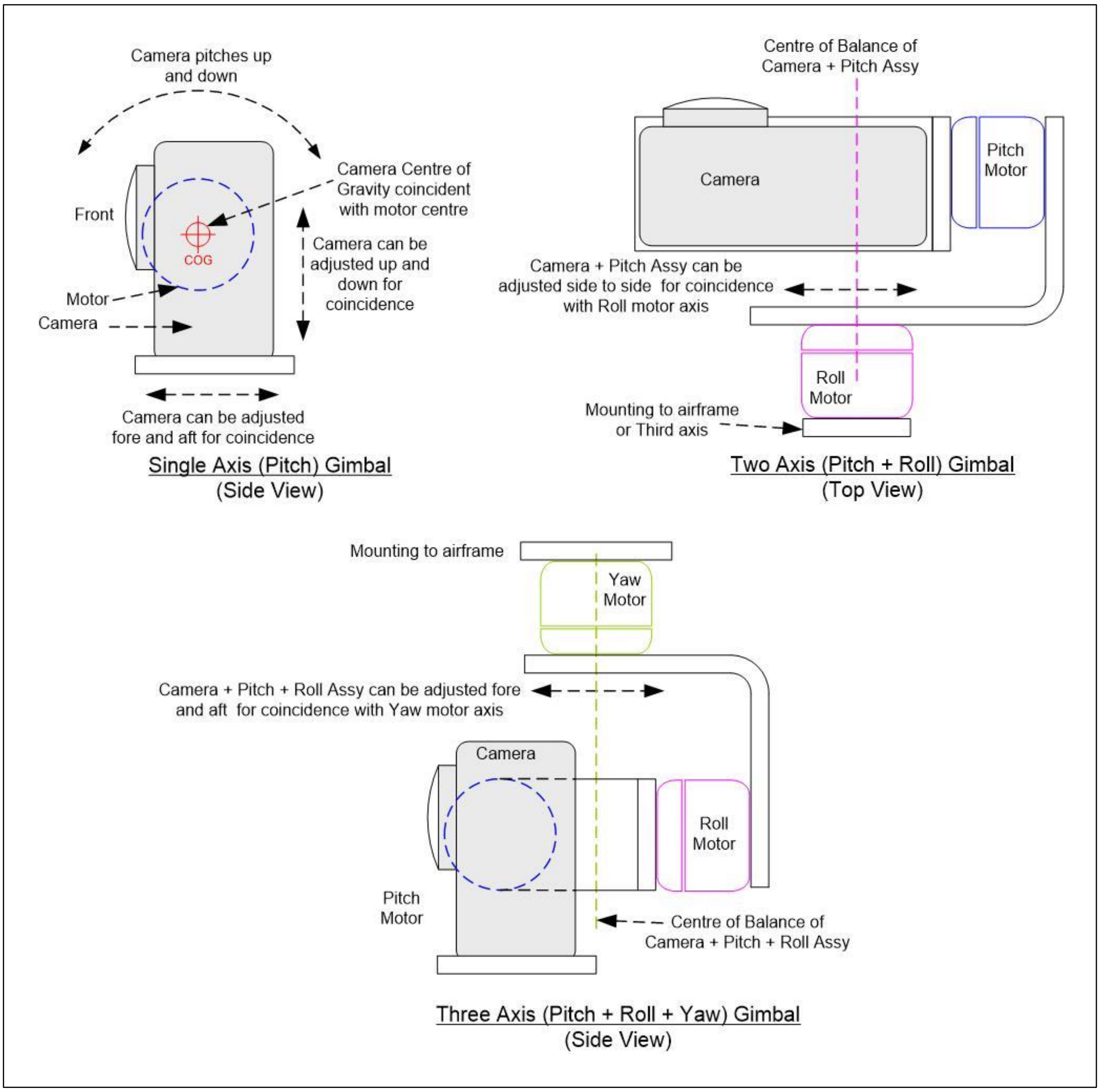



**Illustration 6.61: Gimbal Balancing**

assembly (with camera attached) 'folds' or 'collapses'. I used small lumps of 'Prestic' to keep the motors immobile. What I also did was sequentially balance the various assemblies on a pencil laid flat on a table. The pencil is a 'rounded hexagonal' cross section; the 'flat' face of the hexagon has just enough area to balance the component whilst not supporting it if unbalanced. Once I found the balance point, I would accurately mark it, and transfer this setting to the motor for final checking.

This is also one of the reasons I did not produce any technical drawings of my final gimbal designs. They were evolutionary whilst I made them, and it would have been difficult to predict dimensions in advance. I would make the first part (in both cases the camera mounting), assemble it, balance it; and then transfer this knowledge on to the next assembly. Then I would repeat this stage by stage, slowly building up each complete assembly, and transferring the sizes on to fabricating the next one.

You can buy 'generic' gimbals, but I decided to build the two gimbals myself (the first a 2-axis, the second a 3-axis) for a variety of reasons. The main reason was that the drones on which I deployed the gimbals were particular in their design, and purpose built to my needs. Thus, a generic gimbal would have needed much modification, and would probably still be a compromise on some level. Another reason was that I wanted to understand the intricacies of gimbal design and construction, and by building and modifying these myself I could satisfy this need. Suffice to say that this is no menial task, accuracy and care being paramount when engineering these very small components. I primarily used my very old (built in the late 1950s) but still reliable milling head to carve out the various components. As an aside, I

**<u>Illustration 6.62:</u> Repurposed scrap material 1**

**<u>Illustration 6.63:</u> Repurposed scrap material 2**

repurposed ‘scrap’ aluminium I had in my workshop (this repurposing of old materials wherever possible was a common thread throughout the drones I built). Some of these ‘scraps’ are shown in Illustrations 6.62 and 6.63, above, and a photograph of an initial stage of milling them is shown in Illustration 6.64, alongside. It is always quite satisfying to discover ‘what lies within’ a block of rough material. As in a sculpture there is ‘art’ in ‘craft’ and the resulting shape released from the raw is always intriguing.

**Illustration 6.64: Start of Gimbal Milling process**

Illustration 6.65, below, shows the parts I milled for the first 2-axis gimbal. The various components are annotated in the caption of the picture. Note how everything is hollowed or drilled out wherever possible to reduce mass without compromising the structural integrity or rigidity of the components. Reducing flex in the various parts is vital, and the gimbal must be

**Illustration 6.65: Gimbal Mechanical components; From L – R: Camera mount, Tilt Balancer plate and Spacer, Tilt Motor Mount, Roll Balancer Plate, Roll Motor Mount**

able to withstand rapid, forceful and repeated movement, as well as external forces such as wind and prop wash, without any flexing or warping.

The final mechanical assembly is shown in Illustration 6.66, alongside, together with the motors attached. The camera fits perfectly into a recess milled into the base plate so that its position does not alter every time it is removed or inserted, and is held in place by small pieces of 'velcro' and an elastic strap. The complete

**Illustration 6.66:** **Gimbal Mechanical Assembly**

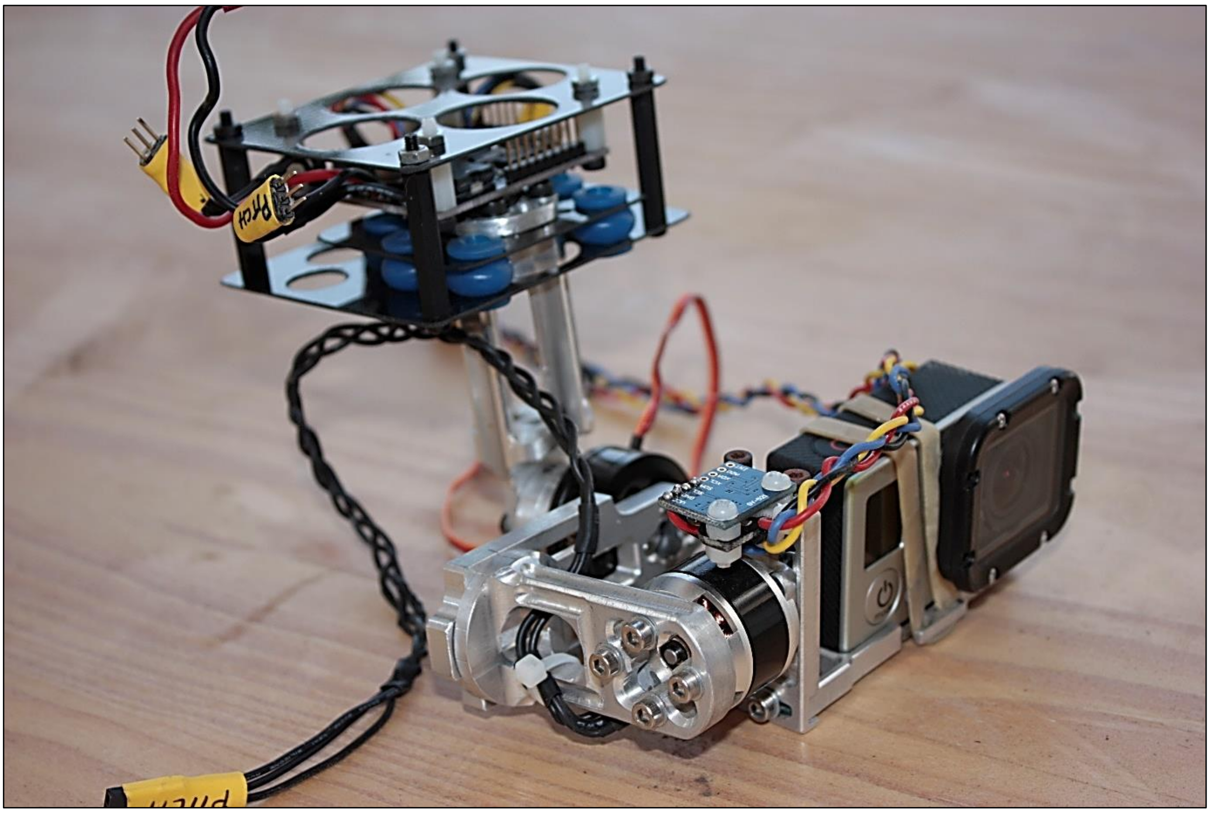


**Illustration 6.67:** **Complete 2-axis Gimbal assembly**

assembly (on a test jig, not installed on the drone) is shown in Illustration 6.67, above. This now includes the camera, the IMU as well as the control board and interconnecting wiring.

The mounting of the IMU onto the camera bracket is shown in close-up in Illustration 6.68, alongside. Illustration 6.69, below, shows a close-up of some blue elasto-polymer anti-vibration mounts. The entire gimbal assembly 'hangs' from a plate (in this case, a carbon fibre plate) which is supported off the airframe of the craft by these elasto polymer 'balls'. This isolates the gimbal from any vibrations that are present in the drone airframe. This method of vibration isolation is used extensively on the drone for critical components. For example, the flight computer is also supported by similar anti-vibration mounts. It is also common to 'tune' these anti-vibration mounts to various intrusive vibrations by squashing in varying amounts of small slivers of soft foam. The more foam you squash in, the higher the vibration frequency you negate or minimize.

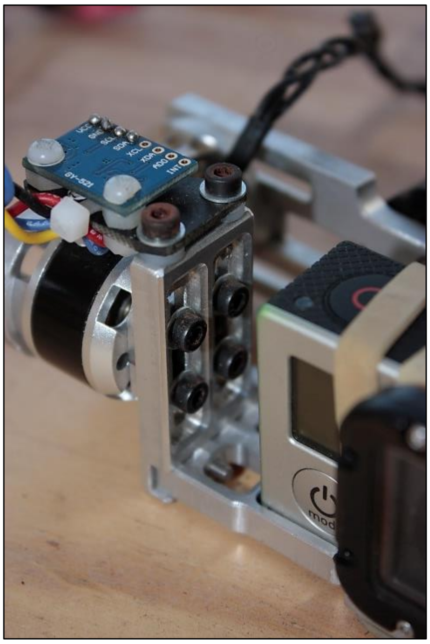


**Illustration 6.68: IMU Mounting**

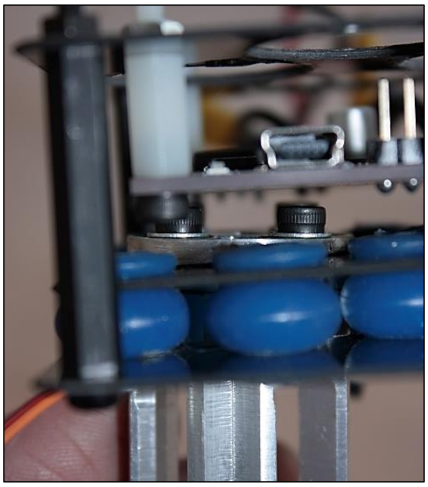


**Illustration 6.69: Elasto Polymer suspension**

I used this idea in another way. The reason requires an explanation, first. As can be seen from prior chapters, I had quite an issue with frame arms, legs and props intruding into the camera pictures. The way to obviate this was to move the camera into a position where these parts could no longer be intrusive, and in my drone designs this was as far forward as possible (see drone drawings in other chapters). Typically, a gimbal – and thus the camera - hangs directly below the frame-gimbal mounting. This is especially so for a 3–axis gimbal. However, I wanted to try and hang the first gimbal I constructed - the 2–axis one – ahead of the frame support, to try and get the camera further forward and away from the drone parts intruding in the shot. The problem with this approach is that the gimbal doesn't hang vertically because its mass isn't centred below the mounting; it hangs at a backward angle. The front anti-vibration balls collapse, and the rear ones extend. The result is that the roll motor axis isn't horizontal, and so when it moves it doesn't affect the gimbal in the plane which the IMU is anticipating. This problem is shown in Illustration 6.70, below. The solution, also shown in Illustration 6.70,below, was to fill the front elasto polymer mounts with more foam to make them stiffer (whilst still having the vibration damping characteristics I needed) and I also machined a small wedge-shaped component to fit above the gimbal mount. Both of these 'forced' the gimbal to hang vertically.

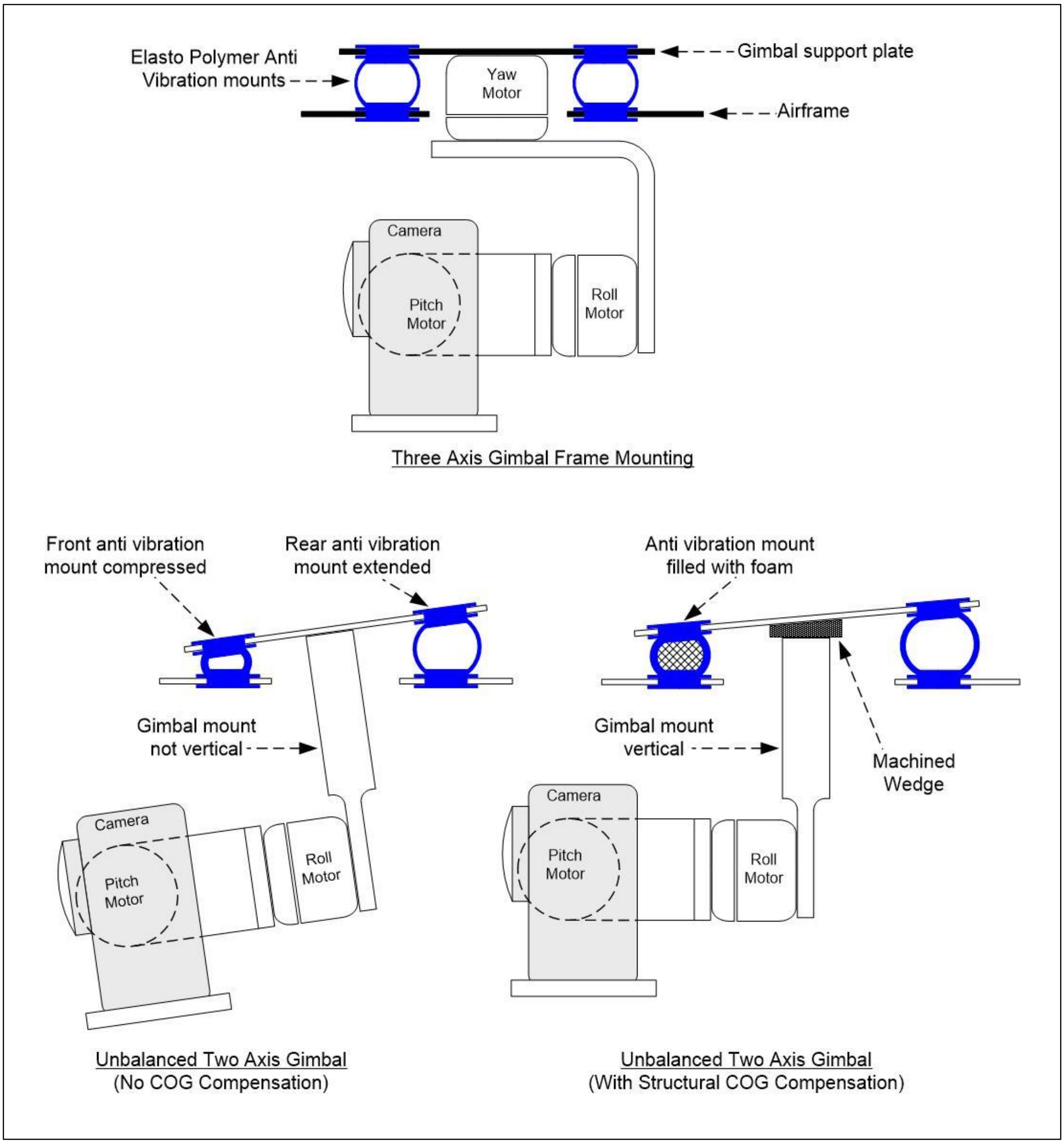
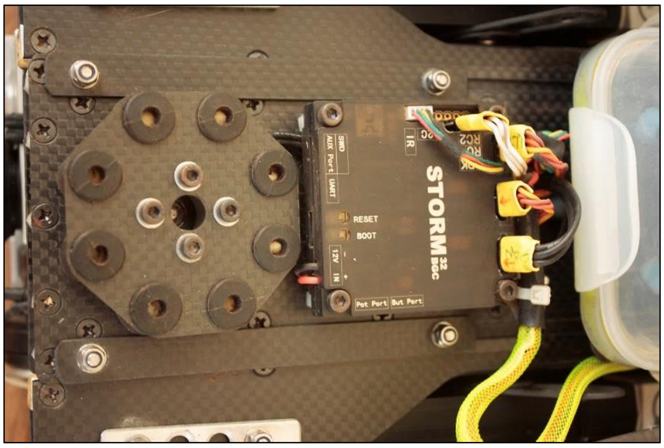
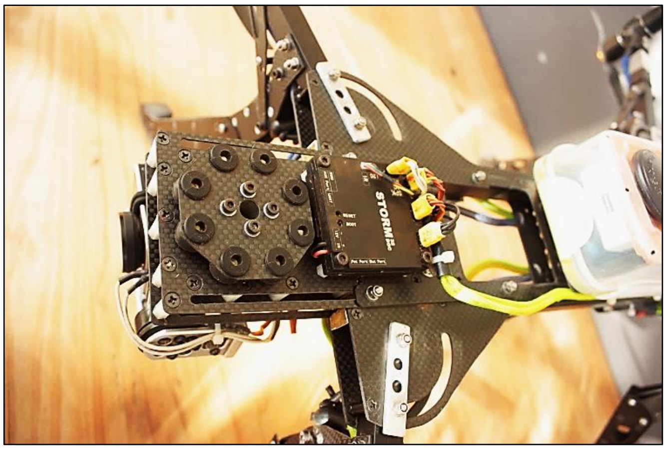



**Illustration 6.70: Diagram showing the Problem and Solution to the gimbal not hanging vertically**

Both gimbals are designed to move forward relative to the airframe so that the camera has a view which is not obstructed by the legs, arms or props of the drone when in flight; and then retract back into the body of the drone so that the gimbals – and the camera – are protected during transport. This entailed that I construct a sliding mechanism for the gimbal support. This sliding mechanism or carriage is evident in Illustration 6.19, above, of the first gimbal as the two sets of aluminium rails; and in Illustration 6.73, below, as the cut-out slots of the carbon-fibre plate for the second gimbal mechanism. Both have captive bolts (similar in principle to the ones used for the folding arms and leg components) which are loosened to slide the gimbal carriage forward or backward and tightened to hold it in place either for flight or transport. There is, however, a notable difference between the two.




**<u>Illustration 6.71:</u> Gimbal 2 in Retracted position**




**<u>Illustration 6.72:</u> Gimbal 2 in Forward position**

Illustration 6.70 above shows that for the first gimbal, the two axis version, the camera is positioned quite far ahead of the gimbal-mounting axis (due to the modifications I explained in the same diagram). This allowed me to slide the carriage far enough forward whilst still keeping it within the main airframe parts. There was thus still structural rigidity at the front of the craft. This can be seen in a previous Illustration 6.7. When I decided to design and build a completely new drone one of the changes was to incorporate a 3-axis gimbal. This had a major impact on the design of the front of the craft, because the camera was now positioned more under the yaw axis of the gimbal (compared to the 2–axis version), as can be seen in Illustration 6.70, above. This had the consequence of having to move the gimbal carriage a lot further beyond the front of the craft, to the point that it moved beyond the frame of the craft. The result would have been poor rigidity of the frame and subsequent unwanted flexing. To solve this, I designed the gimbal carriage in a completely different way. Whereas for the first 2–axis gimbal the gimbal support was just that, nothing more than a support; the second 3–axis design now had to have the gimbal support or carriage as a rigid member of the frame, to avoid flexing at the front. The second gimbal carriage is thus designed and constructed as a lattice girder, which, once tightened with the camera extended, forms a rigid part of the frame. Illustration 6.71, above, shows this second gimbal carriage in the retracted (for transport) position, and Illustration 6.72, above, shows it in the forward (for flight) position. The differences in the craft front frame plates to accommodate this modification is shown in Illustration 6.73, below.

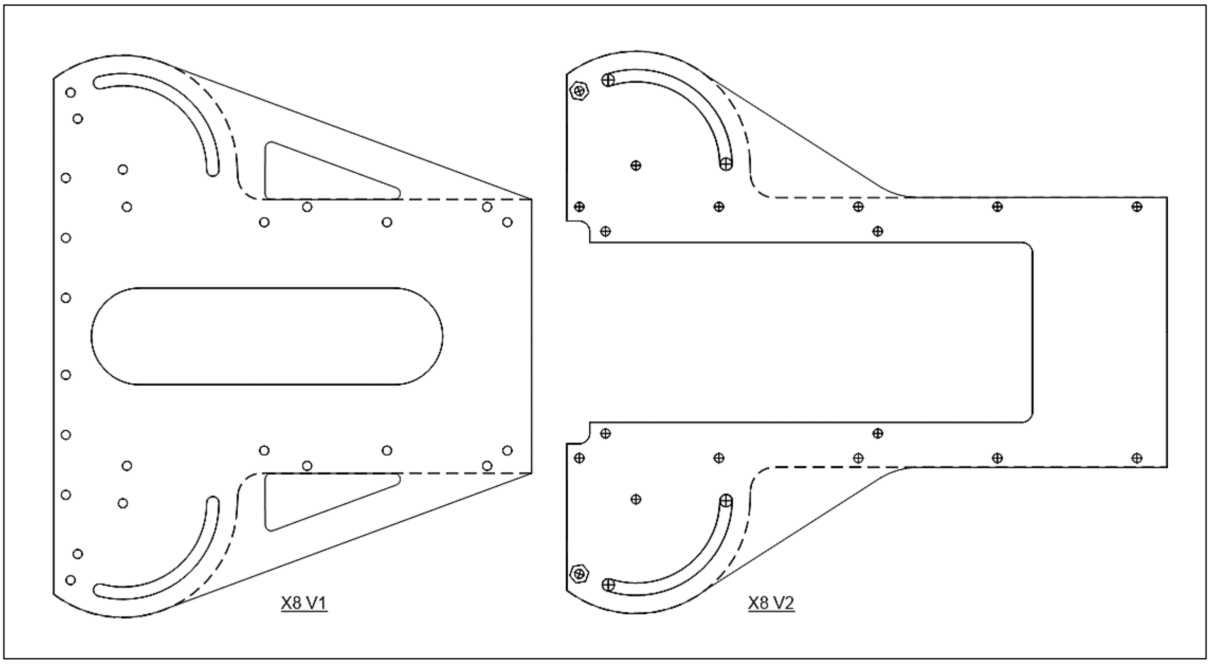



**Illustration 6.73: Front frames plates for Gimbal 1 (L) and Gimbal 2 (R)**

The technical drawings of the first gimbal support are shown in Illustration 6.74, below, and those for the second gimbal carriage in Illustration 6.75, below.

An explanation is required as to why I chose to incorporate a 3-axis gimbal, and the subsequent need for a complete redesign of the airframe. To do so requires an understanding of the yaw control in following a moving target. If we think of the drone as a camera platform only, then the yawing is equivalent to panning a camera.

A camera panning movement is a side-to-side movement of the camera (as opposed to tilting which is an up and down movement). If the camera were fixed to a tripod, you would perform this movement by manipulating the control arm of the tripod by your hand, whilst watching the camera viewfinder to control the framing of the movement. If, for example, a person was walking side to side across in front of the camera, you would watch and follow their movement to hold the framing. The speed at which they are walking would determine the rate at which you perform the panning movement, and the position they are in at any moment in time would determine the direction in which the camera is pointing. If they were to stop walking, you merely stop the camera pan movement to keep them in frame.

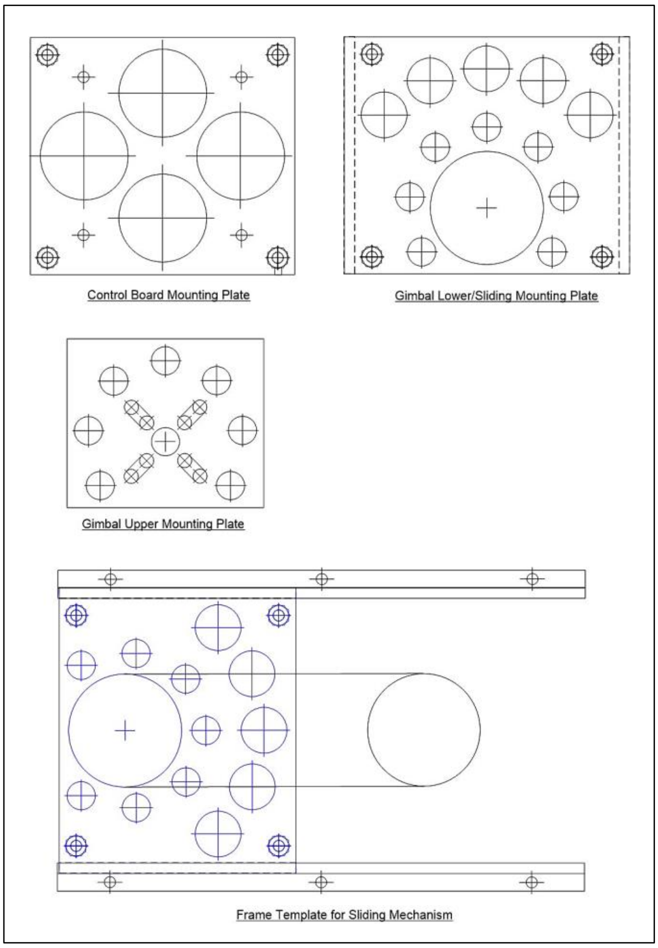



**Illustration 6.74:** **Gimbal 1 Frame components**

At issue is the fact that the yaw control on the radio controller does not have a ‘position sensitive’ setting for the drone. The yaw control can only determine the rate of change of yaw (or, if equated to a camera, the rate of change of panning). The ‘control sticks’ on the radio controller have a centre detented ‘null’ position; when the stick is in the centre there is no rate of change. Move the stick away from this null position, and the drone starts to change its

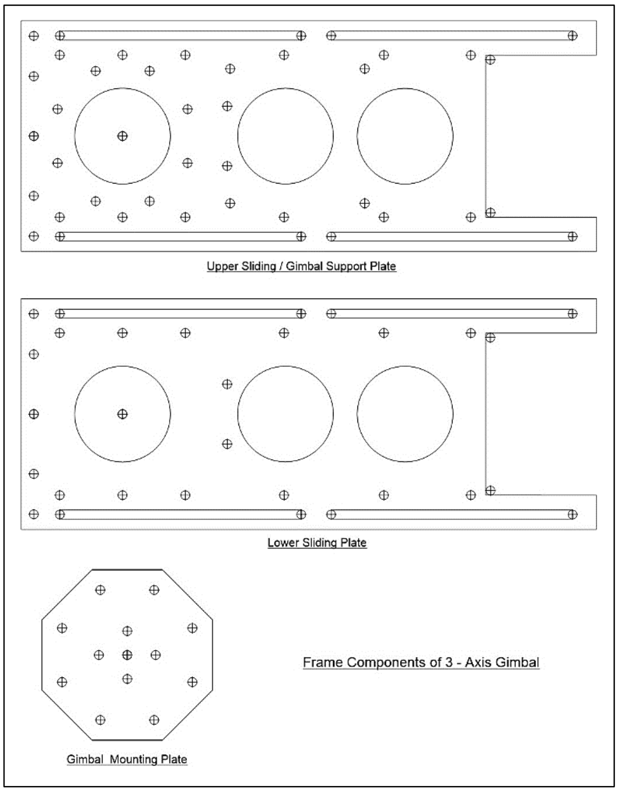



**Illustration 6.75:** **Gimbal 2 frame components**

orientation or flight behaviour. The more you move the stick away from centre, the more pronounced this rate of change. So, with the yaw control, a small position of the stick away from centre results in a low speed of yawing/panning, move the stick further from centre and the yawing speed increases. Unlike with a tripod, if you want to stop the yawing/panning movement, you don't merely hold the stick in the last position, you have to return it to the centre null position.

This has serious implications for controlling the position of the camera and following a moving target, particularly for someone like myself who is well versed in how cameras on tripods work. You need to learn this 'move the stick back to centre to stop panning' skill, and it is not straightforward or easy. You end up having to do multiple 'move and return to centre' adjustments to keep a moving target in frame. If you initiate a yaw, and you don't quite frame up the rider when you return to centre, you have to initiate another movement. Worse, if you perform a yaw and you overshoot the subject, you not only have to return to centre, but you now have to move the stick in the opposite direction to reframe the subject. (Remember that all the time the rider is changing position, which further complicates the following control.) The result is that you end up performing short 'bursts' of movement; move the stick, return to centre, move the stick, return to centre; over and over.

The result is that the drone is constantly yawing, and stopping, then yawing some more, and stopping; repeatedly. (In all honesty this is not strictly true, because the drone takes a short time to respond and change.) The pictures thus end up being 'jerky', the panning movements are not smooth as would be preferred.

My intention was to incorporate the third gimbal axis to smooth out this jerky yawing. Typically, when 3-axis gimbals are employed for filming from drones or helicopters the gimbal movement (and thus camera position) is completely independent from the drone orientation, and you have two people controlling the resultant pictures. One person flies the drone (at the correct altitude and speed for the shot) and another person (the 'camera operator') controls the position the camera is facing (tilting and panning). The gimbal hangs low below the airframe, and no matter which direction it is facing relative to the drone (it can pan through 360 degrees), none of the drone part such as legs come into shot. The camera operator has a sperate set of controls; these controls can change not only the rate of change of the camera, but more importantly the position the camera is facing. With me having to rely only on the radio controller for yawing/panning control, I was not afforded this luxury.

Instead, I set up the third axis on the gimbal to behave as a ‘dampened panning’ movement. This can be done in the gimbal software. The gimbal panning movement is set up slightly retarded compared to the drone yaw movement and it is dampened, or ‘smoothed out’, compared to the oft jerky yawing movements of the drone. This greatly enhanced the viewing experience of the final pictures. This then is the overriding reason to design and build a new 3-axis gimbal, and the subsequent redesign of the airframe. I will also refer to this situation in the Conclusion later.

The two craft are shown side by side in Illustration 6.76, below, which illustrates the gimbals and cameras in the retracted position for transport. A keen eye will discern that on the left drone (the first 2–axis gimbal) the camera is inverted or upside down. There is a reason for this. When I first designed this gimbal, I had to do so within the constraints of the drone frame I was building. This necessitated that the pitch motor to be on the right-hand-side of the camera (facing forward); as shown in all of the diagrams so far. However, if you look at


**<u>Illustration 6.76:</u> Gimbals retracted on both craft**

Illustration 6.77, below, you will see that this places the camera lens quite far removed from the roll axis of the gimbal. This leads to subtle - but not unnoticeable to the trained eye – shifts in the video image as the drone pivots above it and the roll motor retains camera orientation. The solution is to position the camera in such a way that the lens is more in line with the roll motor axis, and on the first gimbal this was easiest achieved by inverting the camera as seen Illustration 6.76, above, and 6.77, below. Otherwise, it would have needed a complete redesign and construction of the first gimbal to overcome the problem. Luckily the GoPro camera has a setting in its menu to 'flip' the pictures vertically, so the image being recorded (and what you see via the FPV monitor) is 'right way up'. I did have to drill a hole into the camera baseplate underneath the camera to access the power switch, and rebalance the gimbal, but other than that no further modifications were needed to accomplish this inverted camera-mounting.

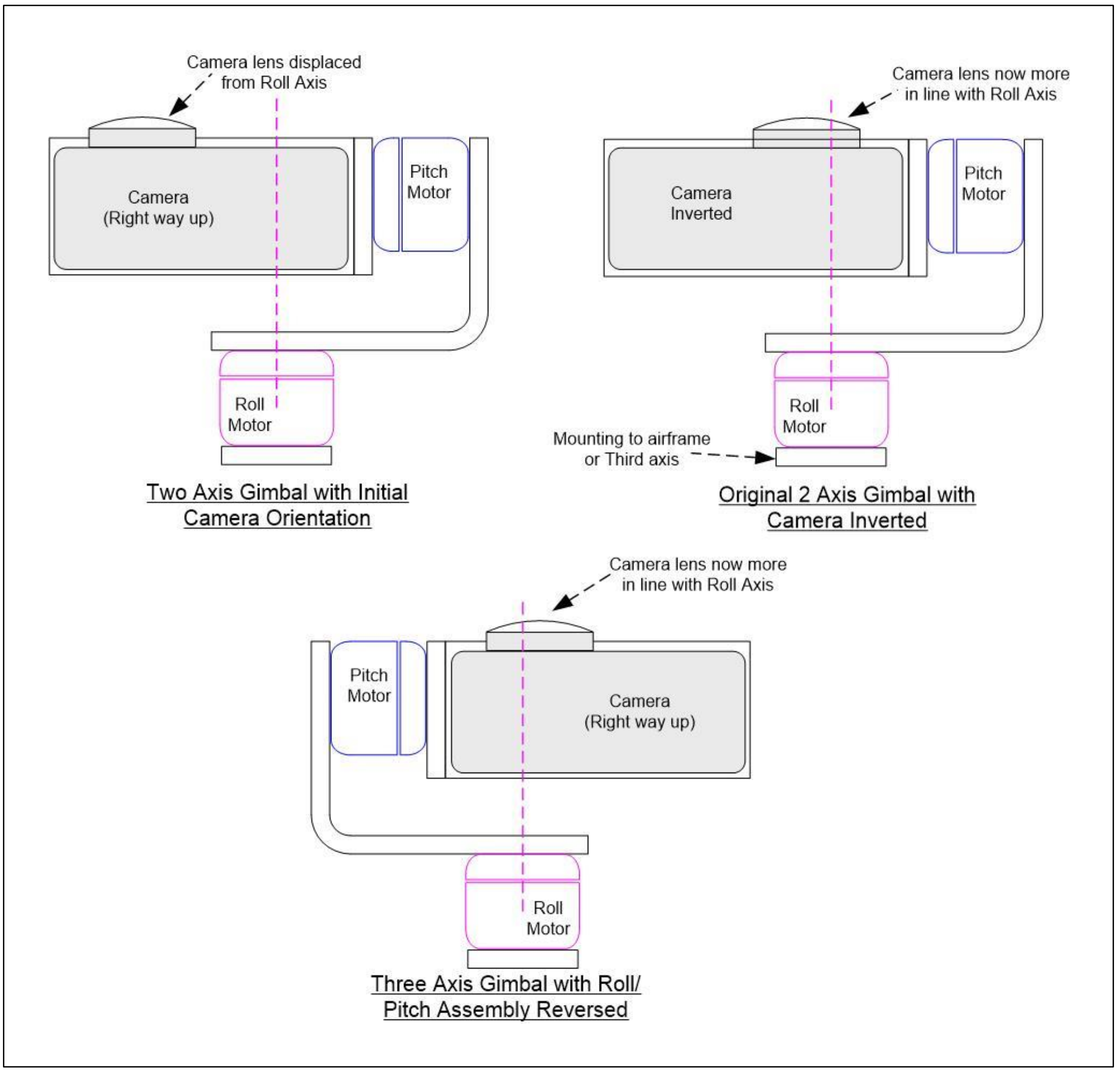



**Illustration 6.77: Positioning Camera Lens Axis close to Gimbal Roll Axis**

On the second gimbal, I decided to mount the camera the right way up and place the tilt motor on the left-hand side of the camera (facing forward) as shown in Illustration 6.77, above. I also did my utmost to minimize the size of the gimbal. This led to a more cramped setup of IMU, video interface board, camera and pitch motor as seen in Illustration 6.78, alongside, but it was far better in many ways from a performance aspect, and the camera lens ended up very close to the roll motor axis.

**<u>Illustration 6.78:</u> Minimised space between camera, video interface, IMU and tilt motor**

Brushless gimbals require an IMU fixed to the camera platform, and a control board typically mounted on the gimbal carrier. An example of the control board can be seen in Illustration 6.71, above. There are interconnecting cables between the IMU, which provides input signals to the board, and the outputs are connected to the various motors. There are other connections for a Universal Serial Port (USB) for programming the board, as well as an input for channels from the Radio Controller. On my particular setup, I assigned Channel 7 of the radio controller to manually adjust the roll of the gimbal (which became unnecessary as I changed to later control boards) and Channel 8 to manually adjust the tilt of the camera. These manual adjustments override the automatic pitch/roll/yaw of the gimbal and set the camera to a preferred initialised setting.

I was party to the early development days of brushless gimbals, which is to say they were still in their infancy when I decided to use them. There were various developers at the time. Since I was aiming to use open-source code wherever possible on my drones, I chose the only open-source system available at the time, a system known as the 'Martinez/BruGi (from *Bru*shless *Gi*mbal)' design (https://sourceforge.net/projects/brushless-gimbal-brugi/files/). Unfortunately, this board and its associated software did not live up to expectations. There were numerous problems both with the hardware and software. I personally sat through many hours of testing and flying trying to get the best I could out of it, but it was not to be.

Although the developer tried initially to address these issues, development of the board and its software stalled and then stopped completely.

At the time enthusiasts of brushless gimbals were having good success with another early developer, the ‘Alexmos/Basecam’ board (https://ardupilot.org/copter/docs/common-simplebgc-gimbal.html). This system, however, was proprietary to Basecam, the company developing it, and was quite expensive. It thus was no longer an open-source system which I was trying to achieve. Nonetheless, I bought one and flew it on a few flights. During one of these the craft crashed (through no fault of the Alexmos system) and the board was damaged beyond repair.

There was a new player in the market though, an open-source system known as the ‘OllieW/Storm32’ board (http://www.olliw.eu/storm32bgc-wiki/Getting_Started). Flyers were having good success with this system, and I purchased the board and uploaded the open-source software. It is the system I use to this day. The developers have been very good at addressing early problems and are constantly updating the software. It should be noted that I am still flying an early iteration of the Storm32 board which has proved sufficient for my needs, but it is no longer available. It has been superseded by the Storm32 NT board and software.

A large part of setting up the brushless gimbal involves the various software settings and configurations. This is achieved by connecting the board to a computer via the USB cable, and opening the boards’ Graphical User Interface (GUI). With the

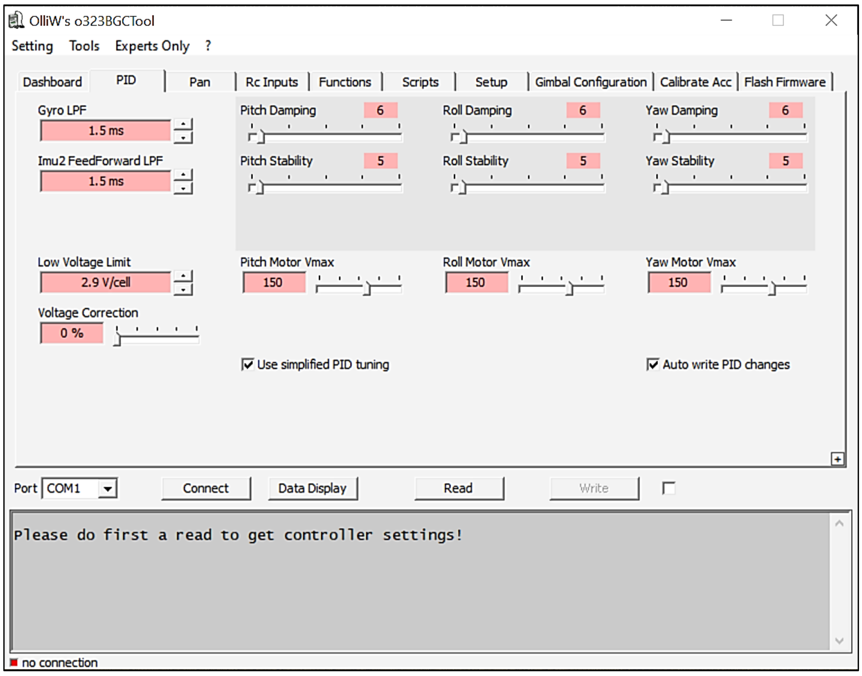
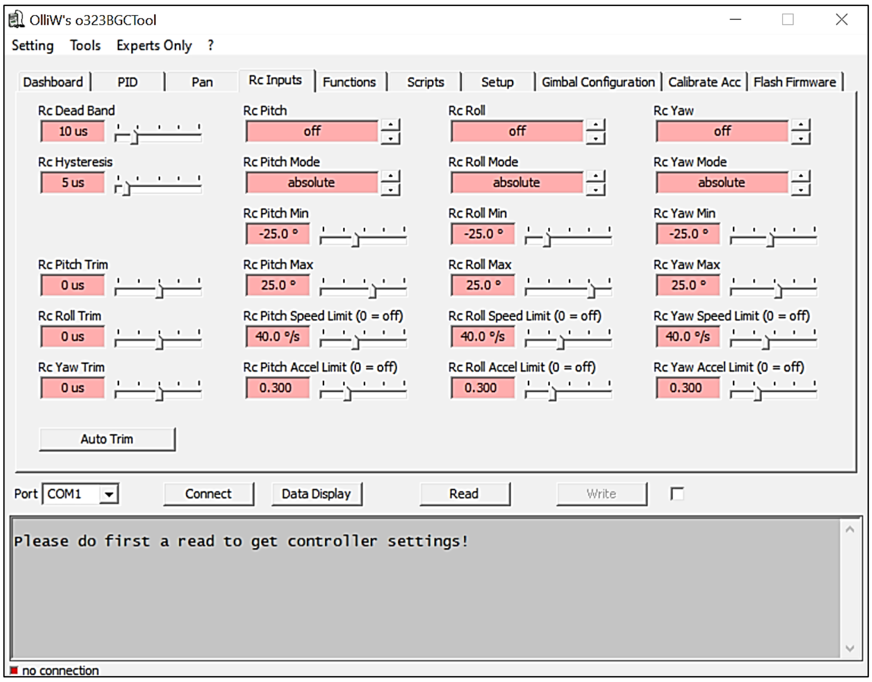
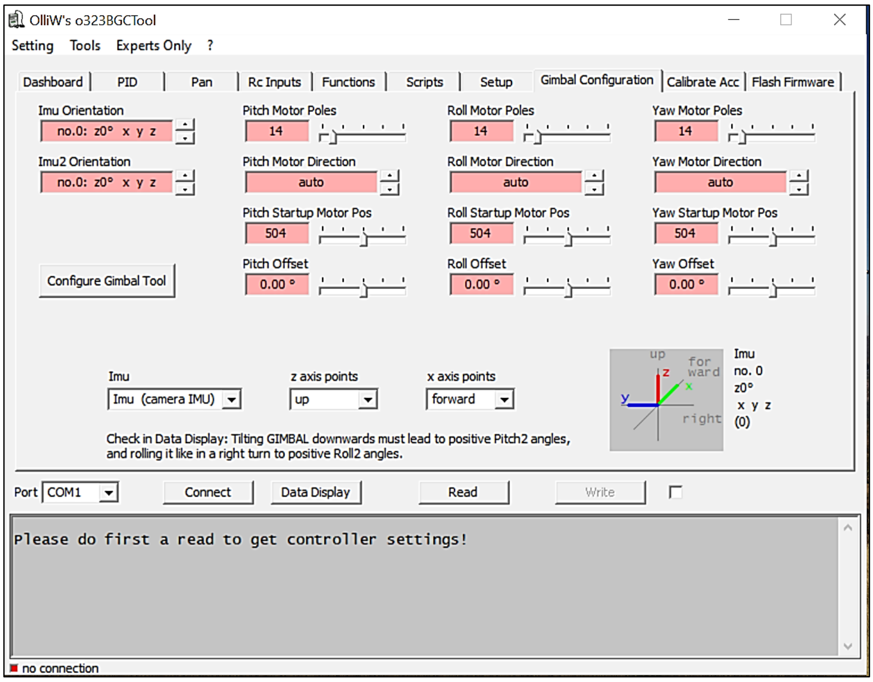


**Illustration 6.79:** Storm32 PID tab in GUI

Storm32 board there are 10 different ‘pages’ or screens to work your way through during setup and testing. I have included a few screenshots from three of the most important Storm32 GUI settings pages - the PID (Potential Integral Differential) page (Illustration 6.79, above), the RC inputs page (Illustration 6.80, above), and the Gimbal Configuration page (Illustration 6.81, alongside). A cursory glance at these images will reveal the complexity of the software, and I am not going to try and explain the process of setting up a gimbal in this writing. Suffice to say that every gimbal has its own individual setup that is different from all other gimbals because of the design of the mechanical parts, the motors chosen, the camera which is being flown, and the position and orientation on the airframe. It requires many hours of settings and testing (largely done by ‘flying’ the drone in one’s hands over the test bench/computer, but then also ‘real world’ flights to check). One of the modifications I did to the Storm32 board was to solder a ‘Bluetooth’ communications daughterboard onto the main motherboard. This allowed me to




**<u>Illustration 6.80:</u> RC Inputs tab in Storm32 GUI**




**<u>Illustration 6.81:</u> Gimbal Configuration tab in Storm32 GUI**

make setting changes and test the gimbal without the interconnecting USB cable, which tends to interfere with your ‘hand flying’ during testing.

A note should also be made about the interconnecting cables between the board, the motors, the IMU, and the video-output cable from the camera to the video transmitter. These cables must be extremely flexible so that they don’t stifle the smooth, fine movements of the motor, and their routing has to be carefully considered so that they don’t constrict the movements of the gimbal. This was particularly important in my case, because this routing had to withstand the rigours of the gimbal carriage being moved forward and backward for flight and stowage. In addition, the signals from the IMU are very small, and vulnerable to what is known as I2C errors. I2C, or Inter Integrated Circuit, is a serial communication protocol that uses two bus wires; a serial data wire (SDA) and a serial clock wire (SCL). Both of these are susceptible to interference from the much more powerful motor voltages running alongside in the wiring, and they need to be ‘screened’ to protect from this interference. I found it very difficult to buy thin, flexible, ‘2 core screened’ cable locally. In the end, I repurposed some old cellphone earpiece cable and, although it was quite difficult to solder the minute wires, it did work admirably when done. Some examples of the wiring and routing can be seen in the various gimbal photographs.

### 6.9 X8 Version 2

As I have mentioned, I also built a second version of the original drone, one which I simply refer to as ‘X8 V2’. I will go into the reasons for this new drone in a later chapter, suffice to say that there were a few major and some minor differences. The major change was to incorporate a new gimbal arrangement for the camera. This necessitated a complete rethinking and redesign of the front frame plates. Also, I wanted to try and shrink the folded size and the overall weight of the original ‘X8 V1’. Although I could have modified this first drone into the new one, I decided to keep it in its original state and build a new one from scratch; the overriding reason being this is a research project I wanted to have both versions eventually to show their evolution. Typically, if I was just using it for flying, I would have dismantled the old one and used whatever parts I could salvage to contribute towards the new one; much as I had done with my very first drones.

Wherever possible I decided to use what parts I already had and which would still fulfil my requirements. So, the same motor mounts, the same arms, the same legs; and even the same rear top and bottom plates (because when I had water-jetted the first drone parts I had made ‘spares’ which I hadn’t needed). The design was quite different at the front, though. Illustration 6.73, above, shows the front plates; with V1 on the left and V2 to its right. As you can see in V1, the frame is enclosed at the front of the plate, while in V2 it is opened up. This structurally was not as rigid, and because of this I had to do a complete redesign of the gimbal carriage, so that it became a structural frame member to compensate for the loss of rigidity in the new frame design. The new airframe is show below in Illustration 6.82, below. It has the same design and construction principles as the first version.

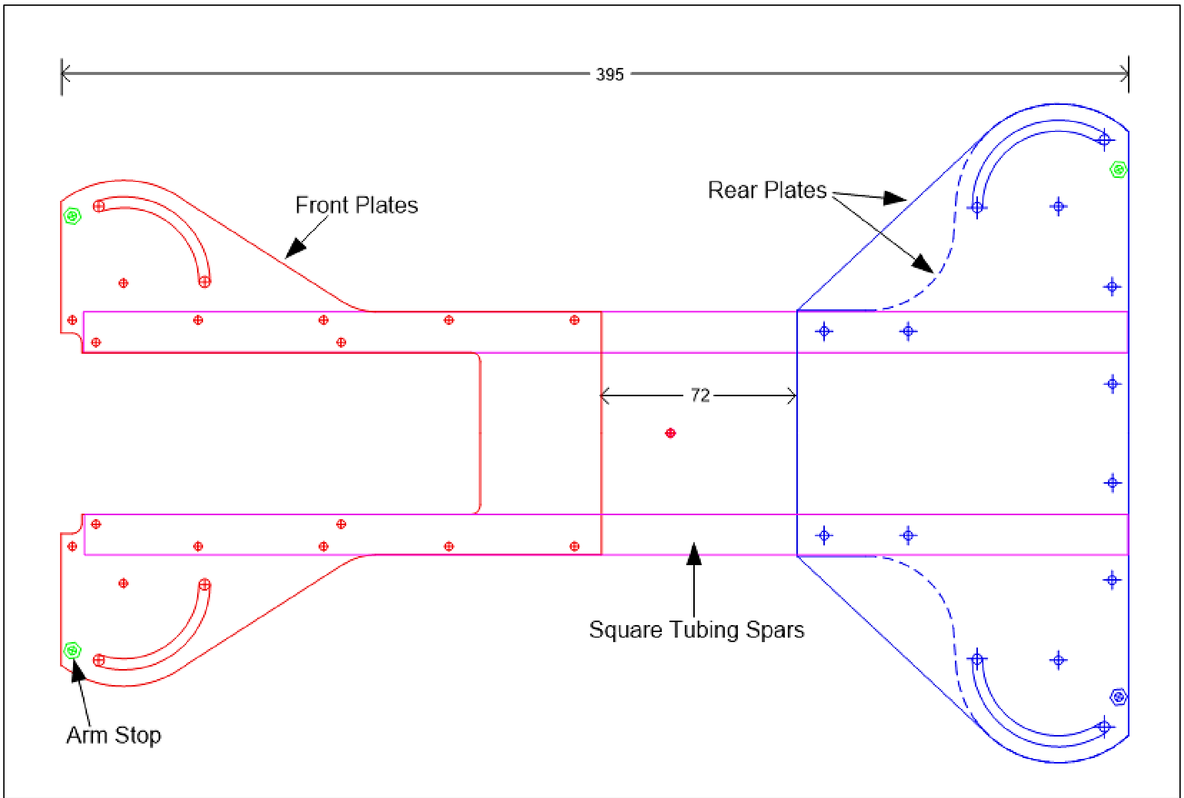
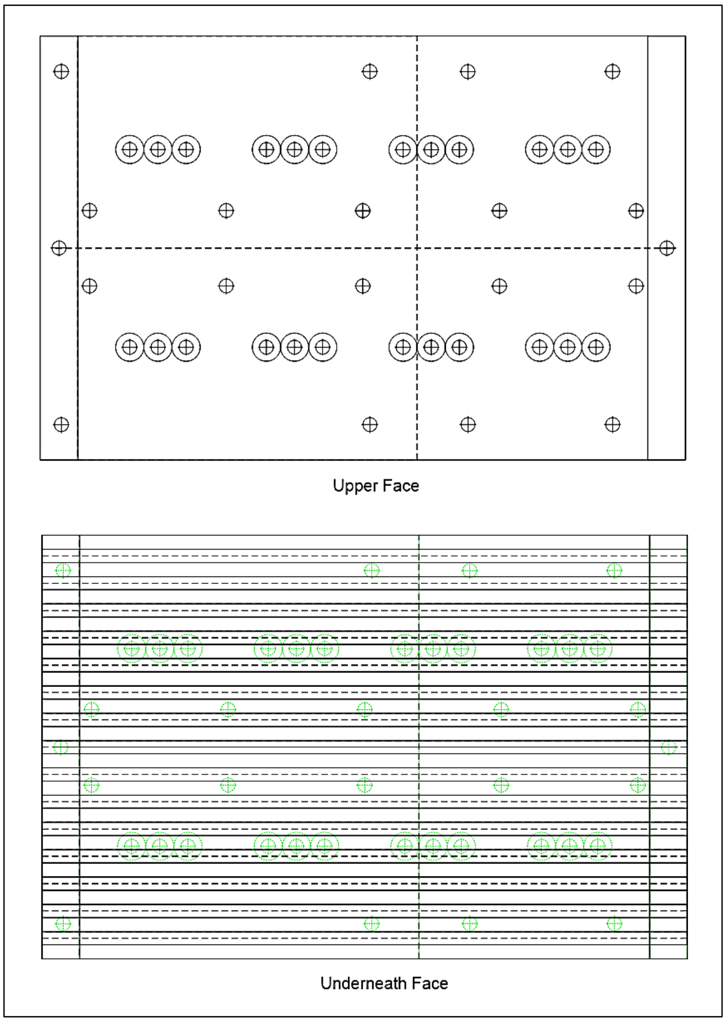



**Illustration 6.82: Version 2 Airframe design and Construction**

In my original design I had anticipated using 12 inch props but found during testing that 11 inch performed equally well. When I had designed the first drone, I wanted the folded components of the drone - including the props - to be within the protective frame ends. With shorter props I was now able to shorten the entire frame and still have the prop tips fold within the frame boundaries. This new drone, therefore, would have a frame approximately 25mm shorter than the original one. This meant that the mid-section plates would need to be shortened, particularly in light of the fact that the new front plates were longer (as can be seen from the comparison Illustration 6.73, above); and this in turn would mean a different configuration for mounting the ESC's, but this was not insurmountable. The bottom mid-plate was still aluminium, and still slotted for improved air cooling. A diagram of it is shown below in Illustration 6.83, alongside.




**<u>Illustration 6.83:</u> Version 2 Aluminium Mid Plate**

Another way to decrease the size of the drone was around its girth. I will need to briefly explain motor choice before I show how. Brushless motors have many ways of being specified, but the two main ways are their physical size and their 'Kv' rating. Kv is a measure of what the Revolutions Per Minute (RPM) that a motor can deliver for each Volt of power that is supplied. A high Kv motor spins faster than a low Kv one with the same voltage supplied. It would thus seem desirable to choose the highest Kv motor you can find, because it will spin at a high RPM and generate more lift. This is not the end of the story, though, because a high Kv motor (for a given size of motor which I will explain next) delivers less torque than a lower Kv motor. Take for example a small racing drone, which is designed to be very fast and manoeuvrable. It normally has very high Kv motors – in the order of 2500

Kv – but it uses very small props, only about four inches across. If you tried to get these motors to spin bigger props they would really struggle, and probably burn out with their efforts. Normally, the bigger props you want to drive, the lower Kv motor you want to utilise; you need torque rather than RPM for bigger props. However, when you want greater torque, the motors grow physically in size.

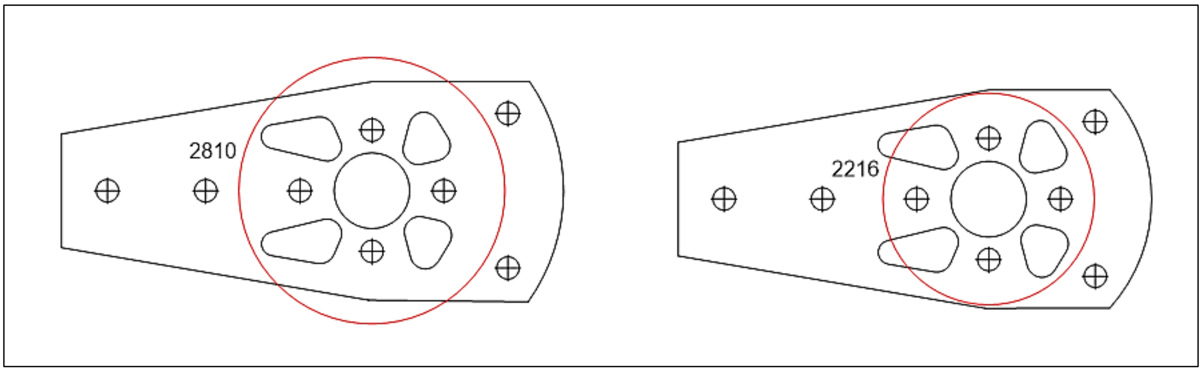
Brushless motors are also categorized by a four-digit number, say for example 2010. These numbers refer to the size of the stator in the motor, the first two digits being the stator diameter, and the last two being the stator height. In the example above, the stator is 20mm in diameter, and 10mm in height. The stator is that part in a motor which develops the power (with a series of magnets around it), it spins, and the props are attached to it. Generally speaking, the larger the stator, the more power and torque the motor develops; and the smaller the stator the higher the Kv of the motor.

I should make it clear that motor size and Kv (and prop selection) is a science in itself, and I am merely 'scratching the surface' in this explanation. eCalc had suggested to me that for my drones I could select motors in the 650 – 750 Kv range and run 11 – 12 inch props on them, with a pitch of between 4,8 and 5,5. So, for the first drone, I looked for 700 Kv motors.

However, 700 Kv motors come in a variety of stator sizes, from 3505 at the upper end of the scale down to lower numbers. For a given Kv, as the stator diameter decreases, the stator height must increase (within limits). Now, motors for drones are very expensive, and the bigger diameter you go the more expensive they get. There is a 'window' in the price range in the 'more common' region of any Kv motor. For my first drone I chose to operate in this window from a cost perspective, and thus ended up buying '2810 700 Kv' motors, to marry with 11 inch 5,5 pitch props. (The 2810 motors are very common, and affordable because of economies of scale in manufacturing.)

The drone flew well with these motors, but there was a problem which not many people would ever see as a problem. The 28mm diameter of the motor was wider than the motor mount I had designed. This meant that when the arms of the first drone folded in, the limits of the folding were when the motors touched the body of the frame, rather than the motor mounts bedding down first. What it meant was that if I could use motors with a smaller diameter, I could fold the arms closer to the frame.

Consequently, for the second drone I looked for smaller diameter motors but, importantly, delivering the same 700 Kv. I found some 2216 motors; although these were more expensive than the 2810's because they are not as common, I chose to go with them. The difference can be seen in Illustration 6.84, below. Now the arms of the frame could fold in, all the way until the motor mounts contacted the frame. This was closer than in the first drone and thus the overall girth of the folded drone was less. These motors were still able to drive the 11-inch 5.5 pitch props. Note that the overall width of the folded drone had not changed, because the widest part was the rear frame plates, and these were still common to both drones. All I had changed was the 'girth' around the mid-section; this was now less, and it allowed me more space for packing things around the drone in the backpack.



**<u>Illustration 6.84:</u> V1 2810 motor (L) and V2 2216 motor (R)**

The other evolution was the actual prop-mounting on the motors. My very first drones I built had a 'collet' system of mounting the props. Simply put, as you tightened the prop-mounting onto the motor all it had was a clamping system which tightened around the very smooth stainless steel shaft. This is not very reliable, with multiple prop changes the collets tend to wear; and the props can shift or spin on the shaft, and in a worst case scenario actually come right off during flight. An example of this system is shown in Illustration 6.85, below.

As drones evolved so did prop-mounting systems. For the first X8 Version 1 I wanted to move away from the collet system, and I chose motors where you could actually use a nut to hold the prop. The shaft of the motor is threaded, and (after placing the prop over the shaft) a nut is screwed down to hold the prop in place. This is a more secure system and is shown in Illustration 6.86, below. Although this system was more secure, I had multiple prop failures during one Lesotho trip (this is expounded on in the next chapter). Although the root cause turned out to be different, I suspected the reason the props were breaking was perhaps caused by me overtightening the nut on the shaft and causing hairline fractures in the props. This is the drawback of the system; the props have to be very tight, because that is the only thing stopping them moving or rotationally shifting on the shaft. In mechanical engineering, typically where you fasten such a system together you would employ a ‘keyway’ principle to stop this slippage, but the motors did not have this; they relied purely on friction for tightness. (As an aside, motors which still utilise this system have in recent years been specified as ‘CW’ or ‘CCW’ depending on which way they spin, and the nuts which fasten

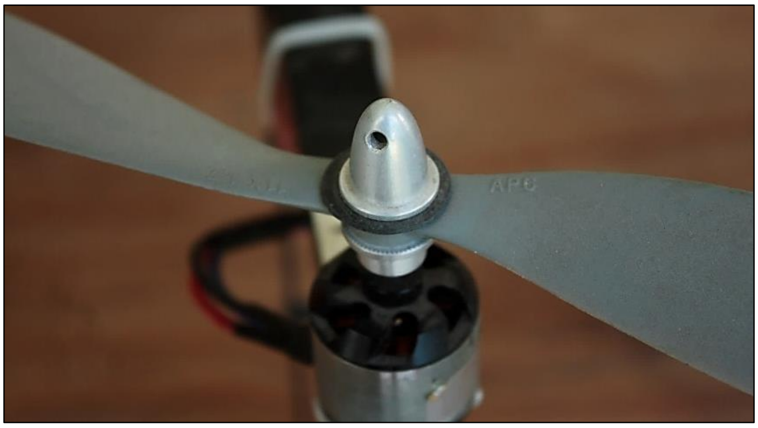


**Illustration 6.85: Collet prop mount**

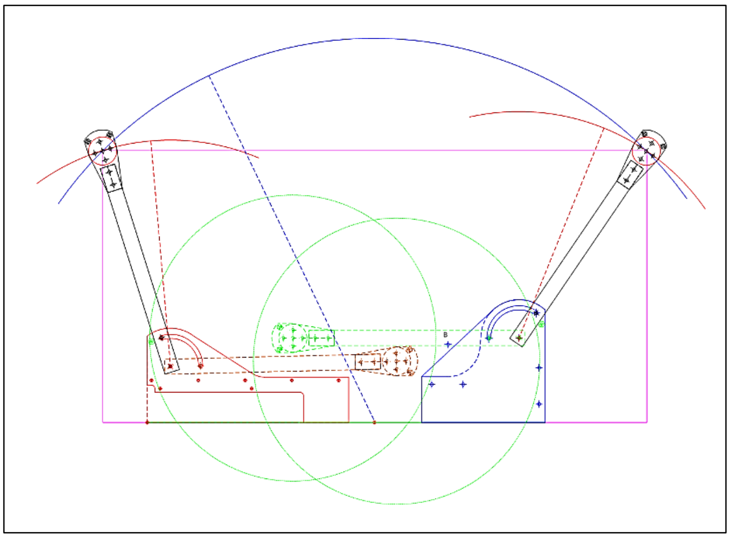

**Illustration 6.86: V1 with Threaded Shaft and Nut prop mounts**

**Illustration 6.87: V2 Prop attaches directly to Stator securely**

the props are also ‘left hand’ or ‘right hand’ thread. This means that the rotation of the motor/prop keeps the nut tightened.)

So, when I ordered the 2216 motors for the final version of the drone, I also chose ones which had a different prop-mounting. Now the stator has two small screws which attach the prop to it. The stator protrudes slightly through the prop in the centre, but on either side of it you can tighten two screws into the stator itself. This has two advantages. Firstly, there is a bigger contact area between prop and motor, which means you don’t have to tighten the screws as much as the nut on the previous system and thus avoid the possibility of overtightening and hairline cracking. More importantly though, is by having two screws you cannot have the prop spinning on the shaft; it acts like the engineering keyway system. This prop-mounting method is shown in Illustration 6.87, above.

Next was to begin the process of arriving at the symmetry of the ‘square configuration’ for the arm position of this new drone. Since I had shortened the overall frame dimension by about 25mm, this would mean that the arms of the new drone would have to fold to different angles to achieve this. Illustration 6.88, alongside, shows my working drawing with the same colours used for the various arcs and oblongs as I showed in the first version. I have included two green circles which are the prop-tips; this is to show how in the folded state they are still just bounded by the frame-end plates for protection during transport. Illustration 6.89, below, is a final version of this frame with the arms folded outwards; the motor axis spacing for this drone is now 540mm as compared to 544mm for the first drone. I have also included an overlay in Illustration 6.90, below, to show the differences in the frame size and final arm positions; the original drone is shown as a green outline and the later one in pink.



**<u>Illustration 6.88:</u> V2 Symmetry working drawing**

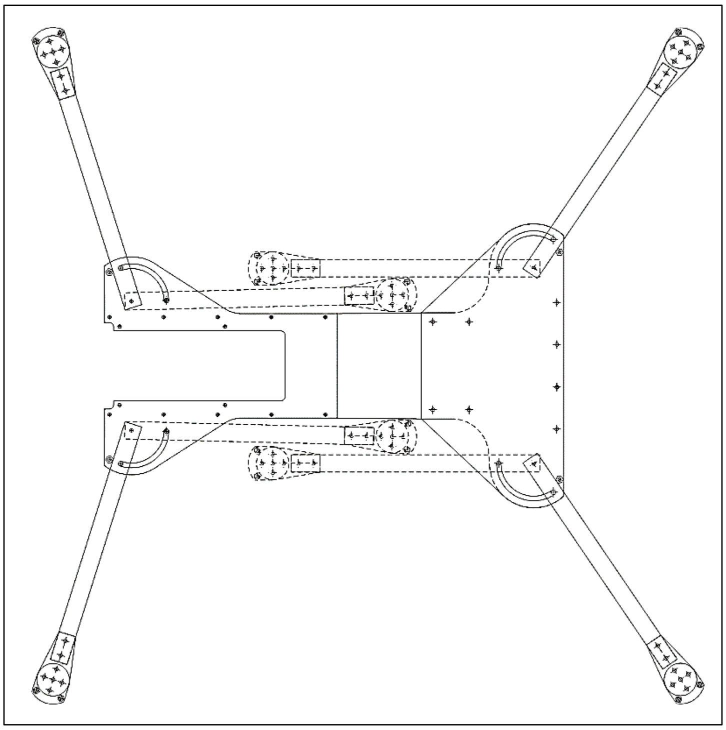
As I had done for the first drone, I wanted to check my tolerances after constructing it. I theoretically had a prop spacing of 540mm in the square configuration. My measurements on the completed drone were:

Left – Right Front: 538mm

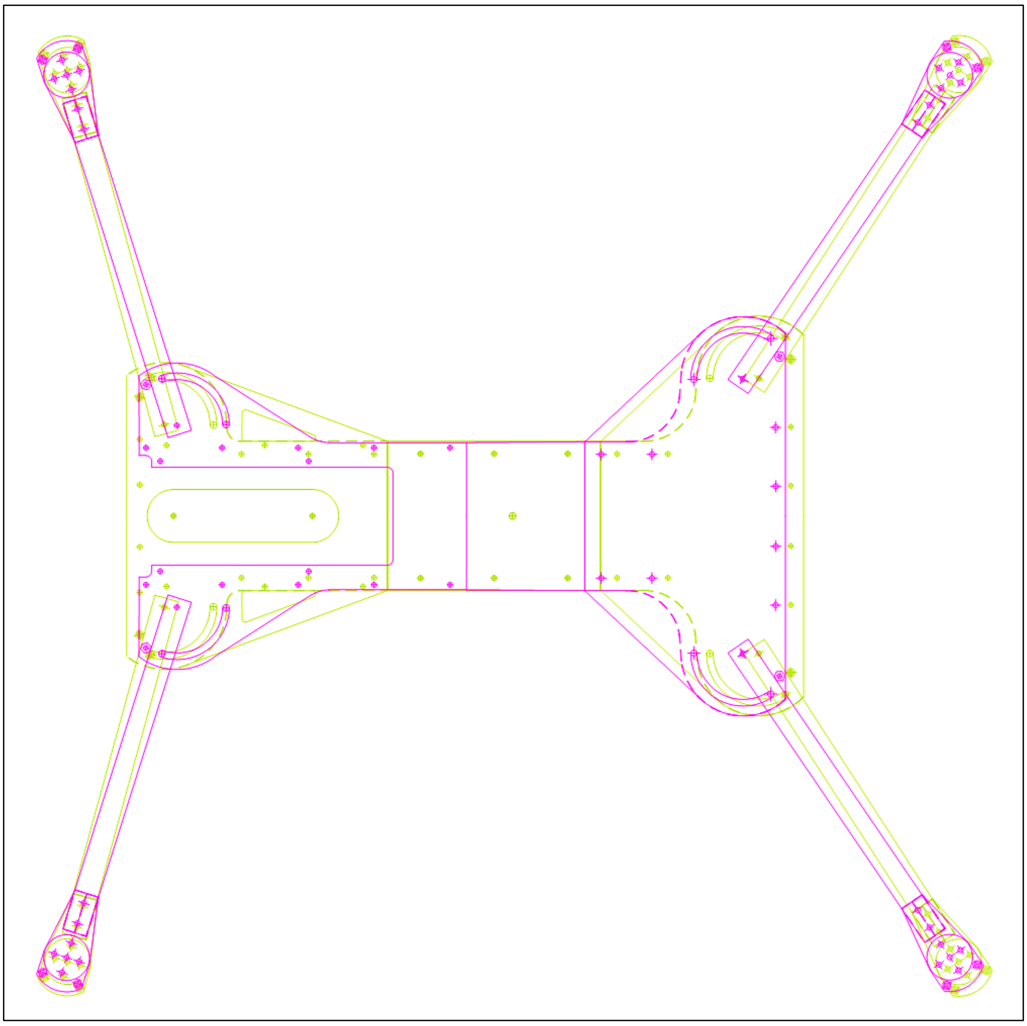
Left –Right Rear: 540mm

Front – Rear Left: 537mm

Front – Rear Right: 537mm



**<u>Illustration 6.89:</u> V2 Final Square configuration**



**<u>Illustration 6.90:</u> Frame comparison between V1 (green) and V2 (pink)**

Once again very close to my planned measurements, and in a worst-case measurement a tolerance of less than 0.6%.

Aside from the new gimbal arrangement on the second drone, I also wanted to achieve a smaller folded size (explained above) as well as a lower mass. I knew that the second criterion would be difficult to achieve, but if I could reduce the mass it should lead to longer flight times because of less battery consumption. At issue was the fact that I had to incorporate an extra motor and linkage for the gimbal system, as well as a far more substantial gimbal-mounting carriage, because it now formed a structural element of the frame. Both of these added considerable weight. Wherever I could I tried to minimise weight compared to the first drone. An example is using only one end-stop for each arm instead of the two I had in the first drone. Such a small change may seem insignificant but if it is done in multiple places with all kinds of tiny parts, the changes eventually add up to a weight-saving which is significant. An eventual physical comparison between the two drones is:

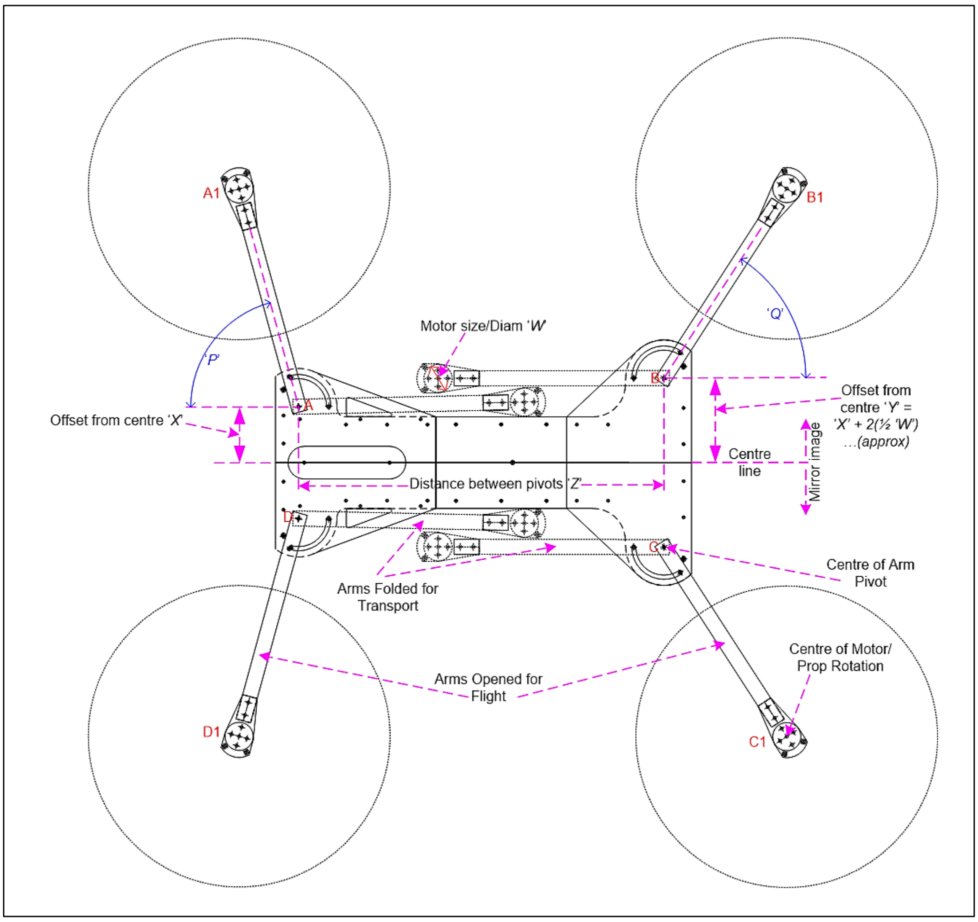
| | X8 Version 1 | X8 Version 2 |
|---|---|---|
| Length | 420mm | 395mm |
| Width (at widest point) | 245mm | 245mm |
| Height | 180mm | 165mm |
| Volume (of ‘box’ it could fit into) | 1852,2 cc’s | 1596,8 cc’s |
| Weight | 2981 grams | 2704 grams |

This equates to a weight-saving of 277 grams; in other words it is just over 9% lighter than the first drone. From a size perspective it is 256 cc’s less volume, and this in turn equates to a (folded) size saving of almost 14%. I was very happy with these results.

## 6.10 Murrel’s Symmetry Model

As I indicated earlier, I had always been intrigued by the mathematical relationship between the arm positions; and as I have also written I engaged the services of Prof Murrell to see if there was a solution. He and I worked together, with me providing the data and testing, while he worked on the mathematical model. We collaborated on a short paper which can be found as Annexure (B). I should add that Prof Murrell went way beyond what I was originally seeking, and actually developed an interactive Graphical User Interface (GUI) which, once downloaded, you can enter relevant data, and it will calculate the results. This GUI is posted as open-source code at Maker.js Playground (hughmurrell.github.io). I am very thankful to him for putting the time and effort into what was to me merely a matter of interest. I will summarize the findings here.

The first thing was to provide Prof Murrell with an explanation of what I was trying to achieve, with an accompanying diagram, which is shown as Illustration 6.91, below. There is no need to explain the Illustration now, since it has previously been covered, other than to say what I was essentially trying to calculate were the angles 'P' and 'Q'. I also provided him with a drawing which showed these angles as I had diagrammatically calculated for the second drone, as shown in Illustration 6.92, below; 72,5° (from the centreline) for the front arm, and 55,5° for the rear one.




**<u>Illustration 6.91:</u> Explanatory Drawing 1 provided to Prof Murrell**

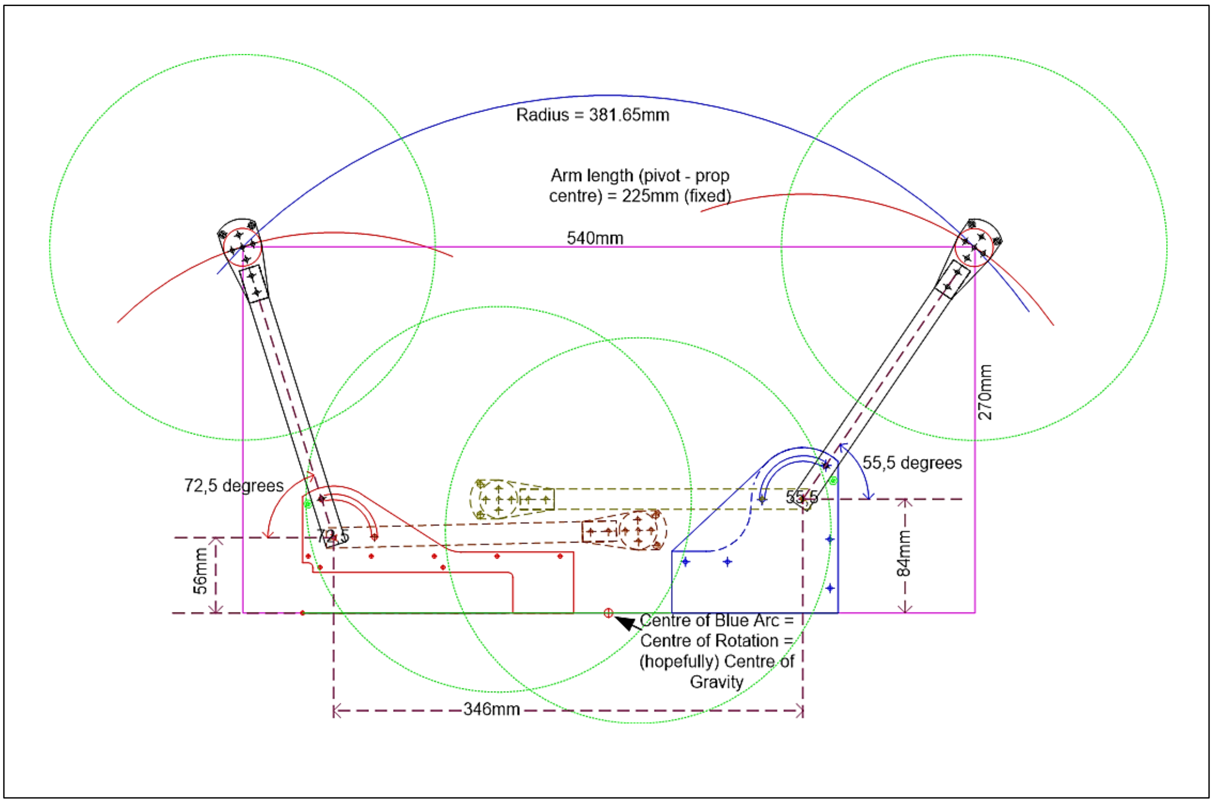



**Illustration 6.92: Explanatory Drawing 2 provided to Prof Murrell**

Prof Murrell's subsequent equations are extracted from the paper and shown below:

'Using the constraint that the rotor centres form a square with sides of some unknown length $S$ we have:

$$S = R\cos(p) + Z + R\cos(q)$$

$$S = 2(X + R\sin(p))$$

$$S = 2(Y + R\sin(q)) \qquad (1)$$

The first equation in (1) is derived from an expression for the horizontal edge of length, $S$, whilst the last two equations are derived from expressions for the vertical front and back edges of length $S$.

The unknown edge length, $S$, can be eliminated from equations (1) yielding two non-linear equations for the angles, $p$ and $q$ shown in equations (2) below.

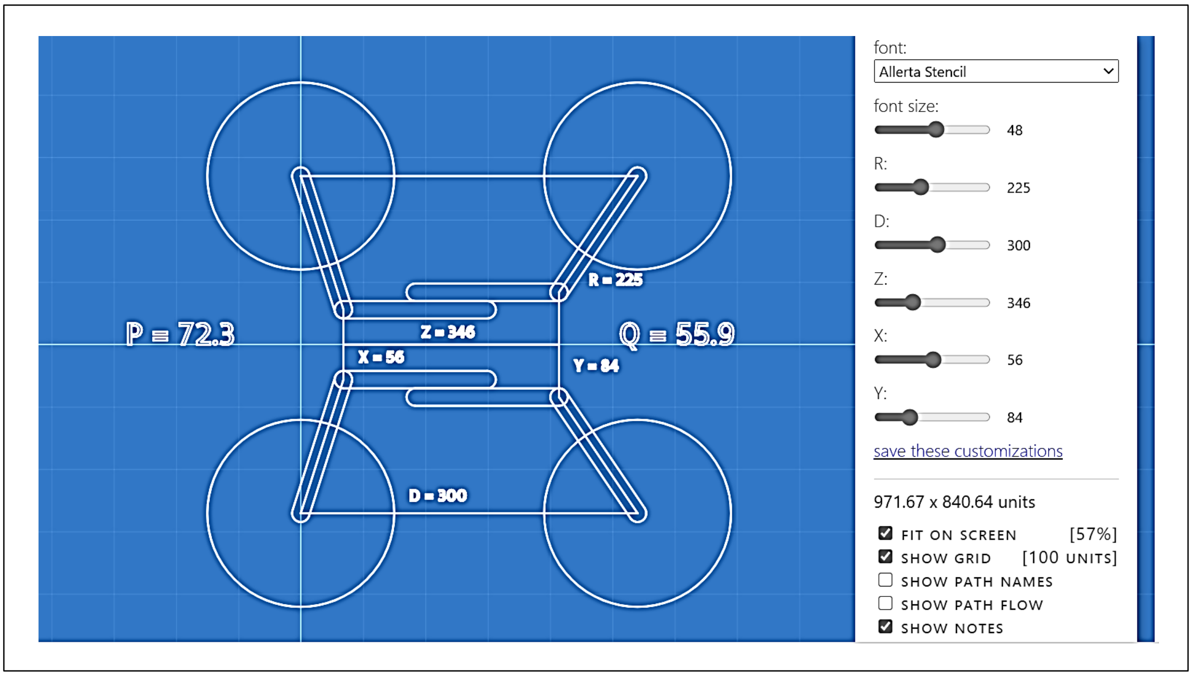
$$\cos(p) - 2\sin(p) + \cos(q) = \frac{2X - Z}{R}$$

$$\sin(p) - \sin(q) = \frac{Y - X}{R}$$

(2)’

Burnett, P and Murrell, H (2021)

Now, although this is interesting, what is really valuable is the interactive model which Prof Murrell produced. Although it went through several iterations as we fine-tuned it, I will not present these but only the final version which is found at the github reference above. I will however present a sample of the results when you enter various values. The first, Illustration 6.93, below, is his calculation of the second drone I built, whose measurements are shown in Illustration 6.92, above. On the right-hand side of the graphic are the various values you can change, as per the nomenclature I had supplied with my drawing. You can either use the sliders to change value, or increase/decrease by clicking on the parameter and using keyboard arrow keys to go higher or lower. As you change values, the graphic changes, and the angles ‘P’ and ‘Q’ are calculated.




**<u>Illustration 6.94:</u> Output P and Q angles for specifications supplied for X8 Version 2**

What is interesting is that the angles I had worked out using my ‘diagrammatic’ method were very close to the angles calculated by the mathematical model. I had Angle ‘P’ at 72,5°, while the model gave 72,3°, a difference of 0,2°. I had Angle ‘Q’ at 55,5°, whereas the model calculated 55,9°, a difference of 0,4°. I trust that the model is correct, and that my drawings were not accurate enough; however, the drawings are still under 1% tolerance which I believe is acceptable.

Anyone can access this open-source model and set in the parameters of the folding drone they wish to design, and the software will configure it for them. As a matter of interest, I have saved two different examples, shown in Illustrations 6.95 and 6.96, below. All I have done in these two versions is change the ‘Z’ parameter (the longitudinal distance between the arm pivots) from my drone; in Illustration 6.95 it is 296mm (i.e., 50 mm shorter) and the angles arrived at are ‘P’ 66,3° and ‘Q’ 52,3°. In Illustration 6.96 I have added 50mm, so ‘Z’ is now 396mm, and ‘P’ is computed at 79,2° and ‘Q’ at 59,1°. I found Prof Murrell’s model fascinating, and I believe it has wide-ranging benefits for drone enthusiasts.

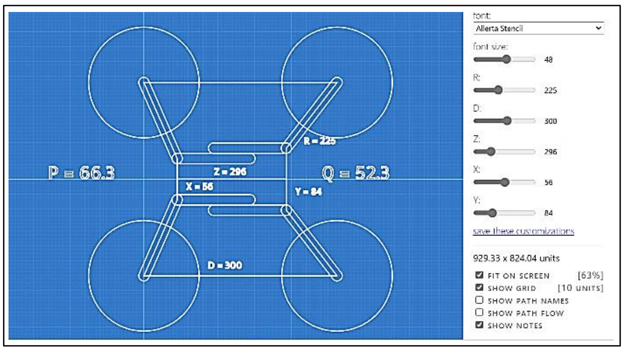



**Illustration 6.95**: ‘Z’ = 296mm

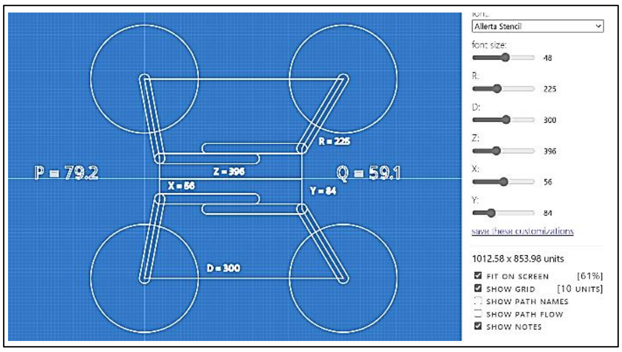



**Illustration 6.96**: ‘Z’ = 396mm

## 6.11 Unfolding and Folding

I include a short photo essay to show the unfolding and folding process of the drone. This example is for the second drone I designed, but the explanation is very similar for the first drone. There is also a video of the process with commentary which can be found at this link: https://youtu.be/YAoLVBfQfUw

Unfolding: Step 1: Illustration 6.97

The easiest way to do this is to find a place you can sit down and work on your lap; out in the bush this is often a rock or fallen tree. Place the drone on your lap on its side.

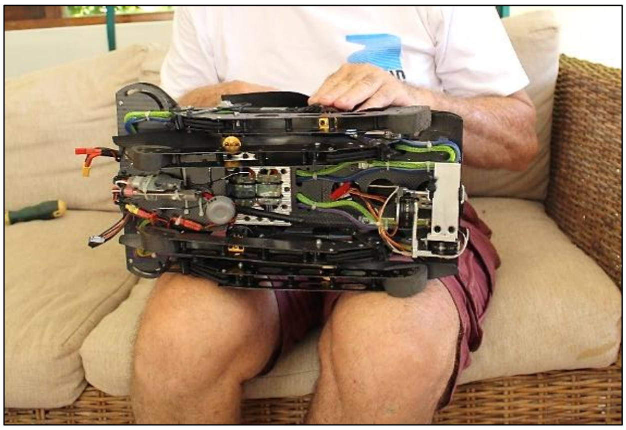


**Illustration 6.97:** **Unfolding Step 1**

Step 2: Illustration 6.98

Locate the two nuts on the top of the drone on each arm stiffener (shown).

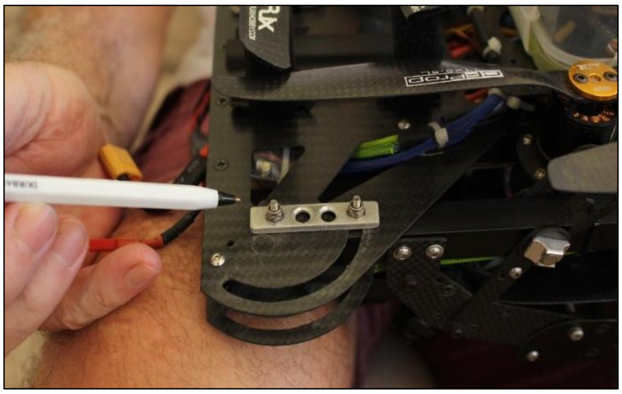


**Illustration 6.98:** **Unfolding Step 2**

Step 3: Illustration 6.99

Loosen the nuts using the nut-driver. Don't remove them, just loosen them sufficiently to move the arm. Do this for both arms which are on top with the drone on its side.

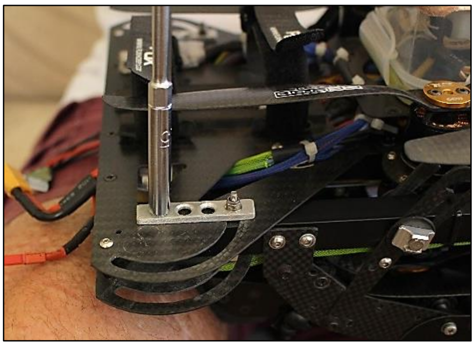


**Illustration 6.99:** **Unfolding Step 3**

Step 4: Illustration 6.100

Open the rear arm first, and then the front one. Make sure the arm moves all the way until it reaches the arm-stop.

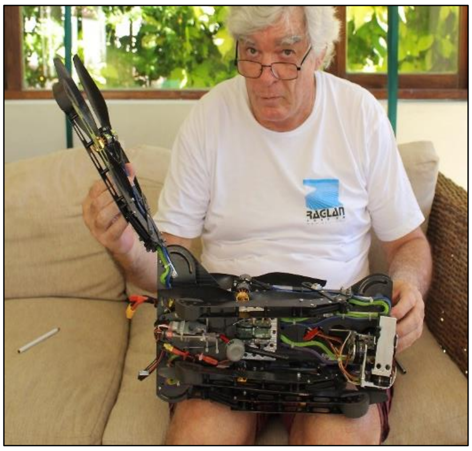



**Illustration 6.100:** **Unfolding Step 4**

Step 5: Illustration 6.101

Showing the arm-stop.

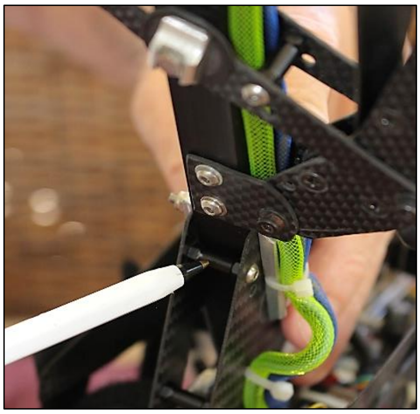


**Illustration 6.101:** **Unfolding Step 5**

Step 6: Illustration 6.102

Hold the arm against the arm-stop whilst you tighten the two corresponding arm-stiffener nuts.

**Illustration 6.102:** **Unfolding Step 6**

Step 7: Illustration 6.103

Repeat the process for the front arm.

**Illustration 6.103:** **Unfolding Step 7**

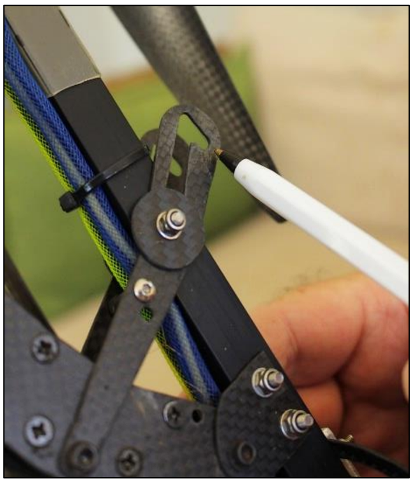
Step 8: Illustration 6.104

Locate the leg-strut pinch bolt (shown).

**Illustration 6.104:** **Unfolding Step 8**

Step 9: Illustration 6.105

Note the ‘kickback’ in the leg-strut slot. The strut must be manoeuvred into this ‘detent’ position. As you open the leg it ‘clicks’ into this position.



**<u>Illustration 6.105:</u> Unfolding Step 9**

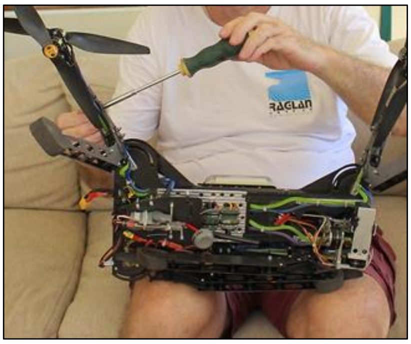
Step 10: Illustration 6.106

Open the leg, and then tighten the strut-pinch bolt.

**<u>Illustration 6.106:</u> Unfolding Step 10**

Step 11: Illustration 6.107

Repeat the process for the other leg.

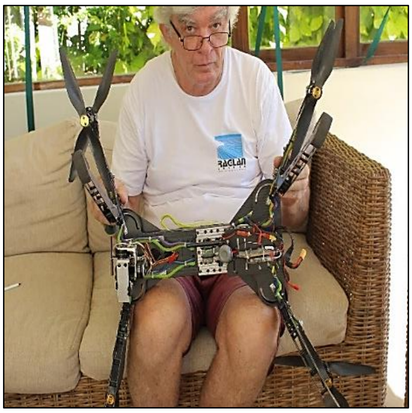


**<u>Illustration 6.107:</u> Unfolding Step 11**

Step 12: Illustration 6.108

Turn the drone onto its other side and repeat the procedure for those two arms and legs.

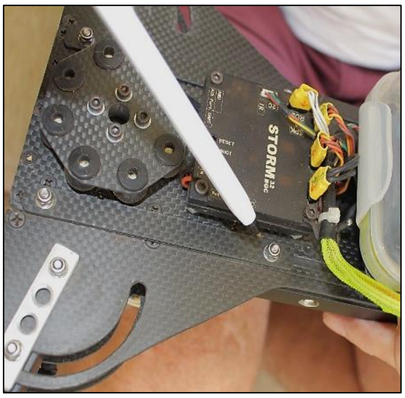
The drone legs and arms are now fully opened and secured.



**<u>Illustration 6.108:</u> Unfolding Step 12**

Step 13: Illustration 6.109

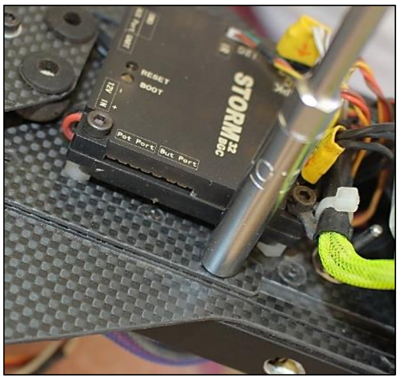
Locate the captive nuts on the gimbal carriage (shown).




**<u>Illustration 6.109:</u> Unfolding Step 13**

Step 14: Illustration 6.110

Loosen all four nuts, once again not removing, just loosening.




**<u>Illustration 6.110:</u> Unfolding Step 14**

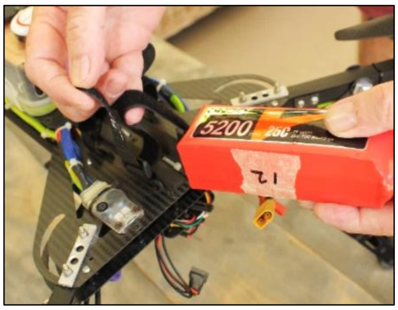
Step 15: Illustration 6.111

Grasp the gimbal carriage and pull it forward until it reaches its stops. Retighten the four gimbal carriage nuts.

**<u>Illustration 6.111:</u> Unfolding Step 15**

Step 16: Illustration 6.112

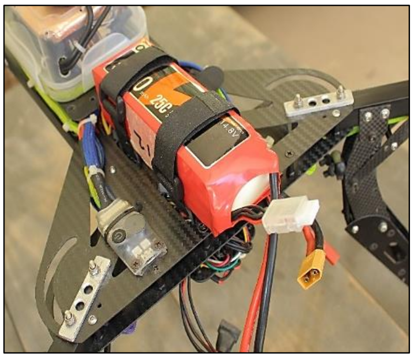
Place the drone on a flat surface, lift up the Velcro straps at the back, and insert the battery.




**<u>Illustration 6.112:</u> Unfolding Step 16**

Step 17: Illustration 6.113

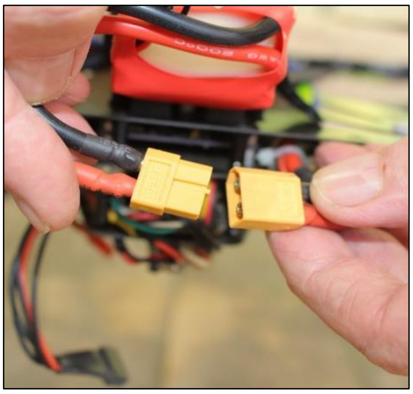
Make sure the battery is seated all the way forward, and then tighten both Velcro straps.



**<u>Illustration 6.113:</u> Unfolding Step 17**

Step 18: Illustration 6.114

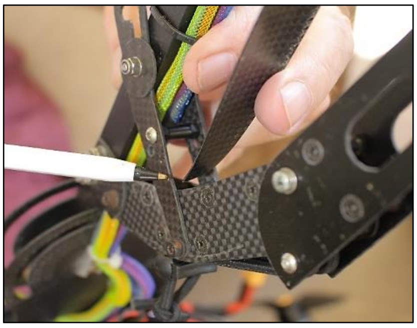
Plug the battery in, and the drone electronics will be activated.



**<u>Illustration 6.114:</u> Unfolding Step 18**

<u>Folding:</u> Step 1: Illustration 6.115

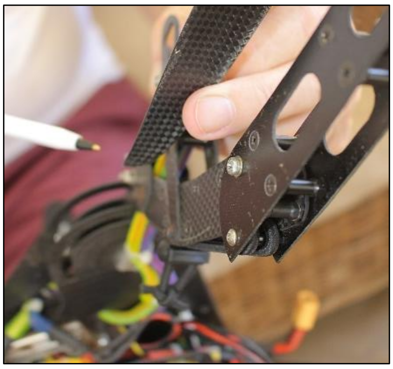
To fold, reverse the process. First remove the battery. Then, return the gimbal carriage to its folded position. Then, once again with the drone on its side on your lap, start folding the legs. To begin folding the legs you need to 'overextend' the leg slightly to release it from the 'kickback' position on the leg-strut, and then fold the leg. As you are about to close each leg ensure that the lower prop on each arm sits between the leg plates, as shown.



**<u>Illustration 6.115:</u> Folding Step 1**

Step 2: Illustration 6.116

This is the incorrect placement of the prop, outside of the leg plates. The arms will not fold all the way into the body with the prop in this position.



**<u>Illustration 6.116:</u> Folding Step 2**

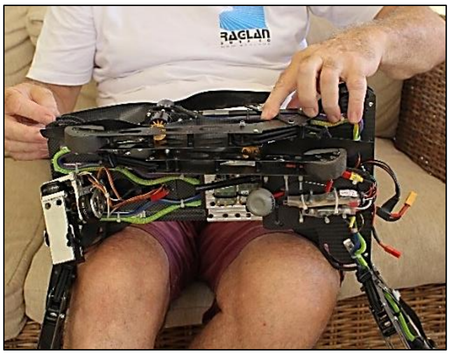
Step 3: Illustration 6.117

Loosen the arm-stiffener bolts and fold the arms into the body. Fold the front arm in first until it is flush up against the body…

**<u>Illustration 6.117:</u> Folding Step 3**

Step 4: Illustration 6.118

…and then the rear arm over it. Tighten the stiffener nuts. Turn the drone over and repeat the leg and arm process on the other side. The drone is now ready for transport.

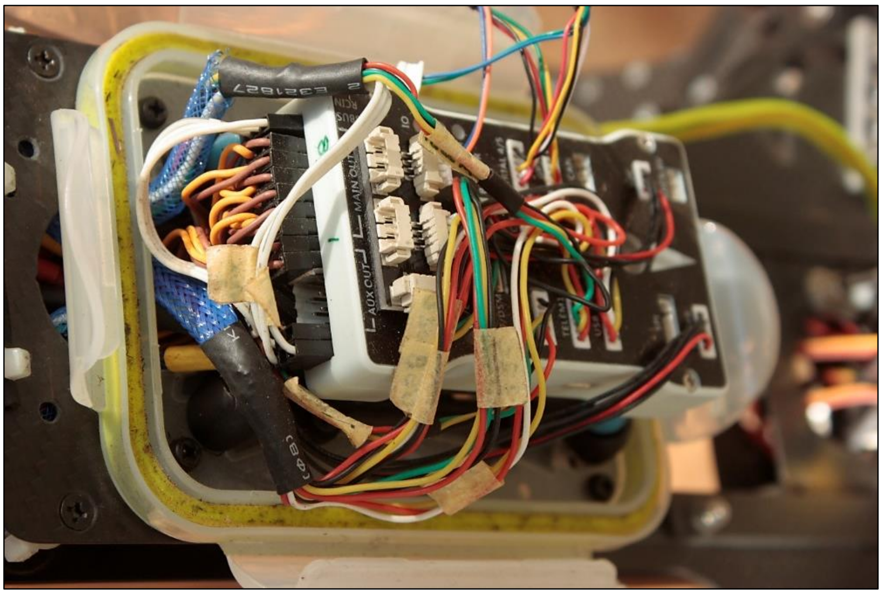


**<u>Illustration 6.118:</u> Folding Step 4**

6.12 <u>Electronics</u>

Much of the electronic components are similar to the original quadcopter and hexacopters which I initially built and have already described, so I will not repeat the description. I did include some upgrades, and I will detail those changes.

The major upgrade was to the flight computer. Originally, I had used the ArduPilot Mega (APM) flight computer, but this was upgraded to a new board known as 'Pixhawk' (https://ardupilot.org/copter/docs/common-pixhawk-overview.html). The APM uses an 8-bit Atmega 2560 main processor running at a speed of 16 MHz whereas the Pixhawk employed a 32-bit Arm Cortex processor running at 168 MHz. Pixhawk also has a backup STM32 F4 processor running at 72 MHz. All of this sounds very technical, but it essentially means the Pixhawk can process information much faster, in more detail, and with far greater memory capacity. It means the Arducopter code writers can employ a more sophisticated code; in fact, the code is evolved to be so complex that the older APM boards can no longer run it. The setup with the Pixhawk is shown in Illustration 6.119, alongside.



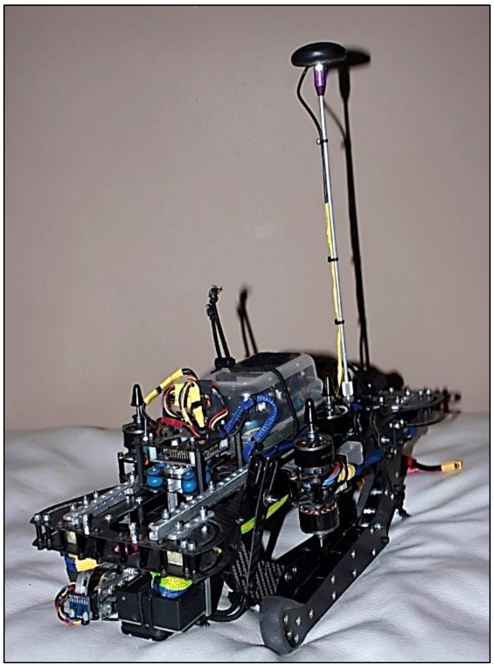
**<u>Illustration 6.119:</u> Pixhawk Flight Management Unit**

This added computing power allows the code to incorporate additional features. There are many of these, but I will just mention one: GNSS redundancy. The APM board only allowed one external GNSS (commonly known as GPS) antenna. Satellite reception can be finicky at times, and your GNSS 'puck' (so called because it looks like an ice hockey puck), which houses both the GNSS antenna as well as a magnetic compass, can 'drop' or 'glitch' in its reception. There can be any number of reasons why it might lose signal, but it only has to do so for a very short period of time for it to become a problem. Since satellite reception is critical when flying autonomously, this can have disastrous consequences. Later Arducopter software (only applicable to the Pixhawk) allows you to incorporate a second 'backup' GNSS puck which 'runs in the background'. As soon as the software recognises a glitch from the main GNSS antenna, it switches over to the second one and takes data from that until the first returns to good health.

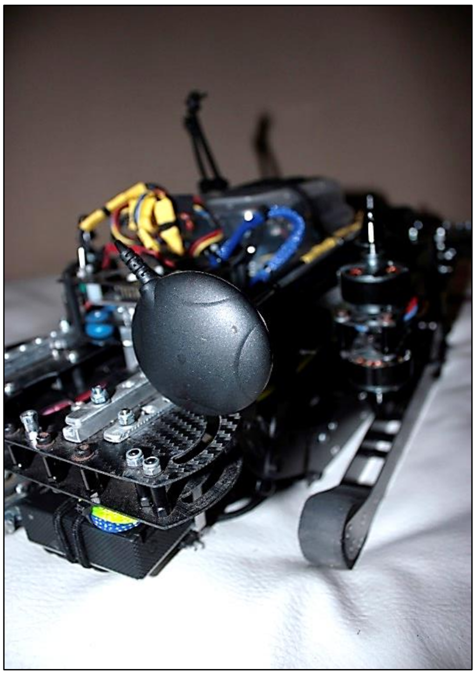
In addition, I also invested in a far better GNSS receiver, one manufactured by u-blox known as a Neo – M8N (https://www.u-blox.com/en/product/neo-m8-series). This has far greater sensitivity than a typical GNSS puck. You can better determine your position and altitude, while it refreshes its data eight times per second compared to a typical once per second. I housed both the main and the secondary receivers on top of the 'lunch box' which housed the Pixhawk on its shock-absorbing system, as can be seen in Illustration 6.120, below. I also lined the top interior of the lunch box with adhesive copper foil. This served two purposes.

Firstly, it provided a ‘barrier’ for any extraneous electromagnetic pulses generated by the Pixhawk electronics which might interfere with the sensitive GNSS reception (the copper foil is grounded internally and shunts these ‘eddy currents’ to earth). Secondly, it provides a ‘ground plane’ for the antenna which greatly improves reception. This lining can be seen in Illustration 6.120. Ideally the GNSS antenna should be far removed from the electronics to avoid the issue of transient electromagnetic wave interference, and this has traditionally been done by mounting it on a long ‘pole. I did try this as can be seen in Illustration 6.122 and 6.123 below, but it was vulnerable during packing (even though it folds down for this purpose) and especially vulnerable during my frequent crashes. The system I employed - mounted just above the flight computer housing - has proved to be both protected and capable.

**<u>Illustration 6.120:</u> GNSS Receiver Antenna ‘Pucks’, Backup (L) and Main (R)**

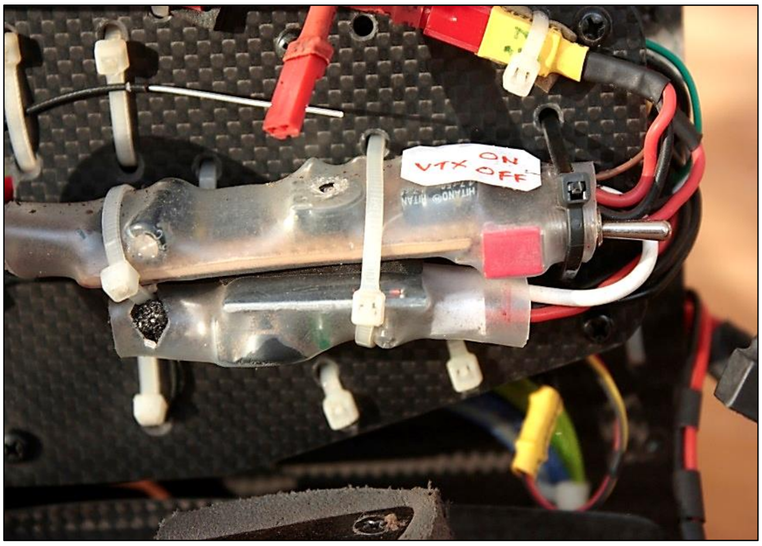


**<u>Illustration 6.122:</u> Experimental GNSS mast erected for flight**



**<u>Illustration 6.123:</u> Experimental GNSS mast folded for transport**

The next issue to address was low battery warnings. As I did with my earlier drones, I rigged up a system to relay audible warnings from the drone back to me. The earlier drones had an on-board microphone built into the video transmitter, but the newer transmitters did not have this feature. So, I built up a microphone and microphone preamplifier circuit for the drone. I also installed a battery alarm, which emits a beeping sound when the battery is approaching a depleted state. This beeping is not loud enough to hear when the drone is some distance away, thus the need to send it via the transmitter. I located the microphone close to the battery alarm and wired it into the system. This mic and preamp can be seen in Illustration 6.124, alongside. Integrated into this board was a switch to power the video transmitter on and off, so that I could leave it off during the flight testing phase, and then only power it up when needed; this to avoid the issues of transmitter overheating when the craft was stationary and address an issue I had which will be explained later on in this chapter. This 'VTX On/Off' switch can be seen in the same picture above.



**<u>Illustration 6.124:</u> Mic Preamp and VTX switch**

Then, the video (and audio) monitoring system which I have to wear. Video monitors and goggles have become more sophisticated than when I started out, and they are also very expensive. I decided rather to just use a cheaper version which is a video-monitor screen, housed inside a polystyrene box which straps to your head. The supplied unit still needed modification for my purposes though.

Firstly, I found that the supplied strap system did not work very well; it needed to be very tight for it to stay in place on your head. I built a new system where there was an extra strap which went over the top of my head. Then (because I wear glasses for reading) I could not see the display clearly. The system does come with a small 'magnifying' glass which you can adjust but even at the limits of the adjustment I still couldn't see. I tried wearing my reading glasses, but they became entangled in the hood when I lifted it up and down on my face, and also I wanted to have my glasses off for visual sighting of the drone (without the video hood) when it launched or landed. The solution was to remove the arms from an old pair of reading glasses and glue them just inside the hood at the correct focal length. This worked very well. When the hood was on, I could see the video pictures clearly, and when I lifted the hood for sighted flying the glasses were removed from my eyes. Illustration 6.125, below left, shows the system, and Illustration 6.126, below right, shows how it is stowed in a plastic box for transport in the backpack.

**<u>Illustration 6.125:</u> Video Monitoring system**


**<u>Illustration 6.126:</u> Monitor packed for transport**

The next issue |I had to attend to was the video receiver. The antenna has to be up high for good reception. I took a small camera case and installed this on the strap, but at the back of my head. Inside this camera case was the video receiver, and the antenna protrudes above out of the case. Onto the receiver I built a small audio amplifier and attached a speaker. This gave me the audible low-battery warnings. The entire system is powered by a battery which fits into a belt bag around my waist. The straps can be adjusted so that the hood stays on my head either when I am watching the video with the hood down, or when


**<u>Illustration 6.127:</u> Video monitoring system in use**

it is lifted for visual flying, or working with the drone on the ground such as changing batteries.

Illustration 6.127, above, shows the entire system strapped to my body, Illustration 6.128 with the hood in the lowered position watching the video during flight, and Illustration 6.129, (both below), with it lifted up for launching or landing the craft.

**Illustration 6.128:** **Hood lowered for flight**

**Illustration 6.129:** **Hood raised for launching or landing**

Another problem I encountered was the reliability of the video transmitter. One day out in the field it would not transmit any video. With the limited resources I had with me I checked all the connectors and wiring and came to the conclusion that it was the video transmitter itself. On returning home I verified this as the fault and opened it up to see what went wrong. There was a burnt-out integrated circuit chip inside, shown arrowed with a pin in Illustration 6.130, alongside. This had happened during my mapping and setup stage of the day before I had flown the drone for the first time. I concluded that the cooling abilities of the transmitter were marginal, and that it needed airflow over the transmitter to keep it

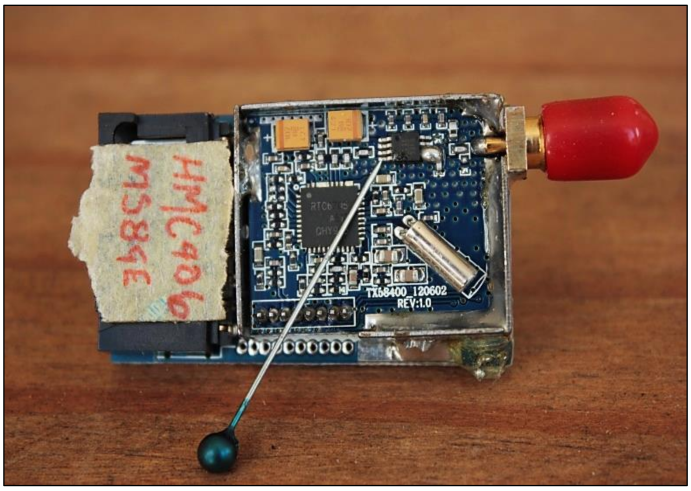


**Illustration 6.130:** **Video Transmitter with burnt out chip**

cool enough. When the drone was just sitting ‘idling’ on the ground whilst I was doing my setups there was not enough airflow, the transmitter had overheated, and burnt out. (This cost me a whole day of shooting, which I will describe in the next chapter.)

My solution was to have the transmitter on only for short periods of time on the ground, and mostly on during flight. To this end I installed a switch (which I could easily access from the back of the drone) that switched power to the transmitter and is shown in Illustration 6.124, above. During setup I would leave the switch off, and only power it up when I got into the video flight-testing phase of the day. I had to order a new transmitter, and I chose to go with the same model since I already had the matching receiver and the system up until then had proven to be reliable. When I got the new one, I opened it up to see if there was some way I could improve the heat transfer capabilities of the burnt chip to the outside of the case, only to find that the manufacturers had already done this! There was obviously a factory design fault with the first version.

This example illustrates another recurring problem I encountered with building the drone, that of delivery times. It often takes around six weeks between ordering from overseas and local delivery; this is unless you use a direct courier service which is very expensive. As in this case that meant six weeks between experiments. At one stage in 2016, the SA Post Office was on strike for several months and the supplies sat in limbo for those months. Included in this order were batteries worth several thousand Rand which were ‘dead’ by the time I received them and had to be scrapped.

Another facility I installed was a standby battery and voltage monitoring system. Some explanation of the Arducopter software in necessary, first. When you plug a battery into the drone it starts a period of initializing the electronics (this is different to initializing the gimbal). Once the drone has configured itself it requires that you upload the next autonomous mission. Then you have a safety switch on the drone which you have to depress, but the drone is still in a ‘disarmed’ state and will not fly. To ‘arm’ the drone for flight you have to hold the throttle at closed but all the way over to the right for a few seconds; now it becomes ‘armed’ and you can begin the flight. Each time you remove power from the drone (such as removing a deleted battery) and power it up again (with a fresh battery) you have to go through this process. As I have said in a previous chapter, I always put my laptop to sleep to conserve its battery while I was flying, so to perform the above I would also have to ‘wake up’ the laptop as a further stage each time I changed battery on the drone. This is a time-consuming exercise.

To avoid this, I installed a ‘pigtail’ out the back of the drone which was wired into the drone power supply. I could use this to connect an auxiliary battery. What this means is that when the main drone battery was depleted, I could connect the auxiliary battery (on the ground), disconnect the depleted main battery, remove it from the drone, install and connect a fresh main battery, and then remove the auxiliary battery. This meant that the drone stayed ‘alive’ the during the entire battery-changing process.

I took this one step further and used the pigtail as a battery-monitoring system. The batteries I was using are fully charged at 16,8 Volts, and the safe discharge is 14,8 Volts. Although I could watch this on the video monitor as an on-screen overlay, as well as having the audible on-board battery warning, I wanted to know easily if I needed a new battery before the next auto mission. I could connect a small voltage meter to this pigtail before every flight. I knew from when the previous flight began what the battery charge was, and now I knew what it was after the flight, so I could work out the consumption during the flight. I have had so many low-battery issues (including crashes) that it became something uppermost in my mind. This was just another check; and generally as a matter of principle I would not begin a flight with a used battery unless the meter was reading above 15,6 Volts. It was just too risky when the drone was far away.

Battery management is crucial. You need to know the state of your batteries, and as I have said previously, I would do many checks at home before I left on a trip. Each battery is numbered so that you can have an idea of its history. In addition, when you have charged a battery, I put an elastic band around it to indicate its charged status, as shown in Illustration 6.5, above. When it is depleted, this elastic band is removed until it is charged again. Lipo batteries are sensitive to all kinds of environmental issues, and they have to be treated with care. They can easily burst into flames not only if they are damaged, but even during the charging process; so charging is carried out with the battery inside a fireproof bag. The first law of charging Lipos is you that never leave them unattended whilst charging; they are volatile. This also meant that I had to be very careful transporting them in a backpack over bumpy terrain. The 12 batteries are housed in a plastic container with bubble wrap separating the layers, as shown in Illustration 6.131, alongside. This is a heavy box to lug around the mountains!

**<u>Illustration 6.131:</u> 12 LiPo batteries in box for transport**

## 6.13 <u>Packing</u>

There is a lot of equipment to pack and carry. Some of it I have outlined in a previous chapter, such as the food, drinks and safety essentials. All the equipment requires two backpacks. It should be noted that the off-road motorcycles we use to access the flying area are not designed to have equipment strapped to them. Neither is it desirable because when riding through difficult terrain it is better to have the bike as light as possible; far better to carry extra equipment on your body.

**<u>Illustration 6.132:</u> Drone stowed in backpack**

The main backpack is a very well-padded video-camera operator’s backpack which has a large main compartment with various side

**<u>Illustration 6.133:</u> Main compartment packing**

compartments and pockets. The drone fits in the main compartment, as shown in Illustration 6.132, above. Above it is a grey box which houses the Radio Controller and in this a small box (with a green lid) of spares as shown in Illustrations 6.133, above, and 6.134, alongside. The spares box holds the telemetry link, the voltage meter, some small tools for changing props and legs, and a variety of nuts and bolts that I might need, as shown in Illustration 6.135, alongside. The two way telemetry radio is attached to a large peg, and once in the flying zone it is plugged into the laptop via USB and then simply clipped on to the laptop screen, as shown in Illustration 6.136, below. The long green box in Illustration 6.133, above, is an old welding electrode box which I repurposed for carrying larger spares. In it are a spare leg, spare arm, and a few spare props as shown in Illustration 6.137, below. From experience I had learnt that these were the most ‘consumable’ large spares I would need.

**Illustration 6.134:** **Radio Controller and small spares box**

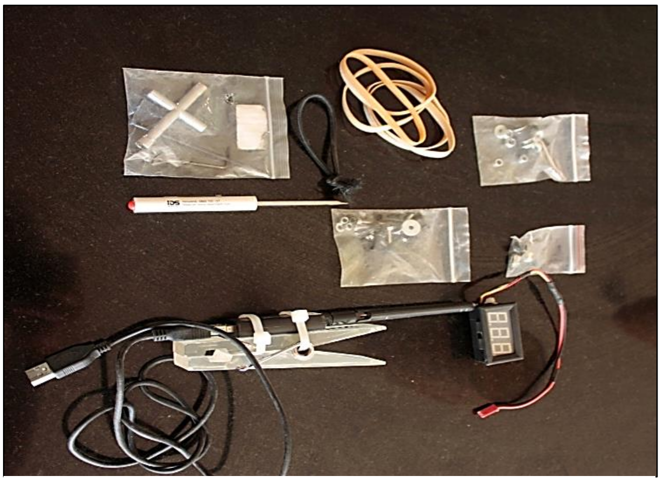


**Illustration 6.135:** **Small spares**


**Illustration 6.137:** **Large spares**

**Illustration 6.136:** **Telemetry Radio attached to laptop**

The laptop travels in its own compartment at the back of the bag, where it is well protected in case of a fall while riding, as shown in Illustration 6.137, alongside. The pseudo drone boom and tarpaulin shade system travel on the outside of the bag as shown in Illustration 6.138, below. Note how the boom is installed face down. This is because it has a 'sharp' end and a 'blunt' end. The 'sharp' end is packed downwards into the compartment, so that in the event of crashing the bike it doesn't impale me. The side pockets of the backpack contain various small items such as the pseudo drone and a box with spare GoPro camera and accessories including camera batteries, spare recording card and lens-cleaning cloth.

**Illustration 6.137:** **Laptop stowage**

**Illustration 6.138:** **Boom and Tarpaulin packing**

The other backpack contains the batteries and the video monitoring system. Distributed between the two backpacks are the clothing, food and drink mentioned earlier. Around my waist I wear a belt bag with motorcycle spares and tools.

## 6.14 Pseudo Drone

As I have stated in a previous chapter, the term 'pseudo drone' isn't one that you will find in typical UAS literature; it is a term I invented for my particular needs and the system I developed. The Oxford English Dictionary defines the term 'Pseudo' as 'Supposed or purporting to be but not really so; false; not genuine'. In other words, I have developed a drone which thinks it is a drone insofar as it thinks it is flying, but it isn't.

Firstly, though, the question must be asked, ‘Why the need for a pseudo drone?’

The Arducopter software has this very valuable ability of being able to set waypoints whilst in flight. As noted previously you can designate a channel on the radio controller to ‘Set Waypoint’; while the drone is flying you can flick a switch on the controller and the drone will remember where it was (Latitude, Longitude and Altitude), and then you can download that waypoint (or succession of waypoints) into Mission Planner and use the settings to compile an autonomous mission.

There are several important factors here, the most important being that the drone must be in flight. The second is that the waypoints must be collected from a single flight. If the drone lands anywhere along the way, and then takes off again and records new waypoints, it will only remember the waypoints from the last time it launched. This is not a shortcoming of the software; it is just the way it has been developed. The coders did not feel there was a need to record more than one set of waypoints at a time.

This then leads to the next question– ‘What constitutes a flight?’. The drone software goes through various stages of initialising, arming, launching, flying, and then landing, and disarming. When you power the drone up (on the ground) by connecting a fresh battery, it goes through a stage of ‘health checks’ to make sure everything is in order (from a software perspective). It then gives a signal than the drone is ‘safe’ (or if it finds something untoward it will report the fault and stay in its ‘unsafe’ mode until you have corrected the fault). At this point there is a ‘safety switch’ on the drone; you push this switch, and the drone is able to take the next step of preparation for flight. The HUD in Mission Planner is still showing as ‘Disarmed’. To arm the drone for flight you hold the throttle closed and all the way to the right for a few seconds. All this preparation is to make sure that both the drone and you as an operator are prepared to fly. When the drone is ‘Armed’ this message appears in the HUD, and the props start spinning slowly to indicate it is ready for flight. At this point if you raise the throttle, the props will spin faster, and if you raise the throttle enough the drone will take off. This is the beginning of ‘flight’, and from this point on you can start recording waypoints.

When the drone lands you have returned the throttle to zero because the drone is now on the ground. You Disarm the drone (to make it safe) by holding the throttle closed and moving it all the way to the left for a few seconds, and until the HUD indicates ‘Disarmed’. The ‘flight’ is between the arming and disarming points in the process. If you want to fly again, you must first arm the drone again. Importantly (for the purposes of this section) there is another safety built into the software. If you land the drone, and the throttle is now zero, and you don’t disarm the drone by holding the throttle all the way to the left, it will automatically disarm itself after the throttle is closed or at zero for a few seconds. This has implications for me as I will explain soon, but it has merit from a safety perspective and the coders of the software are correct in implementing it. If it did not disarm itself automatically after a few seconds, and you forgot manually to disarm the drone ‘in the heat of the moment’, you might be working on the drone after a flight, it remains armed, you (or someone else) inadvertently bumps the throttle, and the drone takes off with you bent over it. This automatic disarming is a very important safety feature.

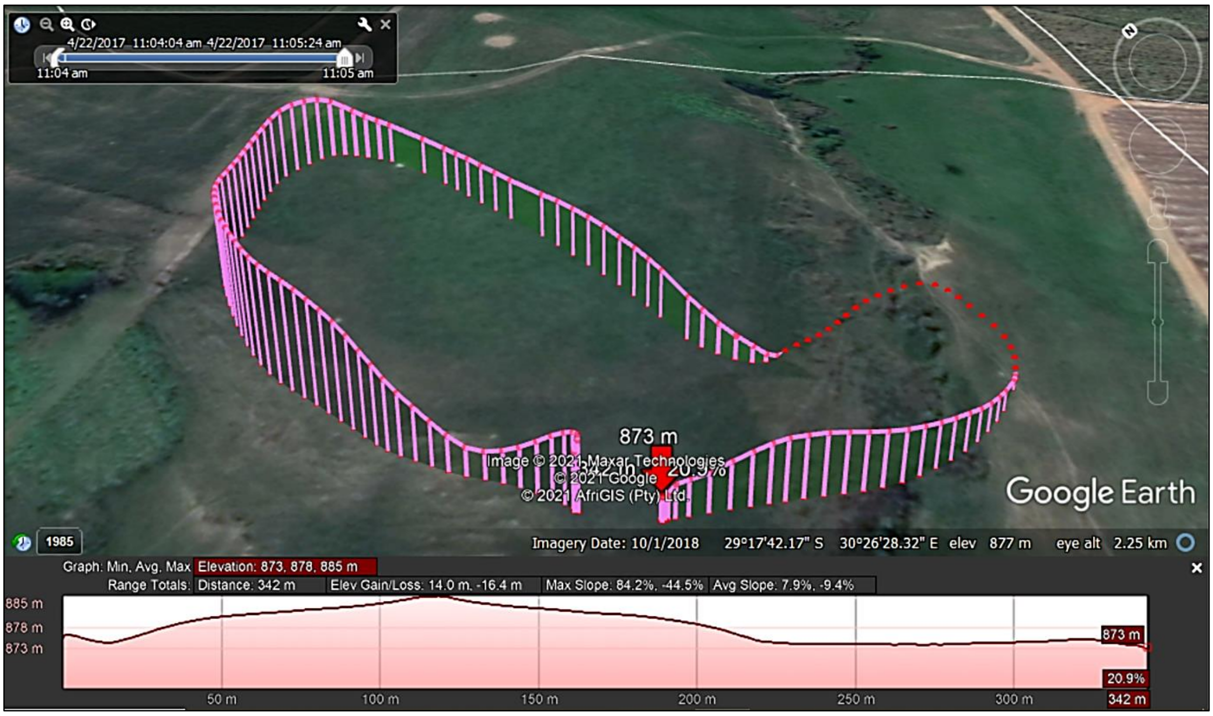
If I want to map the course, I need to gather waypoints accurately. This can become an issue if the drone is quite far away from me. On occasion I have set up on the other side of a ravine or valley from where the drone will first intercept the racers. In other words, my ‘home’ location is far away from the beginning of the video-recording. I will typically set the first waypoint very close to home, but the second one might be on the other side of the ravine. From there I will record a succession of waypoints along the route the racers take, until the point at which I no longer wish to record them. I will then set one or two more waypoints for the ‘return leg’ of the drone’s journey, with the last being just above or close to the home point again. The problem is I cannot accurately, from a far distance away, see exactly where the drone is in relation to the course or where the riders will be. I need to be on the course itself, with the drone close to me, to set the waypoints accurately.

Why not then just walk the course, with the drone flying just above me, and record waypoints? There are two interrelated reasons. The first is battery consumption, and the second is the Arducopter definition of ‘a flight’. Consider how this process might play out. I put the drone in the air at the home point and record a waypoint. The next waypoint is across the ravine. I have to walk up the side of the ravine, cross over near the top somewhere, and walk down the other side until I reach the point where I want to record waypoint two. This could take quite some time out in the bush; and all the time the drone has to be flying. Not only is it consuming valuable battery power, but the battery on the drone might actually become depleted during this time (the batteries last between 5 and 8 minutes of flying). If the battery is depleted, I need to change it, which means landing the drone; and this results in the 'end of the flight' according to the software. All of which means that this system will not work.

Another alternative which we tried a few times (I say 'we' because I need an assistant) was to try and conserve batteries by having the throttle just above zero. In other words, the motors are spinning but the drone doesn't have enough power to take off. What my assistant did was physically hold the drone while he walked along the course and I recorded the waypoints. This however has one serious implication; the assistant cannot hold a drone with spinning props, so you have to take the props off first. This in turn has two further ramifications. The first is the motors need the prop downwash of air to cool them for without props they quickly overheat and burn out, even at low throttle settings. The second problem is you need to remove the props to do the mapping, and then put them on afterwards for flight. Not only does this take a fair amount of time (with eight props, all of them with different orientations and some of them underneath the drone so that the task is further complicated), but it also runs counter to my design imperative of having everything stay attached to the drone for transport and the unfolding and folding process. Although this method of walking the course holding a drone which thinks it is flying gave far more accurate waypoints, it just was not feasible. In fact, even with the throttle barely above zero and the motors just spinning we only got about 20 minutes of 'flight time'; and in some cases this still was not enough to walk all the way from 'home' out onto the course, along the course, and then back home again.

So, why not just use Google Earth for the mapping process? This might seem an obvious way to map the course, but there are two problems which arise. The first, as I mentioned in a previous chapter, is that not all the races are 'GPS' races. Sometimes the riders don't follow a GPS on their bike to follow the course; instead the course is marked with dayglow fluorescent 'stickers'. While I might know the general vicinity in which I wish to work (and would have prefetched the tiles of the area in Mission Planner), until I get out into the region I don't know exactly where the racers will be going. I need to walk the course mapping it following the dayglow stickers.

The next problem isn't immediately obvious, but it has significant implications. The issue is the accuracy of the Google Earth data, particularly its indicated altitudes which, on a small scale at least, are not very accurate. I return you to an image I used in a previous chapter, which is the logs downloaded after a flight covering a race in New Hanover and shown in Illustration 6.138, below. You will notice a series of 'dots' showing the flight on the right-hand side of the image. It seems that the drone has flown 'underground'; it has no altitude whatsoever. This is not the case: it would either have crashed into the ground (which obviously isn't the case because it starts 'flying' again and gains altitude and returns to home) or the data isn't accurate. The latter is the answer. The flight data is superimposed over the Google Earth terrain, and the terrain data isn't accurate or reliable. On a macro-scale Google Earth gives quite good altitudes, say for example if you wanted to measure the heights between the peaks of two adjacent mountains. On a micro scale however, it doesn't give good accuracy, it doesn't show small undulations in the terrain. Google Earth tends to 'smooth out' altitudes over small distances, the kind of distances I am working with. In the example above it has not accurately portrayed the small valley in the right-hand side of the picture, it has




**<u>Illustration 6.138:</u> Flight data superimposed over Google Earth imagery**

averaged out the difference between the ‘high’ of the hill on the left-hand side and the ‘low’ of the valley on the right-hand side. Google Earth’s supplied altitudes are higher than the actual depth of the small valley. Now, with my drone flying close to the ground in the region of the valley its true altitude is higher than the Google Earth data, and it seems to be flying underground. In actual fact if you watch the video of this flight you will see that the drone is flying much closer to the ground along the hill on the left-hand side of the Illustration as well than is shown by the image where it seems to be quite high in this section. This is because Google Earth has ‘lowered’ the height of the side of the hill as it ‘smooths out’ the terrain between hill and valley. Which is not to quash the value of Google Earth; it is an invaluable tool in many ways, but in this scenario it has its limitations.

Why not use more accurate Geographic Information Systems (GIS) software, which very accurately portrays latitude, longitude and altitude? There are two reasons for not doing so. The first is that this data does not exist for all remote regions; it is primarily used for town planning and surveying purposes. The second is that the annual subscriptions are very expensive, and are not available to everyone. For reasons of privacy, only registered land surveyors, town planners, building-code inspectors, municipalities and the like can register to use it. So, this also is not an option for me.

Another possibility would be to map the course with a GPS device. My personal Garmin Etrex 30 has a barometric altimeter built into it, and so can collect altitude data accurately. The problem becomes one of connectivity, accuracy, and correlation between devices and software. To import a track into Mission Planner it needs to be displayed on Google Earth or some similar resource. I would need to generate the data on the handheld device, convert this .gpx format into .kml format for Google Earth, display it on Google Earth, and then import it into Mission Planner. Now, I have only prefetched the tiles for Mission Planner; there is no way of prefetching for Google Earth; I need an internet connection, and this doesn’t exist in the mountains. Also, I would need an accurate synchronism between the hand-held GPS and Mission Planner, hoping that what is recorded is transferred across devices accurately. I reasoned that this process, though in some cases feasible (I could sometimes, for example, create a ‘hot spot’ using cellphone data),might not be practicable.

What I needed was something that would produce accurate altitude data because it had a barometric altimeter built into it; could interface directly with Mission Planner; a device which was 'flying' but did not consume large amounts of battery power; and which wouldn't require a great deal of time assembling and dissembling, for example for removing and replacing props. What I needed was a 'Pseudo Drone'.

**Illustration 6.139: The Pseudo Drone**

The pseudo drone I developed is shown in Illustration 6.139, above, and looks like a plastic lunchbox. Inside are all of the components of a drone, sans motors and props. The innards are shown in Illustrations 6.140 and 6.141, below. Across two levels of aluminium plate I have housed:

- A small battery, but big enough to power the pseudo drone for several hours because there are no motors involved.
- A power supply.
- A receiver for my radio controller.
- A telemetry system for transferring data to and from the laptop, including the antenna; the same system employed on the other drones which interface with the laptop.
- A 'Pixhawk Mini' flight computer, a more compact but less powerful version of the Pixhawk which I used as the flight computer on the other drones. It has less storage capacity,

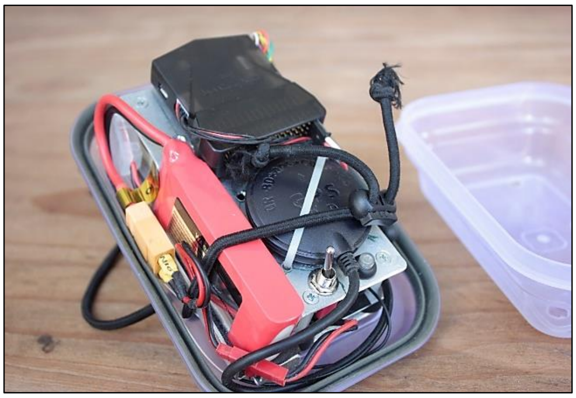


**Illustration 6.140: Pseudo Drone inside 1**

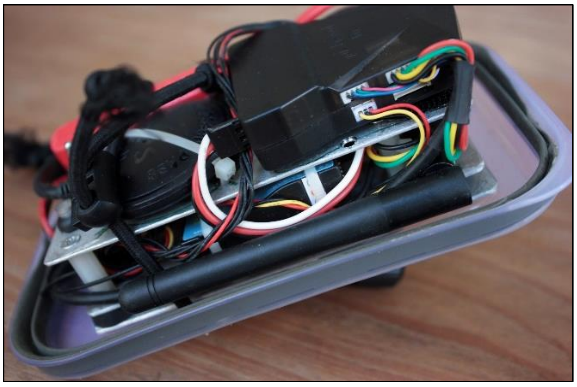


**Illustration 6.141: Pseudo Drone inside 2**

lower processing speeds, and not able to support all the peripherals as can the full-size Pixhawks (such as second GPS puck) but is still perfectly capable of doing what is required in this configuration.

- A GNSS (GPS) antenna puck.
- Various switches for power, safety, etc.

The top cover is drilled at strategic locations to allow me access to the power switch and safety switch without removing the cover. It has extra holes drilled in the top cover to allow equalization of air pressure between inside and outside, since the barometric altimeter reads air pressure to determine altitude (you will notice this on the housing of the flight computers on the drones themselves in previous illustrations). On the bottom side of the plastic housing is an attachment for a retractable sound-recording boom, such as would typically allow a microphone to be attached to the boom. Importantly, this attachment can swivel and lock into position. This attachment and ability to swivel is shown in Illustrations 6.142, above. The boom itself compresses down to a convenient size for transport, as shown in Illustration 6.143, alongside, but then can telescope out to a length of approximately 3.3 metres as shown in Illustration 6.144, also alongside.

**<u>Illustration 6.142:</u> Swivelling attachment**

**<u>Illustration 6.143</u>: Boom compressed**

**<u>Illustration 6.144:</u> Boom extended**

Arriving on site I would assemble the pseudo drone, switch it on, and leave it to gather satellite signals and initialise while lying on the ground, with the end swivelled so that the pseudo drone was horizontal. Then I would connect it via the telemetry to Mission Planner on the laptop. The ‘flight’ mode of the pseudo drone is ‘Stabilise’. Once I was happy with the connection, the number of satellites gathered and the HDOP reading, I would push the safety switch on the pseudo drone. Now it was ready to be armed and prepared for ‘flight’.

However, a very important stage must now be undertaken, and the need for it is based on what will happen while the pseudo drone is ‘flying’. I am (potentially) going to be walking through bush, up and down hills, clambering over rocks, looking out for snakes in the grass (I once almost trod on a puff adder sunning itself in a firebreak!) and such like. I am carrying the pseudo drone, the radio controller, and a handheld GPS, the map of which I am following. All of which means that sometimes untoward things happen, and one of these could disrupt the entire process. The pseudo drone must at all times think it is flying, because if it lands it disarms itself and all the prior waypoints I have gathered will be lost when I enter the next one. Why would I ‘land’ it in the middle of the process? It could (and has, early on) happened inadvertently; as I clamber through the bush I knock the throttle on the radio-controller down, the drone senses zero throttle, thinks it has landed, and disarms itself; only for me to discover this as I get to the next waypoint. So, a very untechnical solution to the problem. I keep an elastic band attached permanently to the radio controller, as shown in Illustration 6.145, above. Once I launch the pseudo drone, I take the throttle to 100%, and then hook the elastic band around it, as shown in Illustration 6.146, above. This prevents bumping the throttle during my walk through the bush mapping my course, and thus the pseudo drone remains ‘flying’ the entire time.

**<u>Illustration 6.145:</u> Elastic band permanently attached to radio controller.**

**<u>Illustration 6.146:</u> Elastic holds throttle open**

The pseudo drone can be used directly above the track (or slightly off to the side) by placing it in a horizontal position and the boom vertical as you record a waypoint, as shown in Illustration 6.147, below. Or it can be used by swivelling the pseudo drone on the boom and placing the boom in a horizontal position as shown in Illustration 6.148, below. This position is very useful if the racers are riding along the edge of a ravine. If you want to capture a shot of them that is level with them, you 'hang' the pseudo drone out over the ravine.

**<u>Illustration 6.148:</u> Horizontal mapping**

**<u>Illustration 6.147:</u> Vertical mapping**

Once I had finished the mapping, I would return to the home position, remove the elastic band, return the throttle to zero and 'land' the pseudo drone. Then I would connect to the laptop via telemetry, download the waypoints and save them in a file. Now I could modify them, and upload to the real drone for flight.

Occasionally in the early days of using the system I would return to the base, connect the pseudo drone to the laptop, and find multiple Vibration, IMU, EKF and Gyro errors; so bad in fact that the pseudo drone had 'locked up' and defaulted to a 'safe' mode; and thus not recorded any waypoints. Note that I could not realise this had happened whilst I was mapping, because I had no way of knowing until I returned to the laptop which had been left at the home location (in sleep mode to save battery). I eventually discovered it was my own fault, and it was something I was unconsciously doing.

To understand why, we need to understand the drone and its software. The pseudo drone is at full throttle (with the elastic band on the radio-controller engaged). It is expecting to be gaining altitude, but its on-board sensors are indicating otherwise. This isn't really a problem, but it has been exacerbated by the way I was carrying the boom through the bush. I would just hoist it over my shoulder between waypoints, much as you would carry a fishing rod down to the beach. But in doing so the pseudo drone – which thinks it is flying and wants to maintain a horizontal attitude – is sitting in a vertical position at the end of the boom by me carrying it this way. It could be in three different vertical attitudes, pointing down, pointing up, or pointing sideways, depending, – quite by chance – on how I had hoisted the boom over my shoulder. The drone could think that it is diving headfirst into the ground (at full throttle!) and is trying to correct this but none of its on-board sensors are giving the feedback it is expecting. Or it could think that it is gaining height at full speed, not in a horizontal attitude but once again vertically, and that it is trying to correct but none of the on-board sensors are making sense. Or it could think that it is flying at full speed, across the ground but yet again in a vertical orientation, and trying to correct. The inertial navigation system was trying to process so much information, none of which made sense to it, so it just 'locked up' and went into safe mode.

The other problem with carrying the pseudo drone like this was the 'whiplash' effect that it was undergoing at the end of the long boom over my shoulder. As I clambered along rough footpaths or through the bush, the pseudo drone was bouncing at the end of the boom. This generated massive IMU and vibration readings into the software, and also caused it to shut down because these were outside of its safe operating parameters.

All I had to do to negate these problems was to modify my style of walking and carrying the pseudo drone. I made sure I would walk with the boom as vertical as possible, and not bump it along the way too much. What also helped was when I got to a place I wanted to record a waypoint I would hold the boom steady for a few seconds, to allow the gyros and IMU's to settle down, before I recorded the waypoint. Once I engaged these protocols, I never had problems again. I am reminded about what McNiff and Whitehead say about action research: that you should think about what you are doing while you carry out the action and reflect on what you are learning. You learn not only from the result of your actions, but also throughout the action (2006: 99).

The use of the pseudo drone helped greatly with my initial mapping of the course. It was quick, straightforward, interfaced directly with Mission Planner, and did not use up the drone batteries. It was one of the best ‘inventions’ of all my experimenting.

I have included multiple diagrams and photographs in my writings so that the reader can better understand and visualize the various drones and allied equipment without physically holding them or seeing them fly in person. I present the drones as the artefact (together with the accompanying video) of this practice-based research.

Mäkelä (2007: 159) explains that the production of creative artefacts are the manifestation of the issues, concerns and interests which have been explored, and that ‘…the creative product is as important as any knowledge embodied in it.’ As such they exhibit the solution-focused thinking of the designer. This is echoed by Candy (2006: 9) who notes that ‘…the written text describes the innovation in the artefact, but it cannot be fully understood without reference to and observation of the artefact.’

# CHAPTER 7

## The Flights: Tracking and Filming the Racers

### 7.1 Test flights

The process of setting up the first X8 I built was much the same as I described for the earlier drones I built, and initially happened in the front garden, but then subsequently once I was satisfied with its performance, at other local open areas. There is not much to describe: it is time-consuming and tedious particularly when you have no data to start off with. One of the flights has significance, though. I was very interested to test the ‘motor redundancy’ abilities of the X8 configuration. To this end (after satisfying myself of the flight capabilities of the rig) I disconnected the drive signals to the ESC’s for motors 5 to 8. This meant that only motors 1 to 4 would receive any power. It was an important test, a ‘worst case scenario’; could the drone lift off and hover with only half of the motors and props providing any thrust. If so, it meant that it could probably remain in flight if it lost any one of the eight motors.

The test was in the front garden, and was a success. I managed to get the drone off the ground with only four props providing thrust. It needed almost the full throttle to get it to ascend, and it would only hover at about 80% throttle (as compared to around 45% with all eight motors powered). The inputs, particularly the throttle input, were very ‘sluggish’, and it did not have the response it normally would. Landing was also difficult, a small throttle change would lead to a big change in descent. This was more than likely due to me having developed the motor skills for all eight motors running, and the actual landing was quite harsh. Nonetheless the important design goal had been achieved, the craft could hover (and thus theoretically get back to me) with only half of the motors engaged. As I will describe later (when I actually had the problem occur in the field) there were limitations to how well it could respond, but in the mean time I was satisfied.

After much testing in the ‘manual’ flight modes of Stabilize, Altitude Hold and Loiter, it was time to attempt my very first Autonomous flight.

What follows is text supported by pictures and a video of the various flights, which is hyperlinked at the end of this chapter. The pictures included are frame grabs taken from the video, without any cropping; in other words, they are exactly as they were recorded by the camera. Further illustrations are taken from the flight data to show the terrain, flight path/s and area. Although I have included all the autonomous flights I have concentrated on the times I was at actual race events. I should add that I have done the best I could with the record I have available at the time of writing; this is because at one stage I had a corrupted SD card from which I could not recover data, but more importantly (as I have written,) I lost two laptops with recordings on them during a home invasion in 2017. This was, and remains, a significant setback; but I have tried to compensate as best possible. The reader will notice that some of the freeze-frame images and video are of poor quality; this is due to me no longer having the original source footage because of the aforementioned burglary. Instead I had to rely on edited footage which I had uploaded to YouTube after each event for the organisers and racers to view; and when I downloaded this again for the purposes of this thesis, it was of poor quality. Thankfully, at least, I had uploaded it and had some form of record.

I also ask that readers only view the video once they have completed the reading of this chapter, so that there is context to what is being watched. In each subsection below, I have given a time reference for where this particular event is portrayed in the video.

What is also noticeable in the video is that sometimes I was operating out of my minivan rather than using motorcycles to access the flying areas. Typically, whenever I had someone to assist me who could ride (not only to carry equipment but also from a safety perspective because I would rather not ride on my own in a remote area) we would use the bikes; but whenever I was working on my own I used the van. On one occasion, I took the bike and equipment on my own, but it required two trips to get everything transported. However, I feel that I have used the motorcycles on enough occasions to prove that the concept of packing everything for a day’s shooting into backpacks is viable.

## 7.2 ‘Champagne’ 5 & 7 September 2015

The first autonomous flights were undertaken on the Westville Boys’ High School (WBHS) upper and lower sports fields. The first, undertaken late in the afternoon of the 5th, was a truly momentous occasion for me. Having said that, I approached it with a great deal of trepidation, considering that I had never attempted an autonomous flight before. I have to thank my son Sam for assisting me; not only for providing moral support but (unknown to him) I also rationalised I might need someone taller and fitter than me to chase down the drone if it decided to head over the horizon!

I flew the drone in Stabilize mode a few metres above the ground in a semi-circle away from us, and along the way I would ‘loiter’ it to collect four manual waypoints using the Channel 8 function. I then uploaded these to Mission Planner, checked them, and downloaded them as an Auto Mission to the drone. I set a fairly low flight speed between waypoints. The moment of truth was upon us. Put the drone in the air in Stabilise, check, then Altitude Hold, check, then Loiter, check; all good, deep breath, switch to Auto.

Off it went. Although I had set a slow speed, it seemed too fast. Although I had set the first waypoint fairly close, it seemed too far. What to do? Bring it home? No, trust the system, and my building and testing.

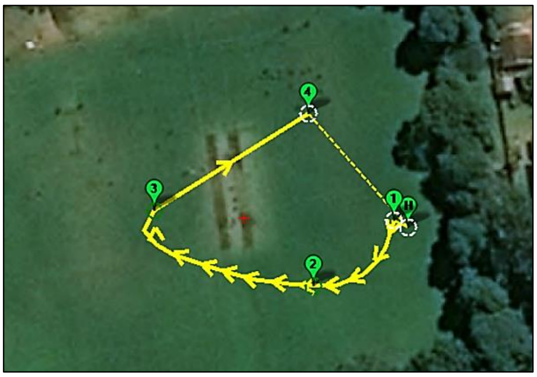
Then suddenly the drone turned right. It had reached the first waypoint and was heading for the second! It was working. Was It? Am I sure, it looks like it’s going too far? Then it turned right again and started coming back towards us. A robot, moving in three-dimensional space, which I had built and programmed, doing everything perfectly. Then it stopped, and sat mid-air looking at us. It’s gone into Loiter mode; exactly as planned. No time to celebrate yet, get it safely on the ground. More relief than joy, a mix of emotions, and a time to take a breath again.

It was late in the day, and very dark; but I have included Illustration 7.1, alongside, a frame grab from the camera recording. Sadly, due to my inexperience with the software I never recorded that Mission itself; instead automatically deleting it when I programmed the next one.

**<u>Illustration 7.1:</u> Frame grab from first autonomous flight, WBHS**

That next flight occurred a few days later, also at WBHS but this time on the lower sports field. A capture from the flight is shown in Illustration 7.2, below. A very similar auto-mission to the first, shown here in Illustration 7.3, below. A similar outcome; everything seems to be working as planned, and I am gaining confidence.

**<u>Illustration 7.2:</u> Frame Grab from second auto mission, WBHS**



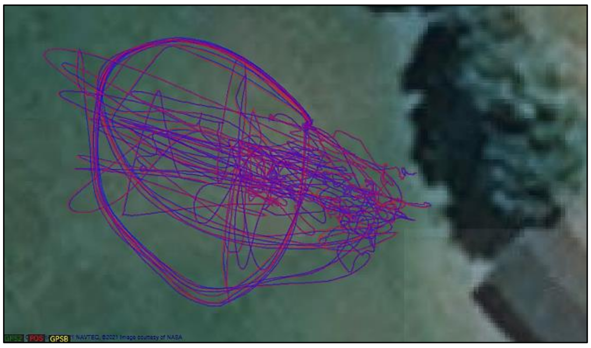
**<u>Illustration 7.3:</u> Second auto mission**

Further autonomous tests were carried out on my late father Albert ‘Toods’ Burnett’s farm, in the Champagne Castle area of the Drakensberg in KZN. The farm has a wide, flat area perfect for testing. Some of the images from these flights are shown in

**<u>Illustration 7.4:</u> Frame grab 1 from auto flight in Champagne Castle area**

Illustrations 7.4, above, and 7.5, below. More tests, to fine tune the drone, the gimbal, the various flight modes and me becoming more adept at the system, were flown at the Westville Athletics Club. A morning of testing is shown by the flight path tracks shown in Illustration 7.6, below. My confidence and abilities were improving; it was time to take the next step.

**<u>Illustration 7.5:</u> Frame grab 2 from auto flight in Champagne Castle area**



**<u>Illustration 7.6:</u> Flight paths from a morning's testing**

7.3 <u>'Rain. Dancing'</u> 6 October 2015

The next step was to be following a rider autonomously, whilst controlling the drone via the video link and monitor strapped to my head. Although I had tested the link, it had only been to try to develop the hand-eye coordination I would need. I had never actually followed a 'moving target'. I have to thank my son Scott for assisting me with the experiment. We would take a motorcycle up to the farm and follow a course I would create.

Although the grass was short in the paddock, I still wanted to cut it so that there was a definite track for Scott (riding the motorcycle) to follow so that it was consistent throughout the flights. We left Durban (with motorcycle and all the drone gear) early in the morning, and arrived at the farm at around 8 am. After a quick cup of tea (a ritual my father always insisted on and which I inherited), I fired up the tractor, hooked up the grass-cutter, and headed down to the paddock. I had the grass-cutter set to a very low level because the grass in the paddock was already quite short, and as fate would have it caught on a mound of compacted sand, stalled; and broke the prop shaft! Back up to the workshop, and I turned up a sleeve on the lathe which I then used to weld the prop shaft back together. By this time a few hours had been lost, but I returned to the paddock and proceeded to cut out a winding track to follow.

As I was finishing this it started to rain! It seemed like all our plans were not going to be (electronics and drone motors cannot operate when wet).

I decided to sit it out and see if the weather might lift. Much later in the afternoon the rain lessened to a drizzle; still too wet to fly in, but Scott and I got prepared in case we got a small window of it easing. Then the rain lifted a bit, and we set out to make the most of the opportunity. I set up the drone, and then marked some waypoints visually while I flew it manually across the paddock. I modified these waypoints after flying the drone autonomously around the flight plan. Now it was time to get a motorcyclist out there.

I had asked Scott to ride at a consistent, fairly slow pace, rather than 'as fast as he could'. I really just wanted to 'see if this all comes together'. I sent the drone out, and then Scott followed soon after on a signal from me relayed through my Dad.

Almost immediately my whole consciousness changed. Up until now, throughout all my testing, I had been concerned about the 'mechanics' of the drone and autonoumous flight. Even though I had attempted to follow Travis and Mark on their bikes with my old hexacopter (what seemed) eons ago, at that time my concentration was almost entirely on flying the drone (because it was still in the days of 'manual' flight in stabilise mode), and I was mainly concerned about bringing it home and not losing it. Now, suddenly, the drone transformed into a camera, and a camera alone. A floating, moving, flying camera. There was no thought whatsoever as to how the drone was performing, it was all about how I was framing the target. A moving target, one that was changing orientation, one that was at times moving in the same direction as the drone and at other times towards the drone, one which was moving left while the drone moved right, and vice versa. My entire focus was on manipulating the yaw control ('stick') to keep the bike in frame. Where the drone was, how high it was, how fast it was flying, what it's orientation was; all these parameters which had been uppermost and almost solely in my mind during testing now not only became secondary, but were completely forgotten. It was a complete change in my thought patterns.

Not only was it a change in my approach to the drone flight, but it was also something I had never seen before in all my years of watching, covering or teaching sports broadcasting. I had seen cameras moving on rails, 'Spidercams' moving on wires, helicopter shots; and a whole host of other innovations in sports coverage. I had worked as a camera-operator many times on sporting broadcasts. I had directed multi-camera productions. I had worked on local, national and international events both in South Africa and overseas. Some of these events, like the FIFA World Cups, had the biggest production budgets of any sports. I had been an avid enthusiast of enduro motorcycling coverage; both covering it for clients as well as a viewer. I had this vision in my head of what I wanted to get from the drone. But this was different.

This was a dance. A dance with the drone and the rider as partners moving independently, but connected by an invisible elastic which stretched and compressed, and I was both the choreographer of the dance as well as a participant.

My Master's dissertation was titled *Planning, Producing and Directing Television Outside Broadcasts*. In it I speak about the objectives of the television sports director. Before multi-camera television, a spectator who had 'the best seat in the house' had paid a premium price to sit in the centre of the 'grandstand'; so named because it offered the best overall view of the event (such as a rugby game) happening on the field in front of these privileged spectators. Then, with the advent of multi-camera sports coverage, the television director was able to position multiple cameras in a variety of positions around the field and 'cut' instantaneously between them. One of the main objectives of the director was to cut to a camera which provided the 'best seat in the house' for wherever the on-field action was taking place. So, during general play, this view might be positioned somewhere on a wide shot from a camera positioned in the centre of the grandstand, much like the high value spectator seat. However, should the on-field play go towards the side lines or corner – for example in rugby a try being scored in the corner of the field – the director could cut to a camera view located close to that corner. At that moment, the best seat in the house for a spectator is close to the action in the corner– even though the seats in the corner might typically be considered the 'cheap seats'. This is one massive advantage (amongst others such as slow-motion replays) of television over actually going to spectate at the game.

What I was trying to do with the drone following the rider was provide this 'best seat in the house', but without cutting between successive cameras and instead having one long-flowing continuous shot. In a futuristic vision it would be like a spectator strapped into a flying seat able to move with the riders as they traversed the terrain, a sort of 'magic carpet'-like ride and view.

Except, as with any dance, practice is needed. It was not easy to track the rider. Even though the course was preset, and Scott was riding at a 'casual' pace, there were differences as to where he was and where the drone was each time we did a lap. So the drone would be intersecting the course and the rider at different places, which meant that nothing was predictable; I had to make instant decisions and corrections continuously. Whereas on one lap he might be ahead of the drone, on a subsequent lap the drone might be ahead of him. I had also (in hindsight) made life a bit difficult for myself by having the motorcycle track double back on itself in some parts, so that at times he was riding left to right, the drone was flying right to left, and I was having to make quick and radical yawing corrections (I prefer to use the term 'panning' since I was treating the drone solely as a camera by this stage and that is the camera term for horizontal sideways movement).

**Illustration 7.7: Final Auto mission for 'Rain. Dancing'**

**Illustration 7.8: Frame grab 1 from 'Rain. Dancing'**

In addition, the yaw 'stick' doesn't respond the same as a camera on a tripod; I was over- or under-correcting (and thus losing the rider from frame) quite a bit. I have written about this in more detail in an earlier chapter with respect to the need for a 3-axis gimbal, and I also I tried in subsequent flight days to address this particular problem which I will refer to later in this chapter. A lot of the poor framing was, however, due to my inexperience. Then after about an hour, the rain came again, and we had to curtail our efforts.

**<u>Illustration 7.9:</u> Frame grab 2 from 'Rain. Dancing'**

**<u>Illustration 7.10:</u> Frame grab 3 from 'Rain. Dancing'**

At the time, in real time whilst flying, I knew that I had made quite a few errors in panning and thus losing the bike out of frame. I also thought that I had captured parts of the action pretty well, and I had one complete lap without any real errors. However, until I could download the footage at home I was not really convinced about that particular recording. Scott and I watched in eager anticipation at home, and there it was - a recording almost a minute long, from start of the lap to the end; framed quite well. It was an exhilarating moment. There were also other takes where I followed, over-corrected and lost the bike, then managed to correct and follow it again.

Overall the day was a success but it was just the first step; there was a long way to go. I had come to the realization, though, that my approach to this had undergone a fundamental change. No longer was it just about autonomous flight; now the 'aesthetic' would be the driving force and what I would need to concentrate on most.

Illustration 7.7, above, shows the final autonomous flight path (after several corrections) which I flew that day, whilst Illustrations 7.8 – 7.10, above, are some frame grabs from the video. A clip relating to this day's flying in the linked video starts at 00:14.

7.4 ‘Down to Earth’ 16 November 2015

Although I had only minimal experience of following riders at this stage there was an event coming up which I wanted to cover, the annual ‘Roof of Africa’ held in the Lesotho mountains; due to be raced over three days from 16 – 18 November 2015. I had gone to this event many times in the past, first as a competitor, then in later years as part of my photographic exhibition which I had completed the year before. I know the mountains and the conditions quite well, so felt confident enough to tackle this next episode. I have to thank my friend Richard Hamman for assisting me on this trip.

Lesotho trips always require considerable planning beforehand, and once there long days of physical endeavour. In the week before we left I had checked over the drone but I only received the course on which the race would be held two days before we were due to leave. Those nights leading up to our departure were taken up by scrutinizing the course to plan where I might want to shoot. I found that one of the areas I was interested in had very poor images from Google Earth in Mission Planner. Whilst researching this problem I found reference to it on the DIYDrones forum that it was perhaps a glitch in the version of Mission Planner that I was using, and it was suggested that I update to the latest version, which I did the night before we left. I had already loaded the van with all the bikes, drone gear, and other equipment we would need for the trip. This meant that I never actually connected the drone to this version of Mission Planner and checked that it was working.

It turned out that the initial problem I was having, that of poor imagery, was not a fault of the software but rather of Google Earth. Once I changed to different satellite imagery to Bing Maps I was able to see the terrain more clearly, and download all the tiles for the areas I hoped to fly and shoot in. By the time I had finished it was very late, and we were due to leave early the next morning.

Richard and I left Durban at around 4 am on the morning of the 15th, crossed the border at about 10am and arrived at our accommodation in Kotso around midday. I wanted to map the area we were due to fly in on the 16th beforehand, because I knew the riders would be on the course from very early and I did not want to be mapping when they were racing. We headed out to a region west of St Patrick's Mission, and got there around 2pm. The part I had chosen to work in was quite remote but it had a small track leading there and was thus accessible by my van, so we were able to drive all the way. It was a fairly and wide flat area which gave us enough room to operate without being on the racing line, but it also had a high ridge alongside this flat section.

When we got there I set everything up so that we could map. However, I could not connect the drone to the Mission Planner software. I tried every option I could think of, including trying to connect via both the radio telemetry as well as the USB cable. We eventually arrived at the conclusion that the 'updated' version of Mission Planner which I had downloaded the night before (and not fully tested) in an effort to overcome the Google Earth imagery problem was faulty. Such is the nature of using open-source sometimes. We decided that we needed to search online for a solution; but in the area we were in there was neither cell phone nor internet coverage.

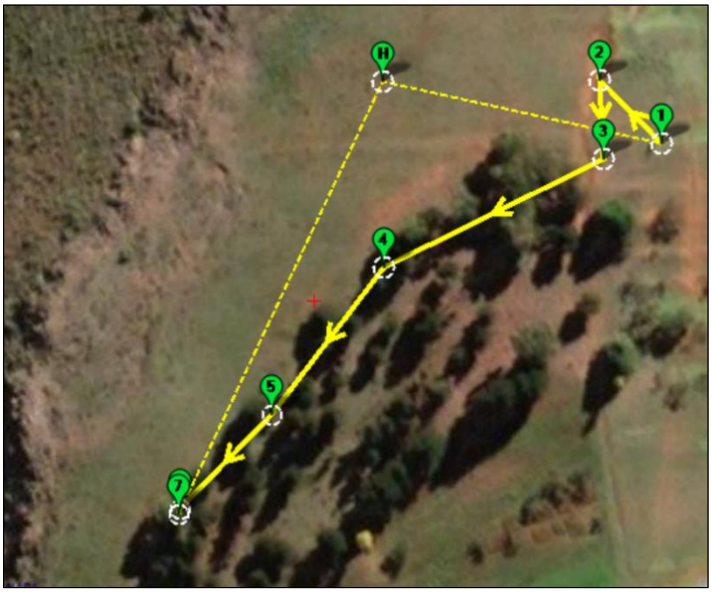
The closest town was Roma, about 45 minutes away. I knew that the National University of Lesotho was located there, so we packed everything up and headed to Roma. At the university the assistants at the reception office kindly agreed that, even though I was dirty and haggard from an all-day drive and working out in the bush, I truly was a visiting academic doing research and we could use their wifi. We did a search online and found that there actually was a glitch with that version of Mission Planner which had been identified; and not only identified but there was an update or 'patch' which we needed to download to overcome the problem. However, the bandwidth available to us at the university was so poor that it would have taken many hours to download this update. After asking a few students at the university what could be done, one of them informed us that there was an ‘internet café’ in town. We set off to find it.

This is not your typical internet café. It was a small one-roomed, corrugated-iron building in an informal settlement which only had pathways leading to it, no road. After a whole lot of walking down the wrong alleys with all our gear and trying to converse with locals in languages which both parties were not fluent in, we eventually found it. Yes, they had a connection, it was R3 for every 15 minutes. I promptly paid for a half an hour, and we set about downloading the patch. We launched Mission Planner, and it connected to the drone! By now we were the talk of the town with our drone and all our gear, and had drawn quite an audience to the internet café. By the time we had finished I think this is the most valuable commodity I have ever bought for R6!

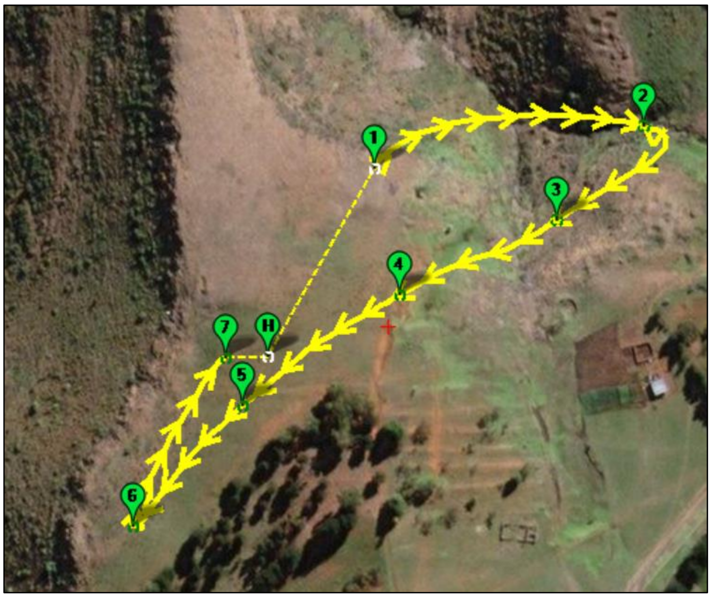
Back into the van, and another 45-minute drive back out to the St Patrick area. Opened Mission Planner, connected to the drone, and it loaded all the imagery tiles for the area. We were back on track and could begin the mapping process.

It was windy at the site, and this was compounded by the ridge which caused the wind to be very gusty and swirl a lot. Rather than risk flying the drone manually to map, we decided to remove the props and simulate flight by having the motors spinning while Richard held the drone aloft (this was before the days of the pseudo drone). There were quite a few trees which had been cut down alongside the path, and Richard stood on these stumps with the drone above his head to get an approximate altitude for the flights, and I captured seven waypoints this way. I would ‘drag’ these waypoints out towards the actual course later. Illustration 7.11, below, shows this initial mapping along the line of trees. By now it was late, we had had a long day, and we were losing sunlight; so we went back to our accommodation in Kotso and arrived there well after dark. Although it had been a very long and trying day, I felt confident that we were as prepared as we could be.

Early in the morning of the Thursday 16th we headed into Maseru to watch the official start of the race, an event known as 'Round the Houses'. At around 10am we left Maseru and headed back out to St Patricks, which we reached at about midday. I opened the map that we had captured from the previous day and modified it according to the racecourse, this final flight path is shown in Illustration 7.12, alongside. The wind was much stronger than the afternoon before, and extremely gusty blowing up and over the adjacent ridge (as can be seen from the way the trees are blowing in the video). Both Richard and I were quite nervous about flying in those conditions. I theorised that if the drone could hold its position in Loiter mode, then it would be fine to fly an auto-mission, so I put the drone into the air, and switched it into Loiter. I was surprised at how well it performed; I had never flown in such gusty conditions before. Although it would drift slightly, it always corrected itself, albeit with a fair amount of power and effort. We decided to risk an auto-flight.



**<u>Illustration 7.11:</u> Initial mapping for 'Down to Earth'**



**<u>Illustration 7.12:</u> Final auto flight path for 'Down to Earth'**

Check. Double check. Recheck. This was the first time I would be following actual racers, the conditions were far from ideal, and I wanted to make sure that I had done everything possible to avoid failure. I had 14 satellites and an HDOP slightly over 1.0 but decided that we would take a chance. Put it into the air and send it out on the mission while observing it to see what the flight path actually looked like. If you look closely at Illustration 7.12, above, you can see the steep ridge which is next to the flight path on the left-hand side, and which was causing the turbulent air from the wind. You will also notice a ravine between waypoints 1 and 2. The drone was disconcertingly dropping down into this ravine, and then flying back out on the other side during its mission. Before I did the second test run, I disabled the sonar which was causing it to 'hug' the terrain and drop down into this ravine. The drone was also traversing too close to the treeline, and I was worried that a gust of stronger wind might blow it into the trees.

I adjusted waypoints slightly and flew a second test flight; all seemed well. It was time to get the video gear rigged and start recording some riders who by this stage had already started coming through. The first flight I completely mistimed the riders coming through and lost them throughout the flight. (I had yet to teach myself the trick of heading out early, then Loitering at waypoint 2 until the rider appeared, then transition back into Auto once they came through.) The racers were also going much faster through this section of the course than the waypoint speed was set to, so I increased this slightly in Mission Planner and uploaded the new settings. Time for another test with the video, switch camera on, send it out, put video goggles on; let's get some pictures…

The drone passed through waypoint 1 and 2, I had a racer come into shot, thenstarted following the rider. (The drone was still going too slowly even with the new speed setting, it passed through waypoints 3, 4 and 5 when suddenly it dipped one corner drastically.) I was watching through the camera, which is gimballed to stay level, so for me to see a dramatic change in attitude means that the drone is undergoing an even greater change. At the same time Richard exclaimed 'Something flew off!'. While I was still watching through the video the drone lost height quickly and yawed around completely (it was still in Auto mode). I panicked, pulled the video goggles off, and it took me a short time to find just where the drone was. This all happened very quickly. Not knowing what had happened, but realising it was quite serious, I flipped the mode switch back into Stabilize, thinking I would bring the drone back manually. This was unfortunate, because had I just left it in Auto it would probably have partly recovered itself, but by going into Stabilize I now had manual control. I brought the pitch control stick down to bring the drone back towards me, not realising that the drone had yawed around 180 degrees; and by doing so I actually pushed it further away. This, together with the strong wind in the same direction, sent it hurtling off towards the tree line, but it crashed into the ground before it got there, and cartwheeled a few times before ending up upside down. I killed the motors and we rushed over. It was a mess, all the props were broken, and two arms bent. I did not know the state of any of the electronics or motors, but it was obvious we were not going to be doing any more flying that afternoon because it needed extensive repairs. Richard was convinced that he saw something fly off of it, but other than the missing prop parts everything else was still attached. I thought maybe a leaf or twig being blown about by the wind had got caught up in the props and been ejected at speed, and perhaps this had caused the crash. There was nothing else we could do, so we packed up for the day.

**Illustration 7.13:** **Frame grab 1 from 'Down to Earth'**

**Illustration 7.14:** **Frame grab 2 from 'Down to Earth'**

Illustration 7.13, above, shows a frame grab from the one flight I had captured, as well as a shot from the camera still recording after the crash in Illustration 7.14, above. On the attached video there is the single (poorly executed) flight at (01:13).

Before we went back to our accommodation in Kotso I wanted to check out how we would get to the next day's area I had planned to shoot, which was down near a small village called Tlali. I knew that we would need to use the bikes to access the spot, but I wanted to see how close we could get with the van. We drove along the little mountain track until we could take the van no further, and identified the footpath we would take with the bikes the next day. I arranged with some local folk in a kraal to look after the vehicle whilst we were away; and then headed back to Kotso. The long drive back gave us some time to reflect and plan how we were going to fix the drone.

## 7.5 ‘Rinse. Repeat’ 17 November 2015

Back at our accommodation I set about dismantling the drone so that I could check for damage; aside from the bent arms and broken props it seemed to have come out relatively unscathed, and I replaced those parts. We watched the video to see if we could decipher what had gone wrong. The craft definitely dipped drastically on the left-hand side and spun around, lost height; but then seemed to recover somewhat. I downloaded the log files in Mission Planner, and it showed a sudden increase in the Pulse Width Modulation (PWM) signal to the second and sixth motors. PWM signals are those which are sent from the flight computer to the ESC’s which drive the motors. The data also showed rapidly changing IMU signals at about the same time, followed by the Yaw angle changing and altitude decreasing. Our analysis pointed to a prop breaking or a motor stalling (either the second or sixth motors), which led to a loss of thrust on that corner of the vehicle, and a subsequent correction by the flight computer to send a higher thrust to this arm. Ultimately, however, the craft had enough height to recover itself with only one prop/motor operating on that arm; unfortunately, my ‘heat of the moment’ switching into manual flight control without understanding the predicament was what hastened it’s crash into the ground. We now knew what had happened, but why had it happened? Perhaps something in the wind had got caught up in a prop and caused it to break? What Richard had seen was probably a piece of broken propeller being flung off, because everything else (other than the subsequently broken prop pieces) was still attached to the craft.

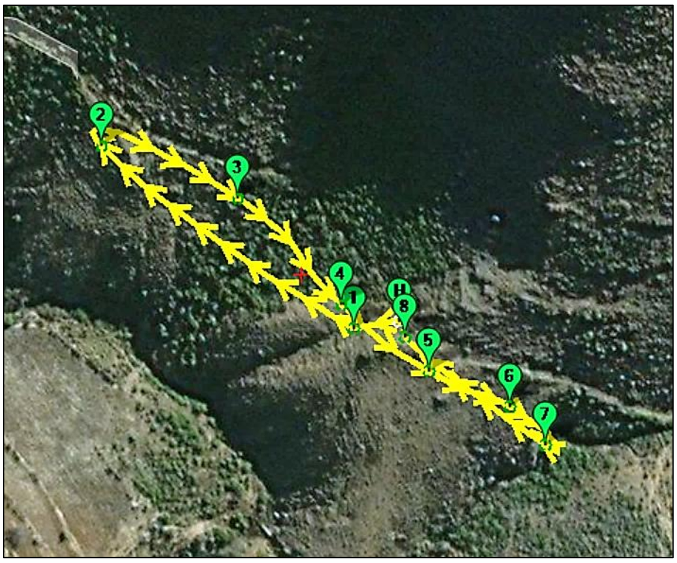
Whilst I was repairing the drone a massive thunderstorm started, quite typical for Lesotho at that time of year. It continued well into the night, so although I could do some checks indoors, I couldn’t actually fly the drone, and where we were staying had no outdoor area which was covered where I could actually put it in the air. Eventually the rain settled a bit. I wanted to check the drone in Loiter mode, at least. I powered it up, got relatively good satellite reception indoors, rushed outside, armed it, put it in the air, and set it into Loiter. It was quite a sight seeing the rain being spun off the props! The craft loitered fine, but I had it in that mode for no more than 15 seconds before I brought it back down, disarmed it, and rushed back inside. It was very wet. I was worried about the electronics and motors being compromised, so I dried if off as best I could with paper towels, and then tied it down to the toolbox inside the room. I started it up, and let it run on low power for a while. It seemed to have survived the rain, and the props spinning had hopefully dried out the inside of the motors.

It was late, we still had batteries to charge, kit to organise for the next day, and bikes to fuel and load. We finally got into bed at around midnight (it had been a long day!) with alarms set for 4am. We needed to make an early start, because it was a long haul through to Tlali, and I knew the riders would be getting to the area I had chosen quite early.


**<u>Illustration 7.15:</u> Setup for 'Rinse. Repeat'**

Thankfully the rain had stopped by the time we awoke, and whilst we were driving, the dawn of 17 November broke to what promised to be a clear day. Our hopes were up. We eventually made it to the kraal we had visited the day before, unloaded the bikes and gear, and rode down the footpath we had previously identified. It was about a 40-minute ride before the GPS showed we were in the region of the racing course, and we headed up a mountain to intersect it. Once we were on the course we were relieved to see that we had got there before the first racers had arrived. The course traversed along the side of a ridge at this stage; it was quite difficult to find a spot we could set up and work from which was level but also not on the racing line. There was no ideal spot to take off from or land in, but we did the best we could.

I mapped the course with Richard walking along the ridge line above the course, holding the drone above his head with props off and motors spinning as if in flight. I then dragged these waypoints out away from the ridgeline but parallel to the course. It was time for a test flight, which I did. This was the first auto-flight since our travails of the day before, and I was anxious, but the drone performed well. I did a few more subtle alterations to the waypoints and sent it off again. It covered the course and came back to us as expected. I switched into Stabilize for the landing and brought it down to the only place possible to land, which was quite a cramped sloping area between us and the course. I was having to be careful. And then it happened, no more than half a metre off the ground and about 2 metres away from where we were. A piece of a prop flew off. We both clearly saw it this time, and it was unmistakable what had happened because it went whizzing past us. Unfortunately, this time the drone was close to the ground, and there was not enough time to react to the loss of thrust on that arm; the arm dipped, the drone hit the ground, flipped over, and broke several other props on impact.




**<u>Illustration 7.16:</u> Auto flight path for 'Rinse. Repeat'**

We looked at each other with the same realization. Nothing we could have done would have prevented the situation; there was an obvious problem with the props. Although I still had enough spares, I was not going to risk any more flying until I had identified what the issue was. We packed up and after watching the racers arriving through, headed back to Kotso. Sadly, whilst watching the riders, I thought about 'what might have been'. It was a really nice section to film and could have led to some excellent visuals. Illustration 7.16, above, shows the waypoints for the two test, and gives some indication of the terrain. There are no frame grabs from video because I had yet to do a flight with the video system engaged, but Illustration 7.15, above, is a view of the setup that day, with me programming the drone beforehand.

The long trip back to Durban was sobering. We had covered almost 2000 kilometres through long hours of driving and hard work, and we had virtually nothing recorded to show for it. I wondered what had gone wrong. Had I overtightened the props when screwing them on to the motors? Or were they too loose? The assumption from the first crash was that perhaps a twig or leaf had been blown into the props by the wind. But this was obviously not the case in the second mishap, because the drone was so close to us that we both had a clear view of it when the second crash occurred.

I suspected that there was a problem with the particular batch of props I was using. I had used this particular brand (a reputable one) previously on the test flights and with Scott on the farm, but I had ordered, received and installed new ones before the Lesotho trip. When I got home, I compared the packaging of this new batch to images online (I did not have any packaging from the earlier ones). There were subtle but obvious differences in the fonts and the colour of the wording. I came to the conclusion that I had been supplied inferior clones of the real product by the vendor I bought them from (who I had used for many different parts of the drone leading up to this incident and never had a problem with the quality of the components they had supplied). The breakages were through no fault of my own. I contacted the vendor and they offered to replace them if I sent the balance of my order and the broken ones back to them, but the courier fees back to them just made the exercise unfeasible (there was also the fact that some of the broken blades were scattered among the Lesotho countryside because although we looked for them, we couldn't find them). The remainder of the props I had with me at home were consigned to the trash bin. I decided to not compromise on props in the future. From now on I would only use higher quality carbon-fibre props. In a roundabout way I did not want totally indestructible propellers, because if I had had a crash and the props hadn't broken the result could have been this force being transmitted to the motor bending the shaft.

There were a few positives to take away from the trip. Not only had the drone performed admirably in the very strong and gusty winds of the first day, but it had also coped with the high altitudes and thin air of the Lesotho mountains.  It had recovered from the first breakage whilst in Auto-mode (and it was probably largely my fault that it had crashed). I was getting better at the auto-missions and mapping. We had managed to get everything done using the bikes to carry all the equipment for the first time. And we had overcome some pretty difficult situations whilst on the trip. I must also commend Richard for his patience, perseverance and support that he gave throughout what was a very trying time.

7.6 ‘Once a Racer…’ 1 May 2016

After the disappointment of Lesotho, it was time to put in more practice on my father’s farm. I had completely rebuilt the drone and waited for the new carbon fibre props to arrive. I had made several test flights in the garden and on the local sports fields and was happy that the drone was performing properly. The first time I tested it following motorcyclists again was with my good friend Victor (‘Vic’) Greyling.

**Illustration 7.17:** **Frame grab 1 from ‘Once a Racer…’**

Vic and I have been racing together since the early 1980s and this extended up until about 2009. To this day we are still riding partners and enjoy many social rides together. Vic is a very enthusiastic and accomplished enduro rider and has a distinguished racing career over many years. During a weekend trip, where we rode in the foothills of the Drakensberg, I asked him to help with riding for the drone practice on the farm.

**Illustration 7.18:** **Frame grab 2 from ‘Once a Racer…’**

Once again, I cut out a small track with the tractor, and then mapped it by flying the drone and recording waypoints. The farm is largely flat, with only a small bank to work with to add some 'variety' to the course. Off Vic went, with the drone following.

Vic is your typical enduro racer, mild-mannered and relaxed when off the bike; but as soon as he puts on his helmet he reverts to what is known in the fraternity as 'race face'. He only knows one speed, as fast as possible. Couple this with an 'easy' track I had created, and he was riding it very quickly. As he got used to the track, he rode quicker still. Then, as racers are want to do because every millisecond counts, he started looking for 'shortcuts' in the corners and interconnecting bits.

**__Illustration 7.19:__ Frame grab 3 from 'Once a Racer…'**

All of which means that the drone was consistently lagging behind, and I got very few shots along the way that had any real value. The drone was performing as expected, and I kept upping the waypoint speeds to deal with Vic's accelerating lap times, but I could not take it safely to within the speeds which were needed to consistently frame the shots throughout a typical circuit.


**__Illustration 7.20:__ Auto flight path from 'Once a Racer…'**

Some frame grabs from the day are shown in Illustrations 7.17 – 7.19, above, the auto mission course in Illustration 7.20, above, and a clip is from 01:25 in the video.

What I learnt from the day was that I would have to deal with the speeds at which the riders were racing at, and these speeds might easily outpace the drone. Essentially what it meant was I that had to select the parts of the course which I wanted to cover carefully with this in mind; in other words, choose to film at places where the drone could match the speed of the riders. This is not easy to do looking solely at Google Earth; the software would only give me some indication because it doesn't show the terrain in fine detail, and I would have to assume what would be a good place to shoot based on my experience of riding.

Nonetheless, it was good to return with the drone in one piece, and also to have shared my new interest with my old friend.

7.7 <u>'Inside, Outside'</u> 20 July 2016

In the prior flights tracking riders I had always mapped a course which stayed 'on one side' of the rider; in other words, the drone was always between myself and the rider, on what I might term an 'inside' course. I wanted to experiment with moving across the track, starting 'inside' the rider with the drone largely facing away from me whilst flying, and then to transition across the track to the other side so that the drone was now 'facing' me and 'outside' the course. This would involve another new skillset; because learning to re orientate yourself while only having a view

**<u>Illustration 7.21:</u> Frame grab 1 from 'Inside, Outside'**

**<u>Illustration 7.22:</u> Frame grab 2 from 'Inside, Outside'**

of the video inside the goggles is unnatural. You tend to want to only 'look' in the direction you were facing before you put the goggles on, and now having to 'look back' when your body is still facing the same direction can be unnerving and disorientating. To this day, I still find my head 'following' the movement of the drone inside the goggles or moving my balance onto one foot; even though there is absolutely no reason to do so. I assume that the reason behind this is that as humans we rely first and foremost on our sight for sensing, and then the brain informs the rest of our senses to act in accordance with this. Thankfully, I have never experienced the motion sickness which so many FPV pilots talk about due to this disorientation.

**Illustration 7.23:** **Frame grab 3 from 'Inside, Outside'**

Once again, I cut a track on the farm, this time through much longer and thicker grass. My sons Scott and Samuel rode for me. I planned to transition the drone over to the other 'outside' portion of the track about one third of the way through, and then transition back to 'my' inside side of the track before it ended, about two thirds of the way through.

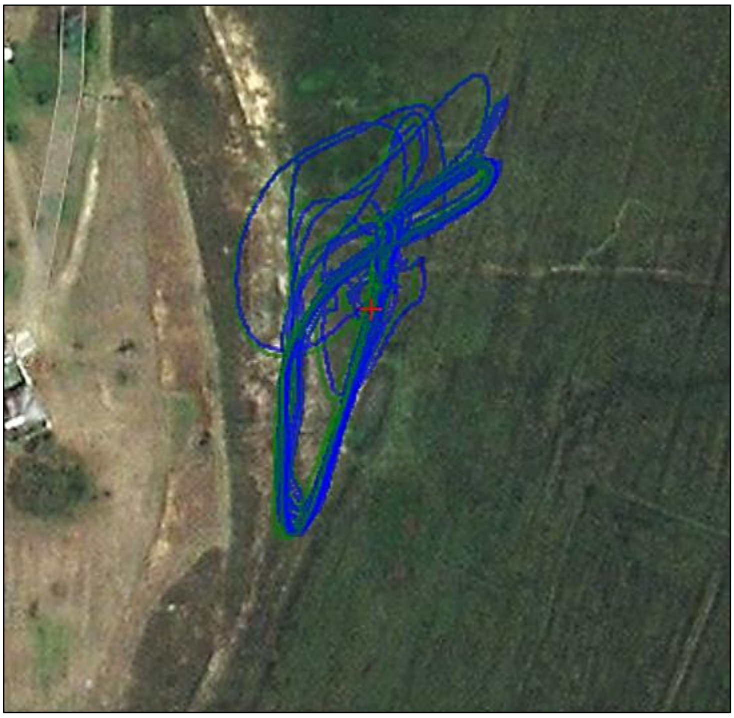


**Illustration 7.24:** **Various flights from 'Inside, Outside'**

Although I got some interesting visuals, I was not completely happy with the result. I was still having difficulty with fast panning or yawing movements while having the result overshoot the position I wanted the drone to end up pointing. This is particularly a problem when you want to pan 180° or more. I do think that the transition to the other side of the track adds a far greater element to the video and allows far greater variety for following the rider.

Some frame grabs from the day are shown in Illustrations 7.21 – 7.23, above, and some of the flights from the auto mission in Illustration 7.24, above,and a clip is from 01:58 in the video.

7.8 <u>'Mielies'</u> 21 July 2016

I had always wanted to explore what it looked like with a rider coming straight towards the drone (with the drone moving backwards), and similarly with the drone behind the rider moving forwards; as well as the rider disappearing or appearing below the drone. Although I had seen snippets of this during prior flights, I had never actually planned it specifically. Once again Scott helped me by riding.

On the farm there was a mielie field which had been harvested, and fortuitously there was a long straight path right down the middle of it. I set up an auto-mission along the length of this path and got Scott to ride along it. I would start with the drone moving backwards, get Scott to ride up to and underneath it, then quickly pivot the drone (this was the intention) as he appeared below it and rode into the distance with the drone following now flying forwards.

**<u>Illustration 7.25:</u> Frame grab 1 from 'Mielies'**

**<u>Illustration 7.26:</u> Frame grab 2 from 'Mielies'**

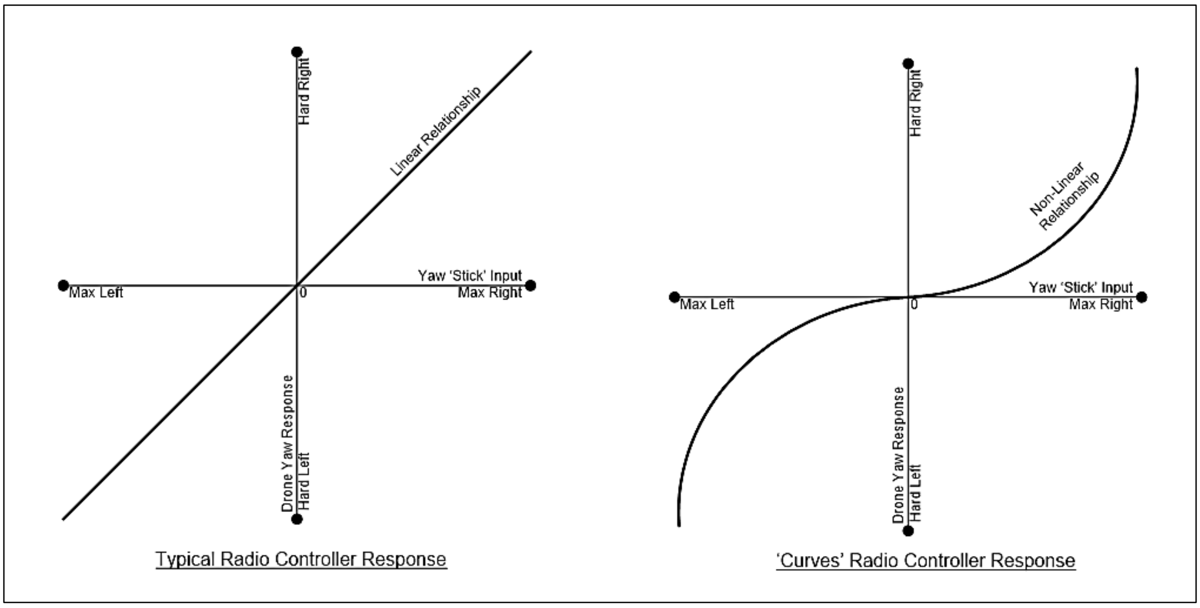
I say it was the intention because once again during the rapid pivot/pan/yaw the drone would overreact and miss the rider until I brought the drone back into line again. This was proving to be a constant problem, one which I will discuss at the end of this sub-section. Having said that I really liked what visuals we were able to capture. It was late in the day and the setting sun provided long shadows, good backlighting for the dust thrown up by the bike, and because I was flying quite low the sunlight rippled and danced across the tops of the mielies. The walls of mielies on either side of the drone created great movement within the frame, and this, coupled with the bike approaching or receding in shot, added vibrancy. All in all, I would say the experiment was a success.

**Illustration 7.27: Frame grab 3 from 'Mielies'**


**Illustration 7.28: Auto flight from 'Mielies'**

Some freeze frames from the afternoon are shown in Illustrations 7.25 – 7.27, above, a flight from the auto mission course in Illustration 7.28, above, and the video clips are from 2:43 in the video.

I tried several methods to address the issue of the drone yawing too much during quick pivots. The first was to programme a 'curves' response on the radio-controller. Illustration 7.29, below, shows how this is done; the horizontal axis is the amount of input you give the stick, and the vertical axis is how the drone responds to this input. On the left is a typical response to any inputs you give on the control stick (in this case yaw). It is a linear relationship between stick movement and the drone responding and is how most radio-controllers are set up. I rationalised that perhaps I was reacting too much 'off centre' with my yaw control during fast movements, and in an effort to counter this I programmed in what is known as a ‘curve’ response, as shown in the right-hand part of the image. What happens is that initial yaw movements need a greater input than usual, and thus I would have finer control over the drone during this portion of the movement. Unfortunately, this was a double-edged sword, because I then lost this fine control over the drone when I needed to make greater corrections, so although to some extent it solved the initial problem at the same time it created new problems. I tried changing the shape of the curve to be less non-linear but there was no effective compromise. In the end I reverted to the original linear response and decided this would be one of the reasons for designing and building a new drone with a 3-axis gimbal as detailed previously in Chapter 6, in an effort to counter this problem.




**<u>Illustration 7.29:</u> Stick inputs programmed with ‘Curves’**

## 7.9 <u>‘Fried Chips’</u> 7 August 2016

The next event I chose to cover would be the 2016 ‘Man and Machine’ navigational enduro in Craigieburne KZN. Since all my friends who had bikes as well as Scott would be riding, it would be up to me to try and do the filming on my own. I had identified three sites beforehand, but since I would need to take two trips on the bike to get all the gear there, I settled on one which was in the hills above Lake Eland. I set off early in the morning with the first load of equipment; it took me about 40 minutes of riding to get to the location. I hid the equipment in a small overgrown ravine, and then headed back for the second load. All in all, by the time I had everything I needed for the shoot back where I wanted to be after the second trip, I was already about two hours into the day.

It was a good location that I had chosen. The riders entered the area in which I wanted to shoot down a long hill. This gave me time to get the drone into the air when I saw them approaching and pick them up at a point at the bottom of the hill where I would intercept them for shooting. They then traversed a small valley (where I was situated) and climbed out of this valley up a rocky slope. This was my first time I was mapping using the pseudo drone, and the mapping and downloading of the mission, and subsequent uploading to the drone went well. It was at this point that I switched on the drone. I then flew a test flight to watch the drone visually to make sure it was behaving correctly, made a few adjustments to the waypoints and altitudes, and flew a second autonomous test flight. Illustration 7.30, alongside, shows a test flight from the autonomous mission I plotted.

**<u>Illustration 7.30:</u> Test flight from 'Fried Chips'**

Once I was happy with the flight path and altitudes it was time to test by watching the video over the course. My timing was good, because the first of the riders was making his way through the place I had chosen.

I got all the video gear out and powered it up. The video goggles just displayed 'snow', no picture from the camera. Surely something simple to figure out; the camera was in the wrong mode, or the transmitter or receiver channel was incorrect, or there was a cable which had come loose with me riding up to the site. The more I tried solving the problem, the more I realised that it was not a simple one. By now there were several riders coming through. I started delving deeper into the issue with what tools I had with me. The drone was in a multitude of pieces, and I was nowhere closer to solving the problem. Eventually I concluded that it was nothing I had done incorrectly, or that had 'worked its way loose' on the trip up to the site; it was actually a hardware fault. I suspected but did not know at the time that the video-transmitter on the drone had developed a fault. I watched in disappointment as most of the riders came through the zone. Eventually Scott came past, and he stopped and asked me why I was not filming. I explained the issue to him and asked him to come back after he had finished the race to help me with the gear, which he did.

I returned home disappointed. As I have explained in a previous chapter, the fault was a chip, which had burnt out in the video transmitter, through no fault of my own. As I have also explained, the next one I bought had a different chip, so the factory had obviously recognised the issue and updated it. Similarly, I have explained how I modified the drone so that I would only turn on the video-transmitter once I was ready to fly with video.

Another venture with nothing to show for it; this was turning out to be quite trying.

### 7.10 'Third Time Lucky' 1 October 2016

The next event I chose to cover was a regional championship enduro race in the Seven Oaks area of KZN. I must thank my friend Warwick Brown for helping me this day. We made an early start and arrived at the part of the course which I had identified beforehand around 7 am. It was in an area above a farm, and there was a small dirt road leading to it, so I took my van rather than using the bikes. We positioned ourselves at the edge of a ridge along which the riders would be riding. They emerged from a forest at the bottom of a hill, climbed the hill through some sparse trees, turned right and then rode along the ridge out of sight. I mapped the section I wanted to film, being careful to stay outside of the tree line, adjusted it, and flew some test flights. I was going to attempt the 'outside/inside' flight path, by having the drone cross over the track, and then cross over again later to 'my side' of the course. The test flight went well, and this time the video was working. It was time to 'hold thumbs' and hope that I would actually get some video.

Warwick was able to act as a ‘spotter’ and I positioned him down the hill so he could see into the forest and signal me as to when a bike would be arriving to give me time to get the drone in the air and position it at the first waypoint in Loiter. The first riders arrived; it was time for action; off we went.

The first few racers were the fastest in the championship, and they were going way faster than I had set the auto-mission speed. I adjusted the speed and managed to follow a few more successfully. It is worth remembering that this was the first time I had actually consistently managed to get proper racers and I was quite nervous and tentative. The next few flights went better, but I was still having problems with the quick pivots of the drone and overshooting the yaw movement. I adjusted the mission course to give me some leeway and things improved. By now, though, there were slower riders coming through, and my drone speed was too high, so they were lagging behind the drone as I manoeuvred. We decided to take a bit of a break, gather our energy and make another attempt when the faster riders came through for their second lap.

**Illustration 7.31:** **Frame grab 1 from ‘Third Time Lucky’**

**Illustration 7.32:** **Frame grab 2 from ‘Third Time Lucky’**

**Illustration 7.33:** **Frame grab 3 from ‘Third Time Lucky’**

However, by the time this happened there were still slower riders – by now very slow comparatively – on the course. I was having to deal with two or more riders on the course at the same time, with faster riders passing slower ones. At first, I thought this was going to be a problem, but in actual fact I could turn it to my advantage. I could set a 'mid-speed' of the drone, track a slower rider, and then when a faster rider overtook this slower rider continue to track the faster racer. Not only did this add more visual variety to the shot, but it also provided a graphic example of the speed differential between 'good' and 'average' riders.

All things considered the day went well. Yes, I was still getting to grips with the fast yawing/panning movements of the craft; but visually the scenes were compelling. The tracking shots looking through the trees at the beginning are introduced the scene while the views along the ridge towards the end presented the 'aerial view' of you 'riding with the rider'. Sometimes even when I was returning the drone to the home position, I would keep it pointing at the track backwards, and a rider would come into view and speed off into the distance. This had the effect of amplifying the speed of the racers. Using Warwick as a spotter also proved beneficial; and the lack of such help in later shoots would show me just how important a role an assistant could play.

I returned home with a huge sense of relief, after the disappointments of my previous two 'race' attempts. Whilst not perfect, the day had come when I could say I had finally reached my main objective: that of capturing the footage of racers. I was also in the middle of building the second version of my drone design, so this was to be the last time that I used the original one (even though I would continue to take it with me on long trips just in case I needed it). I hoped that the incorporation of a

**<u>Illustration 7.34:</u> Some auto flights from 'Third Time Lucky'**

three-axis gimbal on the new drone might help with the problems I was having of jerky panning, fast pivots and overshooting.

Some freeze frames from the day are shown in Illustrations 7.31 – 7.33, above, some flights from the auto mission course in Illustration 7.34, above, and the video clips are from 03:32 in the video. Please note that the image quality is not very good. As I said earlier on, I lost the original source footage in the burglary and instead have used an edited and lower quality version which I had made to show my students at work.

7.11 <u>'Playing it Safe'</u> 1 December 2016

It was time again to attempt coverage of the annual Roof of Africa race in Lesotho. Scott and I travelled up on 30 November and once we had checked in at our accommodation, we set out into the mountains to reconnoitre some of the areas I had identified and for which I had prefetched the tiles in Mission Planner. We spent most of the afternoon checking these areas and narrowing them down to the three parts of the course I hoped to cover on the three different days of racing. The part of the course first on the first day of racing which I wanted to film at was to be in an area above a village called Fosi. We found a small settlement close to the tar road and I negotiated with the farmers to leave the van there while we rode into the mountains on the bikes. Once we had found the spot at which I wanted to film in, I mapped the course using the pseudo drone.

Considering the problems I had encountered the previous year in Lesotho, I wanted to be cautious in my approach this time round. So, my intention was to fly the drone in such a way that I did not 'push the limits' in the first two days of the race, and if everything went according to plan I would be more 'adventurous' on the last day. This was the first time I was flying my 'new' drone in a real-world situation, although I had done innumerable test flights back home to check that everything was functioning. To launch, we chose a spot which had a clear view of the riders approaching in the distance on the other side of a valley. The autonomous mission was mapped from our position, then across the valley to intercept the racers on the far side. I planned to film the riders as they rode along a ridge above the valley and up the side of an adjacent mountain until they went over its crest. In the interests of 'keeping it safe', I mapped the course so that I had good altitude throughout the flight. It took quite a while to map because I had to walk up the valley and down the other side. We finished quite late and were able to ride out just before it got dark. That night I uploaded the mission onto the drone, and double and triple checked everything.

**<u>Illustration 7.35</u>: Frame grab 1 from 'Playing it Safe'**

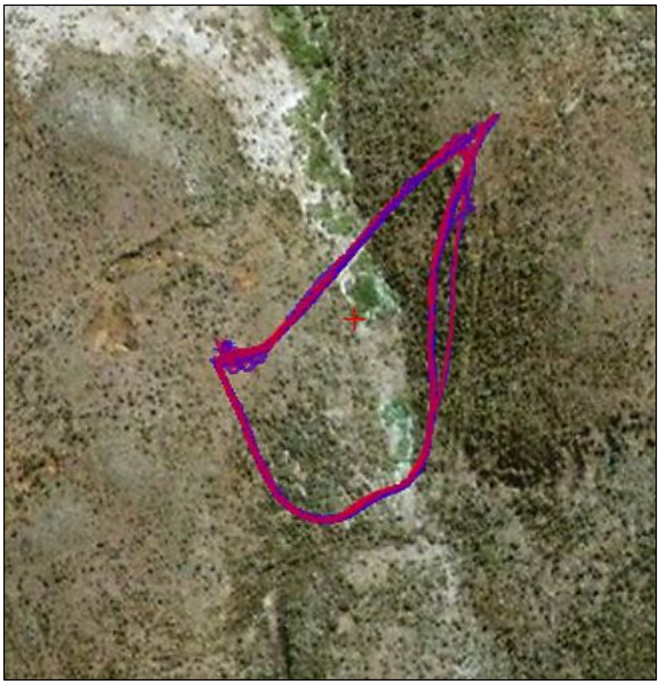
On the morning of 1 December (the first day of racing) we began by driving into Maseru to watch the opening formalities and catch up with friends of mine who would be racing. We then drove out past Fosi, parked the car near the settlement, unloaded the bikes and all the gear, and set out into the mountains. Loaded with all the drone gear in our backpacks made for difficult riding, and it took us about an hour to reach the area to which we had ridden the previous day. When we arrived, I set up all the equipment, double-checked all my software settings yet again, and flew some test flights, each time altering waypoints slightly. Everything was going according to plan, but considering I was in the most remote part of Lesotho in which I had ever attempted to operate and knowing how quickly things had gone wrong the previous year, I was still being overly cautious.

**<u>Illustration 7.36</u>: Frame grab 2 from 'Playing it Safe'**

**<u>Illustration 7.37</u>: Frame grab 3 from 'Playing it Safe'**

The first riders appeared in the distance. We watched a few of them from our vantage point on the other side of the valley to get a feel for how they were traversing that particular section of the course. Finally, it was time to commit, and it was with trepidation that I sent the drone out and covered my eyes with the video-headset.

The drone performed flawlessly, and I got some excellent video. I adjusted waypoints a little more to intercept the racers earlier on the spur where they came into view, but not much else. I would have liked to track them further up the ridge at the end of the flight and reveal the terrain beyond this, but I was wary of trying to do too much on this first day of shooting. In the end I was satisfied with the results, and I think the barrenness of the landscape met the requirements of me wanting to shoot in remote areas. We carried on shooting until about mid-afternoon, by which stage the batteries were depleted and it was time to pack up and get back to the van.



**<u>Illustration 7.38:</u> Some auto flights from 'Playing it Safe'**

Some frame grabs from the day are shown in Illustrations 7.35 – 7.37, above, a few flights from the auto-mission course in Illustration 7.38, above, and the video-clips are from 06:11.

7.12 <u>'Snakebite'</u> 2 December 2016

The area which I chose to film in on the second day of racing was in the Ntsi region, below Bushmans Pass. I had been to this part of Lesotho when I was shooting a photographic essay, so I was not too concerned about checking out what the terrain looked like beforehand. I also knew that the racers would potentially only get there around midday. We chose on the morning of 2 December to first go and map the part of the course I hoped to shoot on 3 December. This was about an hour's ride into the mountains from a village called Lirahaliboene, where we left the van.

After I had mapped that part of the course, we went back to Ntsi, parked at the top of Bushmans Pass (the Start and Finish of the race each day) and rode down into the veld. We would have a good view of the riders approaching, and then they would traverse two small valleys and a spur of the mountain where I hoped to record. We got there at about 11 am, and I thought that would give us a good hour to map and set up before the first riders appeared. I mapped and did some test flights. I was intending to be a bit more adventurous than the previous day and fly a bit closer to the ground.

**<u>Illustration 7.39:</u> Some auto flights from 'Snakebite'**

I remember it being a very hot day, probably the hottest I have ever experienced in Lesotho. We waited and waited for the first riders to arrive, far beyond what I considered the time they should have taken to get there. The racers eventually appeared about two hours later than I expected and when they arrived they were not the top riders we were expecting but instead some very weary looking 'lower order' riders. Something had gone wrong, and that was 'Snakebite'.

The people who set the course for enduros (or, as in the case of the Roof of Africa, extreme enduros) have a very difficult and somewhat thankless task. They have to scout out new sections for the race each year and combine them with traditional sections. This takes many hours of riding beforehand, and once they have found all the sections they want to use they have to integrate them into one long, continuous track for each day of racing. They also have to find sections which will suit Gold, Silver and Bronze level riders, and tailor the sections to the specific abilities of these riders. Sometimes these courses overlap, and the riders will merge for various sections, and then divert away on to their specific routes at later stages.

These course-setters often name specific sections or passes as they include them. Some, such as ‘Belekomo’ or Ke Kopa Sutumetse’ (which translates from seSotho as ‘Please Push Me’) are traditional names used by the local inhabitants. Others such as ‘Two Tits’ or ‘Big Dick’ are named, presumably by men, after geographical features you encounter as you work your way through them, while others such as ‘Boilers’ or ‘Pressure Cooker’ are named after the effect on your motorcycle as you struggle your way up. ‘Snakebite’, so named because of the many winding switchbacks you have to negotiate on your way to the top, as well as the way your body feels when you finally got there, was a new pass for the 2016 Roof of Africa which the organisers had found to test the riders.

The problem was that this pass, whilst within the capabilities of the Gold-level racers, was far too difficult for the lesser skilled Bronze riders. To compound the problem, it was to be attempted by all classes, but the nature of the course was such that the Bronze riders arrived there first, followed by the Silver and then finally by Gold (who had negotiated lots more terrain before they arrived there). When the Gold and Silver riders approached Snakebite they were confronted by a massive bottleneck of Bronze riders attempting (without success and thus getting stuck) to climb the pass, all blocking the only small path up the mountain. Added to this was the fact that it was an extremely hot day. The nett result was a chaotic scene of riders trying to muscle their way up the pass and getting very dehydrated at the time. Sadly, one rider lost his life in the ensuing melee, the first mortality in 50 years of the race. In the months that followed, there was an official commission set up by Motorsport South Africa (under whose auspices the race was held), the findings of which were made public (https://eolstoragewe.blob.core.windows.net/wm-553616-cmsimages/161179-098-FindingsofCOE1188.pdf) and laid the blame firmly at the feet of the course setters.

I had enough experience of the race to know that something had gone seriously wrong ahead of us on the course, but at the time did not know exactly what it was. However, the riders should have reached us hours beforehand, and it was only well into the afternoon when a few of them started dribbling through. They were also not the 'top' riders we were expecting, but slower ones (some of whom had finally made it over 'Snakebite', and some of whom had seen the situation and decided to bypass the climb – which potentially could lead to instant disqualification – and rejoin the track afterwards simply to get home for the day). I could sense that these riders were disorientated, dejected and depleted from the way they had been through.

**<u>Illustration 7.40:</u> Frame grab 1 from 'Snakebite'**

**<u>Illustration 7.41:</u> Frame grab 2 from 'Snakebite'**

**<u>Illustration 7.42:</u> Frame grab 3 from 'Snakebite'**

Nonetheless, we filmed those few that came through, even though there were big gaps between them. Sadly, some of the arriving riders missed the turn at the beginning of where I wanted to film, continued on for a bit, realised they were lost, looked up and saw us; and then took a 'short cut' to where we were back on the course. This meant, however, that the first part of the autonomous mission I had mapped was missed out, and I only was able to start recording the riders about a third of the way into the section I wanted to cover. I would have liked to also follow the riders further into a small valley and river crossing, but a spur of the hillside was interrupting my visuals of the drone.

The result was that I was losing the ‘line of sight ’of the video-link and there would be no signal on the video-monitor. This also meant that the end of the flight had to be shortened.

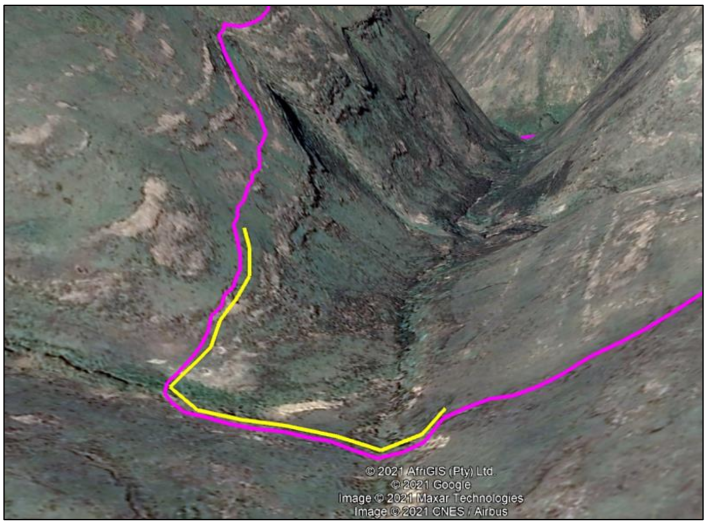
All things considered we got some arresting visuals, but sadly so few riders came through in the time we were there that our filming was compromised. We eventually left the area at about 4 pm (I had planned to leave at about 2pm) because there was still a long drive back to our accommodation and much gear to get organised for the next, and final day. We were due for an early start.

Some frame grabs from the day are shown in Illustrations 7.40 – 7.42, above, some flights from the auto-mission course in Illustration 7.39, above, and the video clips are from 09:07.

7.13 ‘Not with a Bang, but a Whimper’ 3 December 2016

Racing starts at 6am on each day of the Roof of Africa, and the Lirahaliboene area I wanted to film in (which we had mapped the previous day) was quite close to the beginning. I knew that the riders would probably get there about 7am. By 4:30 am we were already on the road, and we parked the van near a planned fuel stop for the race (for safety reasons). We loaded up the bikes and headed off into the mountains and arrived at the shooting location about 6am. Since I had already mapped the course and uploaded the waypoints onto the drone, it was quite quick to get ready for the first flight of the day. It was a beautiful clear day, and refreshing to be operating in the cool morning air compared to the heat of the previous day.

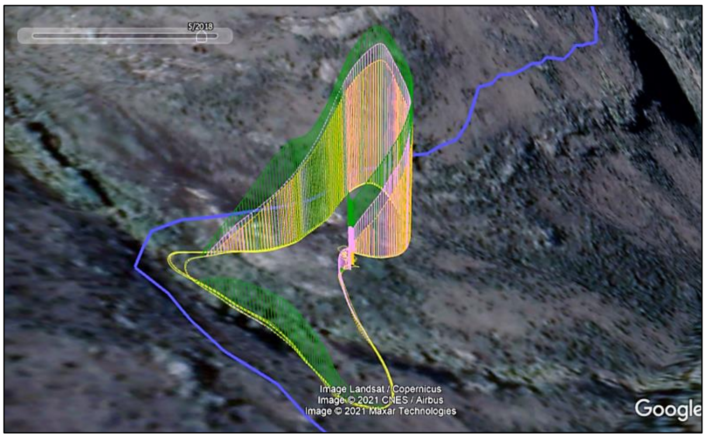
On the first two days I had set conservative flight plans. Knowing what had happened in 2015 I wanted to maximise my chances of getting through three days of flying with minimal risk to the craft. I had made a conscious decision that if we got though the first two days unscathed I would ‘push the envelope’ of flying on this last one. The place I had chosen lent itself to the ‘aesthetic’ scene; early morning sunlight, a small ridge along the side of a valley, crossing over a small river, then a climb up the mountain on the other side where I would raise the drone to reveal the countryside the riders were entering; all things considered probably the most remote and scenic area I had yet operated in. The course which the riders would be following is shown in Illustration 7.43, alongside, in pink, and adjacent it in yellow is the section of the course I wanted to film.




**<u>Illustration 7.43:</u> Race course and intended coverage for 'Not with a Bang, but a Whimper'**

I flew a test flight, adjusted heights and waypoints, and then flew it again. Illustration 7.44 and 7.45, alongside and below, show the test flights to give some idea of the altitude changes I was asking of the drone. It was quite an ambitious assignment, but the drone was performing flawlessly. Then a final check to make sure everything was ready, a quick cup of tea, and a wait for the racers to arrive. Soon we could see them in the distance coming down an adjacent mountain, and we prepared to go.

**<u>Illustration 7.44:</u> Test flight from 'Not with a Bang, but a Whimper'**




**<u>Illustration 7.45:</u> Test flight showing altitude changes for 'Not with a Bang, but a Whimper'**

Except that the riders did not come down the section we were expecting them too; they went down an adjacent spur, crossed over the river further upstream from us, and then headed up the mountain next to us!

At first I thought that maybe the lead riders had made a mistake and were just 'working their way' back towards the course, but as more and more riders followed this course I realised that something had changed. The organisers had altered the course between me receiving it a week prior, and the day of the race. Illustration 7.46, alongside, shows where I had wanted to shoot (as per the previous Illustration 7.43) with the green line now showing the new route of the race.

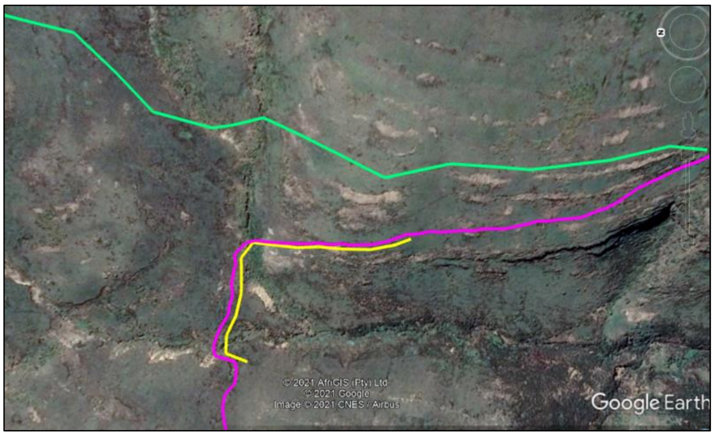


**Illustration 7.46: Race course change for 'Not with a Bang, but a Whimper'**

There was nothing I could do. I hadn't prefetched the tiles for the part they were riding through, and even if I had it was too late. With it being early in the morning the majority of the riders would be through that section within an hour, which was too short to map, test and capture. At any rate, they were already on the course, and I don't believe in 'getting in their way' to map. I always want to do the planning and setup at some stage beforehand. Although we made the effort to cheer on the riders as they went through, it was pretty glum cheering.

I never got a clear answer as to why the route had been changed. It was not because of the previous day's route-setting fiasco, because the riders had been given the routes in advance of the three days of racing. I just hadn't been notified of this change, and they are perfectly within their rights to change up until the first rider leaves for the day. I suspect that there had been a wash-away on a dirt road nearby (there had been a tremendous amount of rain in Lesotho the week before we came) which stopped a route marshal from reaching a pre organised spot to marshal. The route had probably been changed so that the riders would pass through this marshalling spot on a place on the dirt road where he could still get to in his vehicle.

What a shame. I really believe that I had chosen the spot well, that the craft was performing effectively, and that my abilities to follow the action had improved considerably from the previous two days of practice. It just was not to be. I have included a frame grab from the drone as Illustration 7.47, alongside, to show where we setup for the day; and also, although there are no motorcycles involved, I have included a clip from the test flight (it starts at 12:09 in the video) to give some idea of what I was trying to achieve.

**<u>Illustration 7.47:</u> Launch site for 'Not with a Bang, but a Whimper'**

We left Lesotho for the long drive home with mixed feelings, some good days but the one we wanted the most just hadn't happened through no fault of our own. However, on the way home I made the remark to Scott which I have previously written – 'We have to consider it a success, because we never opened the toolbox once'. Considering the challenges of the previous year in Lesotho we had some measure of success this time round. Little did I know what would be in store for me the next time I returned in 2017.

### 7.14 <u>'Mad Dogs'</u> 25 February 2017

The next event I undertook was a KZN regional enduro championship in Lions River. Looking at the route beforehand I chose three spots at which I wanted to shoot, the first two being in the forested areas which the course traversed. Both of these areas required me travelling along forest roads to get there. I was working on my own so would only use the van for access, but although Google Earth showed thick forest, I thought I would be able to get where I needed to be on these forest roads. I marked this access on my GPS to follow once I got there.

The week leading up to the event was characterised by heavy rain in KZN which only stopped the night before the event, but the early morning drive up to Lions River revealed clear skies overhead. I arrived at the access into the forest at about 6am to be greeted by a sight which I was not expecting; the forest had been recently cut down. What looked like fairly decent racks on Google Earth were now churned up by the logging trucks. They were wet and muddy from the rain, and there were still innumerable small branches left behind by the logging company which had yet to be cleaned up littering the tracks. I was worried about my van's abilities to go further, but proceeded cautiously, until I got stuck in the mud. It took me about half an hour to dig myself out and reverse back out along one of the tracks until I could turn around. The day was not starting well. I retraced my steps gingerly until I got back to the main dirt road, then drove around a bit to see if there were not another way in to where I hoped to shoot. I found a farm with what looked like a private road heading in the direction of my desired destination, but the farm gate was locked. Next to it was a pedestrian gate which was unlocked, so I parked and walked through that. It was now about 7:30am. Seeing no obvious signs of people being awake, I walked up the pathway to the farmhouse calling 'Hello, Hello'.

The next thing I was set upon by three dogs which, barking, were running up to me. They were obviously very unhappy about being woken from their early morning slumber by this (by now very muddy) stranger, and were very aggressive, but I could also sense a bit confused. The two very large dogs were my immediate problem because they could have done some serious injury, but they were a little more reticent in their aggression than the small dog, which kept egging them on. I am normally quite confident around dogs, but I was concerned that this could turn nasty in an instant. After what seemed like an eternity, I managed to calm them down. Eventually one of the large dogs lost interest and returned to his sleeping spot on the porch of the house, and the other two soon calmed down as well when they perceived I was not a threat. It was a very dangerous situation, something I will never do again. I backed away carefully; and this meant that Plan A and B were not going to materialise because of the poor state of the logging roads. It was to be Plan C.

Plan C was not going to be as scenic as the areas inside the (now logged) forest; it was section which was very open adjacent to the Lions River itself. The racers were due to come into the section through an open paddock, cross over the river on a small footbridge, and then ride along the river side. When I got there, I was immediately struck by the strength of the wind; typical KZN Midlands anti-cyclonic weather which so often follows continuously heavy rain. I was worried that the drone wouldn't be able to cope with the wind, but buoyed by the thought that I had faced similar wind in Lesotho in 2015 I decided to press ahead. The day had been so demanding up until this stage that there was no point in calling it quits just because of the wind.

By now it was getting quite late, and although this section of the course was far into the loop the racers would be coming soon. I mapped the course, starting in the paddock, moving over the river, back alongside the river, and then back over the river to the launch site. The Lions River, which at this part of its course normally would be a small meandering stream, was in full flood from all the rain, almost breaking its banks. One of the problems I faced when mapping was that there were some tall trees right at the point at where the riders crossed the river; this would have been dangerous for the drone particularly in the high winds, so I had to cross the drone over the river keeping well away from these trees. It was a 'triangle' flight pattern which was quite effective.

I did a test flight. I set the speed of the drone quite low so that it would be able to handle the strong winds and keep its position a little easier. I was quite surprised at how well it flew the course, so I did a few more test flights with ever-increasing speeds while adjusting the waypoints slightly. I also brought the altitude down as far as I deemed safe whilst at the same time giving the drone enough 'headroom' to recover should things go wrong. Soon the first riders appeared. It was time to record.

It was then that I realised just how hard the drone was working against the wind. For the first time ever I saw that props were coming into view because it was pitched so far forward flying into the wind. I have no doubt in my mind that a smaller or lesser powered craft would have been blown away in the wind (this has happened to many pilots of small commercially available drones, the online forums are littered with hard luck stories of how people's drones were 'swept out to sea, never to be seen again'). A graphic example of the strength of the wind can be seen in the video at 13:34 where the speed of a cloud shadow on an adjacent hill easily overtakes the racer riding at full speed below it.

I was disappointed that there was quite a long gap where the riders were out of view as they crossed the river. With the river being in full flood the small rickety footbridge they were crossing took time to negotiate because they were wary of being swept away. Since I couldn't safely get close to the bridge with the drone because of the tall trees surrounding it, I had to start the 'return' leg short of the crossing, and with the riders taking time to negotiate the bridge this left a bit of 'dead' space in the video with no rider in shot. It was unavoidable if I did not want to take the risk of flying too close to the trees. After the day I had had so far, I was beyond any more risk-taking and potential trouble. Looking back I could have switched into Loiter in the middle of the flight, waited for the racers, and then switched back into Auto; but I was still relatively inexperienced at that sort of control and hadn't yet perfected it. I did have one crash. I had kept lowering the altitude along the bank of the river in Mission Planner to try and improve the shot and on the return leg across the river the drone clipped some reeds, got tangled (I think) and went down. Luckily it fell on the bank of the river about a metre away from the swollen waters without any damage. It seemed my day's luck had turned by that stage!

**<u>Illustration 7.48:</u> Frame grab 1 from 'Mad Dogs'**

**<u>Illustration 7.49:</u> Frame grab 2 from 'Mad Dogs'**

**<u>Illustration 7.50:</u> Frame grab 3 from 'Mad Dogs'**

Although it was an ‘easy’ section for the riders with not much motorcycling ‘action’ I was quite pleased with the results. There is lots of movement in the pictures, not only the movement of the drone and the racers but also the wind in the trees and reeds, the fast flowing river and the cloud shadows; all of which contribute to the visual effect. The end of each shot, where the rider goes from a close-up on camera and then disappears into the distance round the hills in a wide expansive shot, also gives a very visual insight into the life of an enduro racer and the terrain and landscapes they have to conquer alone. I packed up and headed home, it had been a long and trying day.


**Illustration 7.51:** **Selected auto flight paths from ‘Mad Dogs’**

Some frame grabs from the day are shown in Illustrations 7.48 – 7.50, above, a few of the flights from the auto mission course in Illustration 7.51, above, (notice how I have extended the southern loop on successive flights to capture more of the action), and the video clips are from 12:58. (Once again, I apologise for the very poor video quality, I only managed to get a Youtube download – which luckily I had uploaded after the race for the riders to watch - to use for the this video, due to losing all the source material.)

## 7.15 ‘Mid-Summer Snow’ 15 November 2017

With the home invasion and the loss of key computer and camera equipment, together with my psychological state, 2017 had been a very difficult year. I had to ‘pick up the pieces’, both literally and mentally, and regroup. The first chance at which I felt both ready and motivated to shoot again was the end of the year Roof of Africa, once again in Lesotho.

The weather forecast predicted a cold front for southern Africa in the days before the event. It was an absolute anomaly for Lesotho to have snow – and lots of it! – in the middle of summer. Illustration 7.52, alongside, shows an image posted by the race organisers at the Start/Finish area on the day before the race started. I have to thank Lourens Graaf, the son of a friend of mine, for agreeing to help me on the trip. He was travelling up there with his father Steven who was seconding one of the racers. We arrived on 14 November to bitterly cold conditions, and once again after getting through the border and checking into our accommodation, we headed out into the mountains to reconnoitre the areas I had identified prior to our leaving. I was honestly more concerned about access to the sites in the extreme conditions than the actual pictures I might get. The snow and precipitation made the access dirt roads treacherous, and in fact many people were getting stranded as they tried to get around. Nonetheless I managed to identify where I wanted to be on each of the three days, and although we did not actually take the bikes out to reconnoitre, I at least had a good look as to where we would leave the van each day, and where our paths would begin.


**<u>Illustration 7.52:</u> Image from the Start of the 'Roof of Africa' the day before the race began**

Thursday 15 November dawned to the snowing having stopped, at least in the lowlands; but the weather was still numbingly cold, particularly with the wind which was still blowing. Many of the racers were voicing concern about the race but the organisers decided to continue. For riders who had been training through what until then had been the heat of summer, this was to be mentally and physically challenging. We headed out to the first place I wanted to shoot, a river valley about 10 kilometres from the nearest small settlement, Ha Paramente. Illustration 7.53, below, shows the scene on the way, with the snow in the direction of where we were heading.

The scene I wanted to shoot was the riders' progression along a small river valley, and then the crossover of the river and them exiting up into the mountain alongside. Once we got there I readied the gear, and mapped the course I wanted to fly using the pseudo drone.

**<u>Illustration 7.53</u>: Heading out for the first days shoot of 'Midsummer Snow'**

Then I prepared the drone for a test flight and sent it off. The entire mission was meant to be about three minutes in total, but about 30 seconds into the flight, before the drone had even reached its most eastern point, it suddenly tried rising up and began a return flight back to us, only to fall onto the ground near us (luckily on its legs, and nothing was damaged). The battery alarm was beeping. At the time I did not know why, and assumed it was a battery which I had overlooked for proper charging. I have a whole variety of batteries, and during testing usually grade them from 'good to poor' depending on their condition. I usually use my 'least best condition' batteries for the test flights, and save my 'good' batteries for the flights when I am using the camera/video transmitter for actual shooting.

I tried another battery, but the fault recurred. Now I was getting concerned. Was it a fault with the drone, my battery monitoring settings in Arducopter, or something else? I tried again; the same, but slightly better. When I measured the voltage on the used batteries, they seemed low but still within the limits. So next I put a 'good condition' battery in and flew another test flight. Similar outcome, the drone flew a short way, rose up and returned.

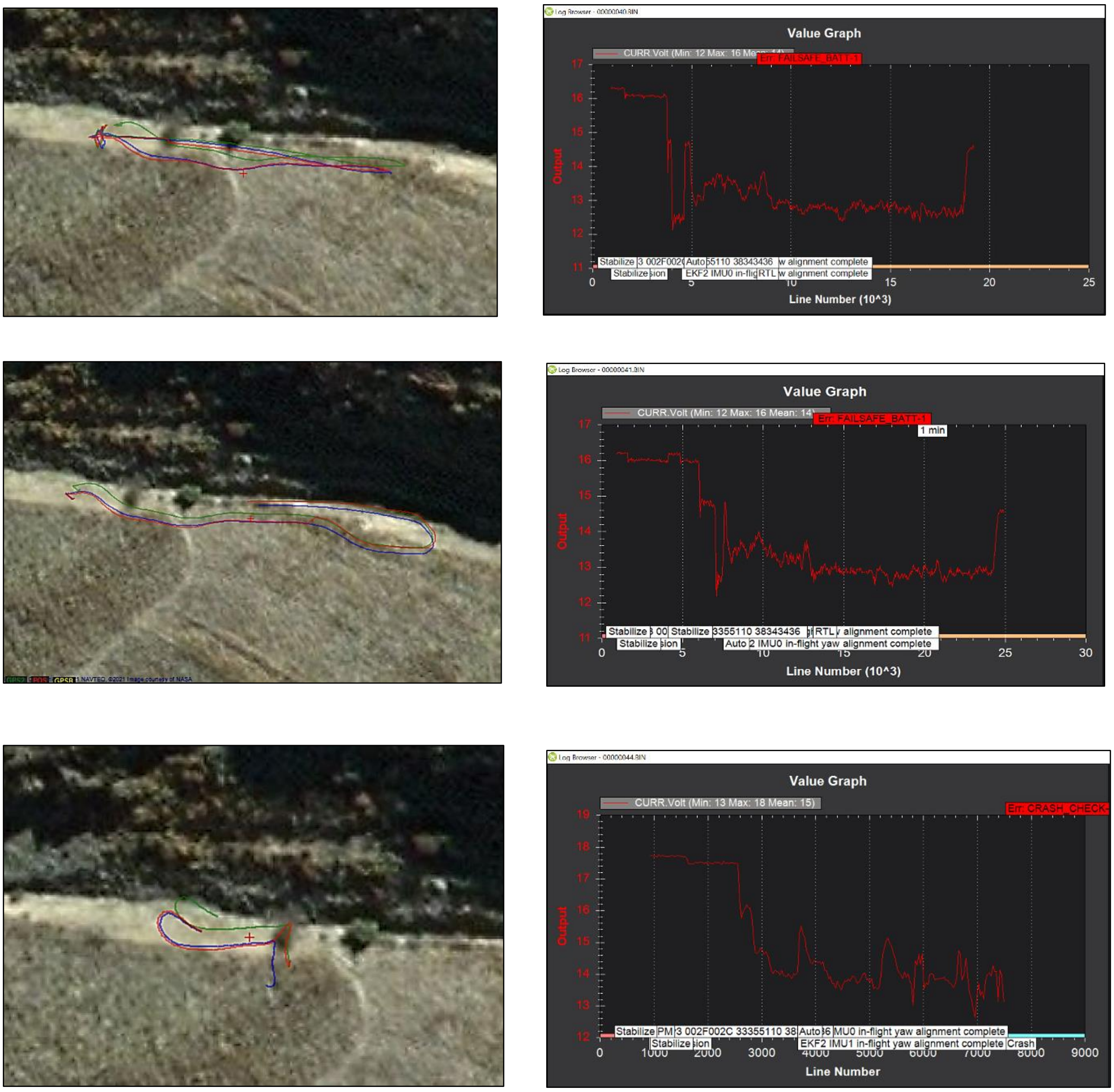
I connected the drone to Mission Planner and downloaded the logs of the flight. It showed the batteries getting to a very low voltage (around 13 volts) when they should have been close to 15. It also showed the auto-flight being interrupted by a 'Battery Failsafe' message and the drone entering a 'Return to Launch' (RTL) mode. I thought that perhaps there was an error in the voltage monitoring, so in the software I changed the settings to a lower voltage before RTL would initiate. Then I tried a fifth test flight.

This went very badly. The drone went about the same distance it had previously, but this time because it was not sensing the battery drop it did not initiate the RTL sequence, and instead just crashed. Not only crashed, but did so into a very muddy ploughed field next to us. It buried one of the arms into the mud, and when I extracted it both motors on the arm were saturated in mud and water. That was the end of the day.

In fact, that was the end of the weekend. By the time we had returned to our accommodation the mud had dried and caked inside the motors. Even though I tried to clean them by dismantling the motors they were still very gritty when I turned them by hand; the mud had penetrated the shaft bearings. I only had one spare motor with me (in fact, I only had one in total) so I couldn't repair the drone, and I couldn't risk flying with gritty bearings.

The drive home was a set of mixed emotions. Yet another trip to Lesotho with nothing but a broken drone to show for it. What had caused the problem? I suspected the freezing conditions, but couldn't understand why. I discovered after some research back home that LiPo batteries are very temperamental in cold conditions, and they couldn't deliver the current I was asking of them to fly the drone, and thus the voltages were dropping tremendously. In fact, they were so badly damaged that even with multiple charges afterwards they still wouldn't reach to their nominal voltage. I had to scrap all five batteries (at almost R2000 per battery it was an expensive lesson!). Had I known at the time I would not have persevered, and instead just cancelled the day and waited for the weather to improve (which it did) over the final two days of racing, and instead flown the drone then.

Illustration 7.54, below, shows some of the attempted the flights from the day, and the battery data alongside which I downloaded once I got home (the red, green and blue traces are the 3 IMU's I have overlayed). You can see along the bottom of the graph the 'Stabilise', then 'Auto', then 'RTL' modes initiated (as the 'Batt Error' warning comes up at the top of the graph). In the final flight you see the drone has reported it has crashed. You can also see that the batteries all start at fully charged (above 16 volts) but then immediately drop as the flight begins to around 13 volts (minimum for these batteries is about 14.8 volts). They return to about 16 volts only when the flight has ended and there is no more current draw on the batteries.




**<u>Illustration 7.54:</u> Flight paths and Battery Data from 'Midsummer Snow', Top to Bottom: Flight 1, Flight 3, and Flight 5**

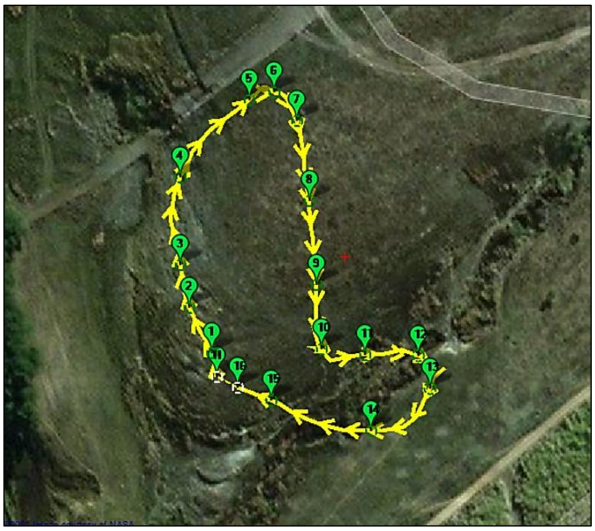
I was especially sad about the weekend not only because of the cost and frustration but also because I had identified what I expected to be very scenic spots to shoot in. But it was not to be.

7.16 <u>'Over the Hill'</u> 22 April 2018

The next event I wanted to cover was a regional enduro championship event in the New Hanover area of KwaZulu-Natal. I identified three areas which had potential according to my inspection of the course relative to Google Earth. Since I would to be working on my own, the racecourse had to be accessible using my van. When I arrived early in the morning I had a look at the three possibilities, and chose one which I thought would be best suited. In Chapter 5 I have previously discussed this particular shoot.

The riders would enter through a forest far below me. I would have a good sight of them arriving from the drone in Loiter. They would then climb the hill behind me. At the base of this climb I would start the Auto-mission and follow them up the hill. At the top of the hill, they would turn to the right through a farm gate and head down the hill to my left. During this stage I planned for the drone to fly much lower (relative to the ground but still above my 'launch' spot). At the bottom of the hill, they turned left into a small river valley; once through the river they turned right and proceeded down the adjacent side of the valley, which was now almost in front of me. I planned to have the drone descend into this valley, but was wary of taking the drone right up to the river-crossing which was surrounded by thick bush. Once the racers had gone down the adjacent slope, the drone would return to me. Illustration 7.56, alongside, shows the planned Auto Mission. It was an ambitious course for the drone, not least because the hill (and where I had to park the van) would mask my visability of the drone at times because it would be flying,

**<u>Illustration 7.55</u>: Frame grab 1 from 'Over the Hill'**



**<u>Illustration 7.56:</u> Auto Mission for 'Over the Hill'**

relative to me, beyond the crest of the hill and just above the long grass. I was concerned about the line of sight video link, but decided to test this and adjust where necessary. I mapped the course using the pseudo drone, and uploaded it to the laptop and the drone. I did a test flight. This was one of the few times I did my first test flight with the camera and video link switched on. Even though I was keeping an eye on the drone visually where I could see it, I watched the video-monitor when the drone went beyond the crest of the hill. The video link held.

The drone was still too high at the top of the hill, so I adjusted altitudes there, and flew again. The video link still held, but the drone was still a little too high. I adjusted the altitude lower and flew it again. Now it was too low and crashed! It took a surprisingly long time to find the drone in the long grass because I was not able to see where it had gone down. Luckily, however, the grass cushioned the fall, and the drone was not too damaged. I adjusted the altitude to a median between the first and second flights and sent it off again. Now it was just where I had been aiming for. Illustration 7.60, below, is a snapshot taken from the folder of my laptop showing the adjusted flights.

**<u>Illustration 7.57</u>: Frame grab 2 from 'Over the Hill'**

**<u>Illustration 7.58</u>: Frame grab 3 from 'Over the Hill'**

When the riders arrived, it was time to capture the action. I was well-pleased with the results. This was the longest flight where I would continuously be following riders. The altitude changed significantly along the way. The drone was required to fly forwards, backwards and sideways at various points along the way. The shots

**<u>Illustration 7.59</u>: Frame grab 4 from 'Over the Hill'**

varied from very high and wide, to very low and close-up. At times the drone was barely skimming across the top of the grass whilst it was changing both its direction of flight as well as its orientation, in particular down into the valley. There were a several racers with different skill levels and thus different speeds appearing at the same time, and I was able to adjust for this and take advantage of switching the viewpoint between the riders when this occurred.

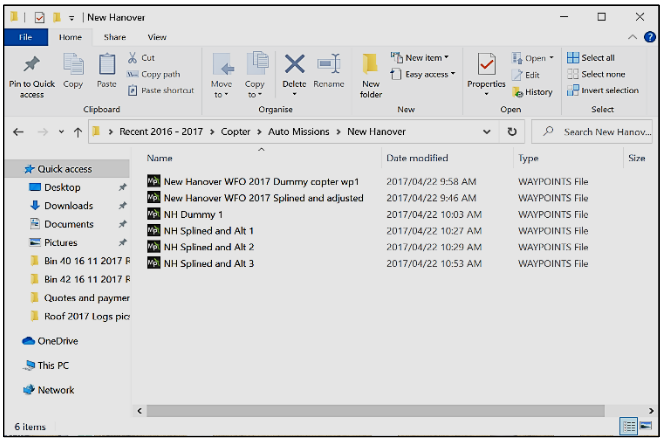



**Illustration 7.60:** **Screenshot of adjusted Auto Missions**

Considering the problems of the previous attempt in Lesotho, I had a more satisfying drive home.

Some frame grabs from the day are shown in Illustrations 7.55 and 7.57 – 7.59, above, and the video clips are from 16:29.

7.18 ‘Monochrome’ 18 August 2018

I was working in Russia for the 2018 FIFA World Cup in the middle of the year, so my next opportunity to cover any racing was the annual Man and Machine event, this time held in the Impendle area of KwaZulu-Natal. Since I was working alone (my friends were all riding the race) and I did not want to replicate the double motorcycle trip I had made the last time I covered this event in 2016, I was limited to working from my van. I identified a likely spot beforehand. I was also hoping for more success this time considering the burnt-out video-transmitter that I had encountered at the previous Man and Machine event.

Once I had seen my friends leave from the start, I set out to navigate to the region in which I wanted to shoot. I had marked on my GPS how to get there. However, I hadn’t done more than 10 kilometres of the trip when, while working my way down a winding pass into a valley, I came upon several emergency vehicles. A minibus taxi had overturned, and the road had been closed while the injured passengers were attended to. Since there are very few roads servicing the area, this was going to be a long detour.

Added to the complications of the detour was the fact that the GPS I had with me only showed the riders' course, and the way I had mapped to get to where I wanted to shoot. It isn't a typical vehicle GPS which shows all the roads. I also had no map book with me, so it was going to be a 'seat of the pants' attempt to find my way. Needless to say, I got horribly lost. I backtracked to the scene of the accident and the emergency vehicles were still attending to the injured. I tried to talk my way through but by then there were numerous vehicles caught up in the queue and the authorities wouldn't let any of us pass. Eventually the road was opened again but I had lost a few hours in the process. I only managed to get to the flying site by mid-afternoon, and by that stage the majority of the racers had already progressed beyond this point. I decided to do the best I could, and quickly set up and mapped the course; then flew a test flight. The action I wanted to shoot had the riders appearing from behind a ridge, traversing the side of a hill,

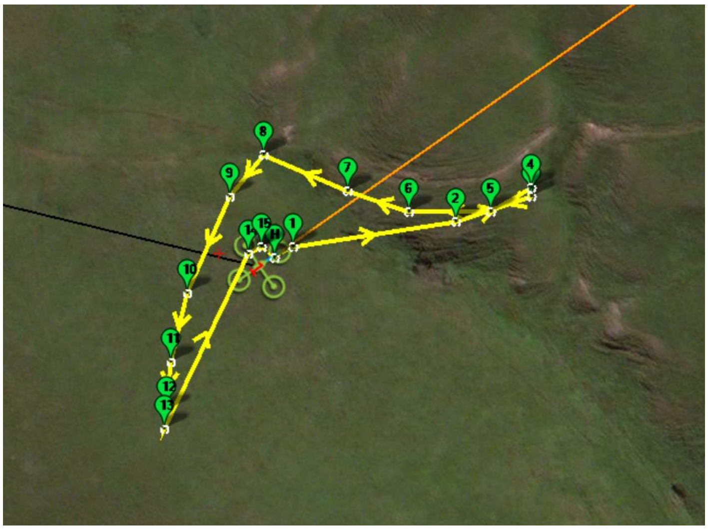
**<u>Illustration 7.61:</u> Frame grab 1 from 'Monochrome'**

**<u>Illustration 7.62:</u> Frame grab 2 from 'Monochrome'**

**<u>Illustration 7.63:</u> Frame grab 3 from 'Monochrome'**

dropping down into a valley, then proceeding up an adjacent hill (where I was parked) and eventually riding over the ridge of that hill.

I followed the first rider with video. The drone speed was way too low compared to the speed of the riders over that part of the course. I upped the speed of the mission substantially. This was a mistake. When the drone went down into the valley it was now going too fast to gain altitude safely as it came through the valley and up onto the next hill. The next time I flew it crashed – now at this much higher speed – into the ground before it could pull up and gain altitude. It was a very hard crash because of the speed it was doing. The damage was substantial; a few broken props, a broken leg, and a bent arm.



**<u>Illustration 7.64</u>: Auto Mission for 'Monochrome'**

I was faced now with a long repair, with fewer and fewer riders coming through. Thankfully - due to my doing this many times! – I got it repaired in about half an hour. I adjusted the altitudes through the valley and tried again. By now it was late, and the sun was beginning to set behind the hill. This compromised the pictures because the first part of the course proceeded along a face of the hill, which was now in shadow, and I was shooting directly into the setting sun. I also had a problem trying to anticipate the riders arriving. On Google Earth beforehand it looked as though I would be able to 'see over the ridge' from where I was launching, but this was not to be the case; the ridge masked the riders' arrival. A few times I would think I could hear them arriving, launch the drone and send it out, and then put it into Loiter to wait for them. I would wait three or four minutes and nobody would arrive. I would have to bring the drone back because I was worried about battery capacity. I really needed a 'spotter' on the far hill who could prompt me as to when the riders would arrive in sight. Had I had more time in the day I would have relocated myself on the adjacent hill; but this would have meant packing everything up, moving and re mapping. In the end I did the best I could.

The visuals, though scarce, were dramatic. The grass in the area had just had its annual burning, leaving a black carpet everywhere. The lines cut by the bikes through this ash were stark and white in comparison, very graphic and monochromatic. The few paths along the hill sides, normally obscured by the long grass, were revealed and amplified. The few bits of colour in the bikes (and the blue skies when the camera was not pointing into the sun) stood out in contrast to the countryside. The backlighting and the dust created by the bikes set racers apart from the terrain they were traversing. It was a very interesting set of complimentary, but also supplementary, layers of aesthetic. I only wish that I had been able to capture more riders through what was in some ways a lunar landscape.

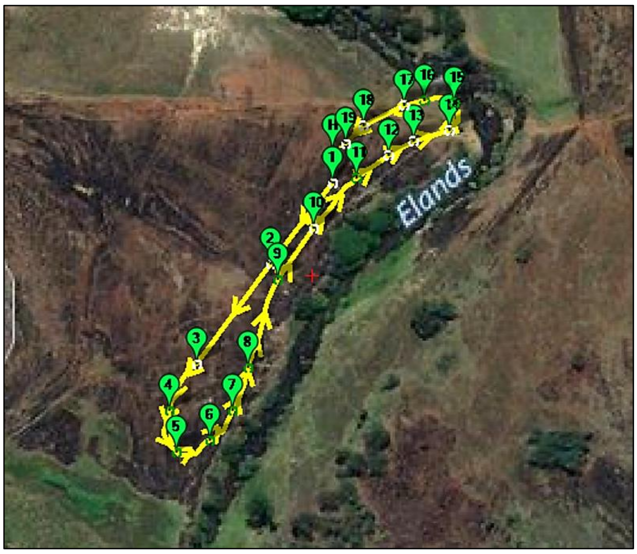
Some frame grabs from the day are shown in Illustrations 7.61 – 7.63, above, the auto mission course in Illustration 7.64, above, and the video clips are from 21:10.

7.19 <u>'Nadar's Nadir'</u> 25 August 2019

In early 2019 I sought, and was given permission, to change my doctoral studies from the Cape Peninsula University of Technology to the newly introduced PhD at my university DUT. At CPUT I was registered for a Doctorate in Design, at DUT my registration was the PhD: Visual and Performing Arts. Although the essence of my studies was much the same, it required a different contextual framing of the research. My main focus in 2019 was to adapt my studies to this new qualification, and get my proposal submitted and approved. I thus spent less time on the mechanics and practical aspect of the studies and more time on the theoretical. My objective was to re-engage with the practical at the end of 2019 and into 2020 before writing up my results.

The nett result was that I only managed to prepare for and shoot one event in 2019, the annual Man and Machine event, this time held in the Boston area of KwaZulu-Natal. (I had originally planned to cover the Roof of Africa once again, but in October 2019 had an accident whilst out riding my off-road bike and badly injured my shoulder, which incapacitated me for a few months.) I planned to shoot both days of the event and prepared two sites of interest for each day. Once again, I would be working on my own, unfortunately, so would have to settle on sites with which I could access with my van.

The site on which I eventually settled was not everything I had expected. When I looked on Google Earth I thought the riders would be riding right next to a river, but instead they rode along the river, but instead they rode along the embankment above the river. This meant that where I was expecting slow, interesting technical riding they instead were able to cruise almost in a straight line. The riders then crossed the river.




**<u>Illustration 7.65:</u> Auto Mission for 'Nadar's Nadir'**

I did not have much choice and mapped the course. Initially during my test flights, I stopped short of the river-crossing since I have made it a policy to avoid flying over water wherever possible in case of a malfunction and crash. However, once I saw that the ride along the embankment was not really enthralling in any way, I decided to try a new technique at the river-crossing. I extended the waypoint out until it was directly above the crossing, then when the drone got to this point I changed the mode into Loiter whilst at the same time tilting the camera directly and vertically downwards. This is quite a bit to

**<u>Illustration 7.65:</u> Frame grab 1 from 'Nadar's Nadir'**

**<u>Illustration 7.66:</u> Frame grab 2 from 'Nadar's Nadir'**

think about in the middle of a flight when you have to 'feel' your way through the controls (because of the goggles still over your eyes), but I got the knack with practice in successive flights.

I thought the results were both compelling and refreshing. Refreshing because I had not used this technique before, and so it was a new way of interpreting the scene. Compelling because this long, lingering overhead wide-shot allowed the viewer to scan the scene and take in different aspects of the travails of crossing the river. Riders are negotiating the rocks and deep pools, some are struggling to climb the far riverbank, some are falling off on the slippery rocks, other are coming to assist their friends by picking up fallen bikes and helping them through. The action evolves within the scene; the camera doesn't move as usual. I was very happy that the software and mechanicals were set up perfectly so that in Loiter the drone neither changed altitude nor orientation, but was 'rock steady' in its positioning. The riders' struggles alone provide the action and drama.

**<u>Illustration 7.67:</u> Frame grab 3 from 'Nadar's Nadir'**

I have previously referred to the early French balloonists, in particular the earliest-known aerial photographer, Gaspard-Felix Tournachon. His profession at the time was photographing family portraits, and he practised under the pseudonym 'Nadar'. I imagine that if he were able to tether his balloon to the riverbank almost two centuries later he would have looked directly down and been as fascinated by the scenes unfolding below him as I am by these visuals. A confirmation of the 'aesthetic' potential of the aerial view!

Some frame grabs from the day are shown in Illustrations 7.66 – 7.68, above, the auto mission course in Illustration 7.65, above, and the video clips are from 22:55.

7.20 <u>2020</u>

My intention was to hone my skills further in subsequent events in 2020, but the world was hit by the totally unpredicted Covid-19 pandemic. One of the results of the ensuing lockdowns was that all sporting events were put on hold, including enduro motorcycling. At first all events were cancelled, but as the lockdowns became less restrictive some events returned but under strict conditions. One of these conditions was that no spectators were allowed, and this continues into 2021, as I write. The result was that I was not able to attend or shoot at any further events. Not knowing what the future might hold and when we would be allowed to attend again, I decided to write up what I had done so far, up to the end of 2019, to avoid what might become an interminable delay in my research.

7.21 <u>The Video</u>

The video which accompanies this written account forms part of my practice-based research; and ultimately constitutes the end goal of the research. The other inseparable component of this project is the design and construction of the drones and unmanned aerial system specific to the research. The video is about 29 minutes long and includes selected scenes from each of the locations that I shot. The individual locations are subtitled according to the sections of this chapter to provide a reference. I have not made any adjustments to the video; the shots are as they are downloaded from the camera without any post-production such as slow motion or changes in frame-size. (Obviously, a skilled editor would make many changes to the final product for broadcast.) All I have done is cut and join the various selected shots. This video is not meant to be part of a broadcast, it is an 'archive' of some of the work I have done and should be viewed in that context. I have also included a few 'out takes'; the significance of these will become apparent as you watch the video.

I have elected to include a music track to accompany the visuals, in order to aid the viewing experience. The only 'live' sound I had recorded is the whine of the drone motors and props. Whilst this is interesting to listen to – particularly the change in tone as the drone yaws and changes direction – it does after a while become a little incessant. The sound of the motors would never be presented as part of a final broadcast video. So, to ease this whine and in an effort to make the viewing experience more pleasant, I have erased such sound and included the music. At the very end of the edited video, I have included a clip of what the drone sounds like (at 28:17), just for reference and so that the viewer can experience the change of tone of the motors change as they correct for in flight manoeuvres. The music I have chosen is entirely personal, and includes the following tracks:

| | |
|---|---|
| Pink Floyd: | 'Learning to Fly' |
| Talking Heads: | 'This Must be the Place' |
| Frank Zappa: | 'Watermelon in Easter Hay' |
| Yes: | 'And You and I' |

The video is archived for viewing here: https://youtu.be/hMdoe9I8dlU

[Browser keyword search: Pete Burnett PHD Drone Edit]

# CONCLUSION

What has this study meant for me, personally? It raises three questions. Did I achieve my aims? What did I learn? And what does the future – and my involvement in it – hold?

I achieved the aims I had when I set out on this journey. I designed, I built, and I deployed an autonomous unmanned aerial system in the form of a purpose specific Unmanned |Aerial System. I applied the tenets of Action Research whilst doing so. I took this system out into the remotest of regions and, through trial and error (fundamental to Action Research) got the drone to work successfully. I followed enduro racers in their 'natural habitat' and brought back footage which in my assessment was not only compelling but, more importantly, suggested new directions in both filming and portraying the sport. What I hope to have done is to lay the groundwork for further development – en route to market – of both the purpose specific drone design and the filming of outdoor sporting events.

What have I learnt? I hope that the written component of this has provided the necessary corollary information to the design of the drone. Early on I mentioned that this would be a test of my abilities as a researcher, a designer, a constructor, and a videographer. Thankfully I had a wide body of tacit knowledge on which to draw, and from a construction perspective I only had to develop from scratch the techniques for working with carbon fibre. Getting familiar with the software was a steep and continuous learning curve, but made easier by the support of the online forums. Working in remote areas was made easier by the prior experience I had from both riding and photographing enduros. Understanding what I wanted to achieve was made easier by having worked in the field of sports broadcasting for many years.

Having said this however, I am aware that doctoral studies are in no way meant to be easy. If I look back through what I learnt the most was about my character, in particular my resilience. I cannot count the number of times I had to 'pick up the pieces', both literally and figuratively. I was drawn to the parallels between my work and what is also a current study, albeit on a much larger scale; that of South African-born entrepreneur and Spacex leader, Elon Musk. I have followed – I realise – a similar path to that of Musk's Starship project. Design, Develop, Deploy, Crash, Gather the Data, Analyse it; then repeat the process, again and again, until the craft flies (and lands) successfully. Spacex has crashed so often the company have even developed an acronym, RUD; which stands for Rapid Unscheduled Disassembly. When my drone crashes the result is a few arms, or legs, or props to replace; Starship crashes, on the other hand, are accompanied by great balls of fire, ejected slivers of metal, and total destruction of the aircraft. That is Action Research in its most brutal and grandest form, and yet Musk too picks up the pieces and continues, whilst at the same time achieving incredible success and progress along the way in his vision of conquering space. My personal tribulations may seem trivial in comparison; yet at the time they were sorely testing to me and those closely involved in the project.

I developed a symbiotic relationship with the drone. I have spent so much time thinking about it, building it, flying it, seeing it crash while at the same time at marvelling at its potential capabilities. I was often in awe of the pictures it had given me; the advancing and receding changing landscapes, the insight into the riders' movements and control of the motorcycle, the sense of the 'enduro rider' single-handedly tackling the vast open terrain. I was particularly struck by the change in perspective of the pictures, as the drone circled around a moving rider, providing viewpoints from the rear, the side, and the front; all within a long lingering shot. Such changing perspectives – not possible with conventional ground based videography – promises a future in the portrayal not only of enduro-riding, but television coverage of outdoor remote sports more widely.

What I learnt also was to trust both myself and the systems with which I was working. I will try to describe one example. I have written about how the drone performed by flying forwards, sideways and backwards; with the only view I had being that of whatever the camera is pointing at. The only way I can describe this feeling is to say it is akin to sitting in the back seat of a car which is moving down the freeway, but has no driver. The only view you have is out of the back window. It is, at first, unnerving; both not being able to see where you are going, but also knowing that your fate rests entirely in the systems which have been programmed into the vehicle. Even though you are concentrating almost entirely on the camera view, there is a subconscious but close-to-the-surface feeling of helplessness. This was something I had not expected or anticipated when I set out on this project. It took many autonomous flights before I could subdue this feeling, and even to this day there is an element of nervousness as I change the mode switch to ‘Auto’. But I learnt to trust the systems which I had built and programmed, so that now I am at a completely different level of confidence when I do so.

To reiterate, this study has moved beyond just a ‘means to an end’ of completing my PhD, and instead has become a new interest in my life; something with which I want to stay engaged and take further still. I have already begun the design of a new drone, much like the current designs; but with the commercial availability of folding props I am able to build it smaller and more compact than the two I have referred to in this project. Not only will this give me a smaller package to transport, but it should also increase flight times from the same batteries. There are also two new systems I might include, one has already been developed and the other will require much work.

The first is known as Real Time Kinematics (RTK), and it is a system which I seriously considered when building the first two drones. RTK is used for autonomous navigational purposes, and can give centimetre-level accuracy in positioning the drone in all three dimensions. This is unheard of when using ‘domestic’ level commercial GNSS navigation, which at its best can only position the drone to a level of about 2 metres (in a three-dimensional sphere). RTK uses specialised antennae for GNSS reception, and includes an extra ‘reference’ base-station from which the drone receives data (via the mission software). These antennae are prohibitively expensive (of the order of R25 000 each) and I would need three of them, one for the reference station, one for the pseudo drone, and one for the actual drone. It was not only the expense though that put me off integrating this development into my system; it would require carrying a large, very stable tripod for the reference antenna out into the mountains, as well as several hours of setup at each location. Interestingly, the RTK software known as RTKLIB is also available as open-source, developed by Mr Tomoji Takasu of the Tokyo University of Marine Science and Technology, and is available on github (https://github.com/tomojitakasu/RTKLIB).

The second is a system which at this stage I can only anticipate. As I alluded to in Chapter 6 when I wrote about the gimbals, I would like to incorporate a function on the drone yaw which is both rate and position sensitive. I envisage a potentiometer with a revolving knob wired into the radio controller. I could launch and land the drone using the traditional yaw stick, but once I engaged Auto flight it would at the same time deselect the yaw stick and engage the rotating knob. The drone heading would be referenced to this knob; as I rotated it, the drone would yaw in unison, and if I stopped the movement the drone would stop as well. Essentially the direction of the front of the drone (in a 360 degree continuous arc) would correlate with the position of the knob whilst in autonomous flight. This would alleviate the problems I had with only having control over the yaw rate, and not the position. To achieve this, however, would require a substantial rewrite of the Arducopter code, something beyond my abilities and something I would need to pose to future developers.

This leads me to where I think related research might be most valuable. I believe that employing autonomous flight greatly simplifies the process of shooting from drones. Having to fly the drone manually – and competently – requires many hours of practice. By mastering the intricacies of autonomous flight and letting the drone do the flying whilst the operator concentrates on the pictures shortens this learning curve tremendously. Not only that but it allows the operator the opportunity to get the shots from the side, and from the front flying backwards, that would otherwise be impossible flying manually because you need to 'see where you are going'. This opens up shooting from drones to a whole new field of videography. For example, it creates an easier way for 'traditional' ground-based camera operators to progress and develop new skills, simply because the drone (actually the entire UAS) is doing most of the work for them, leaving them to hone their skills at camera coverage rather than drone flight control.

I also made a prediction in Chapter 5 of the racers having their own personal drones (supplied by the broadcaster) which would 'wake up' as the racer got in the vicinity of the drone staging area, would launch autonomously, and follow the rider through a specified section of the course, then return and land autonomously. This may seem farfetched but I believe I have enough knowledge of autonomous systems, enduro-racing and television broadcasting to predict that this will be common in the future; and not too distant future at that. Drone development (in all sorts of different fields and applications) is progressing extremely rapidly and it will not be long before broadcasters decide the viewing benefits of such a system outweigh the expense in developing and maintaining it.

To end, I return to the epigraph to Chapter 4: a quote from Prof Donal Fitzpatrick when he said to me '…if you think it will be impossible, you will find a way to do it.' At the time, this suggested an impossible dream. Yet here I am reminded of a quote from the father of our young nation, Nelson Mandela, who in a speech in 2001 said, 'It always seems impossible, until it is done'.

It is done – the drones, the videos, and the thesis.

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visio.microsoft.com

www.sketchup.com

# **ANNEXURES**

Annexure A (1)

CONCEPT:

FLY A CAMERA PLATFORM BEHIND A MOTOR VEHICLE TOTALLY (??) AUTONOMOUSLY.

WHY?: * TYPICAL 'PILOTED' HELICOPTERS CAN'T GET DOWN/IN AMONGST THE ACTION.

* VEHICLE/HELMET CAMERAS ONLY GIVE THE 'FRONT WHEEL VIEW' OF THE ACTION.

* FOR OFF ROAD BIKES HELMET CAMS ARE 'BUMPY'

* NEED TO SEE ENTIRE VEHICLE/BIKE IN FRAME, MOVING AROUND THE FRAME

↳ TYPICALLY ~~HERE~~ WITH VEHICLE MOUNTED CAMERAS/HELMET CAMS THE FRAME MOVES WHILST THE VEHICLE IS STATIONARY.

↳ THIS IS THE OPPOSITE OF WHAT REALLY HAPPENS – ESP OFF ROAD BIKES THE BIKE MOVES & THE SURROUNDINGS ARE STABLE.

* THE PLATFORM MUST BE STABLE: USE GYRO TECHNIQUES.

HOW?: * CONTROL?: TOTALLY AUTONOMOUS? OR HUMAN CONTROL?

TOTALLY AUTONOMOUS: PLACE MARKER ON BIKE/CAR

CAMERA PLATFORM DECIDES TO BE ~~[illegible]~~ SO FAR BEHIND/ABOVE RIDER.

HOW? * MARKER GIVES OFF INFO. GPS? (ACCURATE ENOUGH?)

GPS COORDINATES + SPEED SENT TO CAMERA PLATFORM.

& DIFFERENT CARS/BIKES CAN HAVE DIFFERENT MARKERS/BEACONS.

CAMERA PLATFORM DIVERTED TO EACH IN TURN BY 'MASTER CONTROL'.

HUMAN CONTROL: NEED TO BE CLOSE - RADIO CONTROL/LINE OF SIGHT

WILL NEED LIVE FEED FROM CAMERA PLATFORM TO PROVIDE VISUAL TO 'FLY IT'.

(FOR 'AUTONOMOUS' VERSION RECORDING CAN HAPPEN ON CAMERA PLATFORM).

AUDIO: DEPENDING OF CAMERA PLATFORM. IF MODEL CHOPPER (NOISY) WILL NEED MIC ON CAMERA, RELAYED TO VIDEO RECORDER. BUT WILL NEED T/C SENT TO BOTH TO SYNC AUDIO/VIDEO)

Annexure A (2)

ONCE WE HAVE THE BASICS RIGHT, WE COULD:

* IF ~~B~~ RIDER FALLS / ~~S~~ STOPS IT COULD CIRCLE AROUND.
* IF 2 RIDERS CLOSE ~~BE~~ BY THEN STAY BEHIND 2ND RIDER, IF HE PASSES PERSON IN FRONT THEN DROP BACK BEHIND 2ND PLACE AGAIN.
* TRACK RIDER FROM FRONT, FACING BACKWARDS. (COULD BE DISCONCERTING TO RIDER)
* PROBLEMS WILL OCCUR WITH TREES / BRIDGES.
  - ↳ ON PRE DETERMINED TRACK PLATFORM COULD BE PROGRAMMED TO FLY LOWER / THROUGH BRIDGE (OVER?)
  - ↳ OFF ROAD WILL NEED SYSTEM WHICH RECOGNISES THINGS IN THE WAY, ~~&~~ 'DODGES' THEM.
  - ↳ THIS LIMITS THE SIZE OF CAMERA PLATFORM. MUST ~~BE~~ BE SMALLER THAN MOTORCYCLE WIDTH TO FIT BETWEEN TREES.

Annexure B

# Optimal rotor arm pivot angles for a collapsible drone.

by
Peter Burnett and Hugh Murrell

January 9, 2021

## Problem Description

Consider the CAD drawing of the collapsible drone shown in figure 1 below:

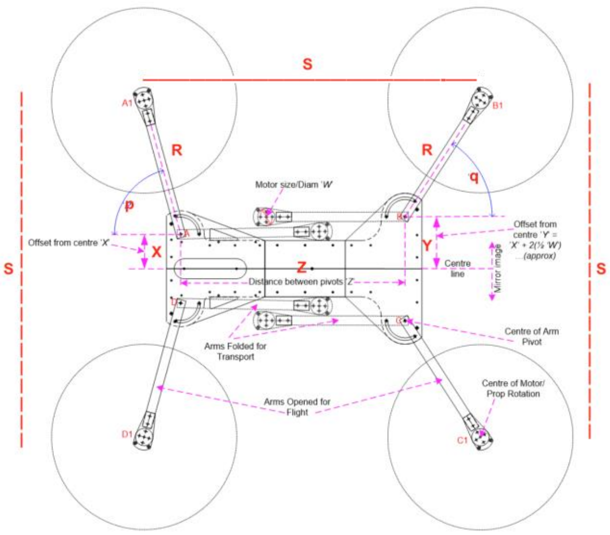


Figure 1: CAD drawing of drone with collapsible arms

In this diagram all lengths are measured in *mm* and the annotated lengths are design parameters for the construction of the drone:

*R* the length of the rotor arm (all rotor arms have the same length) *Z* the distance between

rotor arm pivot points.

*X* the offset of the front pivot arm point from the horizontal axis of symmetry.

*Y* the offset of the back pivot arm point from the horizontal axis of symmetry.

The problem is to determine the rotor arm angles, *p* and *q*, under the constraint that the rotor centres form a square.

## Constraint Problem

Using the constraint that the rotor centres form a square with sides of some unknown length *S* we have:

$$
\begin{aligned}
S &= R\cos(p) + Z + R\cos(q) \\
S &= 2(X + R\sin(p)) \\
S &= 2(Y + R\sin(q)) \qquad (1)
\end{aligned}
$$

The first equation in (1) is derived from an expression for the horizontal edge of length, *S*, whilst the last two equations are derived from expressions for the vertical front and back edges of length *S*.

The unknown edge length, *S*, can be eliminated from equations (1) yielding two non-linear equations for the angles, *p* and *q* shown in equations (2) below.

$$
\begin{aligned}
\cos(p) - 2\sin(p) + \cos(q) &= \frac{2X - Z}{R} \\
\sin(p) - \sin(q) &= \frac{Y - X}{R}
\end{aligned}
\qquad (2)
$$

Although it is possible to find a closed form solution for *p* and *q* the calculation requires finding the roots of a quartic polynomial which is extremely tedious as one can see from the Wikipedia entry [1].

So instead we use standard non-linear root finding technique. For example, the scipy python package allows us to construct the solution shown in the appendix.

To make life easier for the reader we have also coded a javascript solution to the problem, again using a numerical equation solver. This time we found that Martin Donk's javascript library, nerdamer [2] allowed us to compute *p* and *q* using a non-linear equation solver. And we also made use of the Microsoft javascript CAD library, Maker.js [3], to produce drawings dependent on the user's parameter settings.
To access the javascript application goto:

https://hughmurrell.github.io/DroneDesign/index.html.

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## Appendix

### pythod code for calculating rotor arm pivot angles

```
from scipy . optimize import fsolve from math import sin , cos , pi

def equations ( vars ): p, q = vars R = 225
        Z = 346
        X  = 56
        Y  = 84
        eq1 = cos (p) − 2∗ sin (p) + cos (q) − (2∗X−Z)/R eq2 = sin (p) − sin (q) − (Y−X)/R
return [ eq1 , eq2 ] p, q = fsolve ( equations , (1 , 1))

p = (p / pi ) ∗ 180 q = (q / pi ) ∗ 180

print (p, q)
```