Modernisation of Fault Detection for Diagnosis Routines in Elevators

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By

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Declaration

I, Olalere, Isaac Opeyemi, do hereby declare that this dissertation is the result of my own investigation and research, except to the extent indicated in the Acknowledgements and References.

I undertake that all materials presented in this dissertation are my own work and any published work of another person has been duly acknowledged and referenced.

This work is being submitted for the degree of Master of Engineering (Industrial) in the Department of Industrial Engineering. It has not been submitted to any other university for any other degree or examination.

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Olalere, Isaac Opeyemi Date

Dedication

This research work is dedicated to God Almighty for being my constant help and for taking me this far in life.

I also dedicate this research work to my late parents Mr and Mrs Olalere, I admire the legacy you left us, and may your souls rest in peace (Amen).

Acknowledgement

My most sincere gratitude goes first to the Almighty God for helping me through to this point of my research and making my progress a great success.

I would like to express my profound gratitude to my supervisor Prof. B. Nleya and co-supervisor Mendon Dewa for their great support, guidance, and encouragement during the course of the programme. I am very grateful, and I can’t thank you enough.

I also want to acknowledge my brother, Dr F.E. Olalere for his support, morally and financially.

My gratitude also goes to my siblings, Olalere Oluwaseyi, Olalere Kemi, and Olalere Paul for their togetherness and encouragement always, and also my guardian, Ms Gladys for her support in all ways since my arrival to the republic of South Africa and my uncle, Mr Akintola, for his support.

Abstract

Maintenance of elevators has become critical in ensuring continued operation by preventing excessive wear and breakdown. Maintenance greatly affects elevator downtime and uptime, hence the need for modernising elevator maintenance to stay abreast of other competitors. This research focuses on the modernisation of maintenance in elevator systems to reduce breakdowns through scheduled maintenance via remote condition monitoring for fault detection using the Internet of Things (IoT) technology. The monthly scheduled maintenance policy for the elevator system, however, increased the downtime of the system due to lengthy response time to attend to elevator breakdowns. This research therefore adopts remote monitoring of the elevator system's condition for early detection of malfunctioning and faults notification for a just-in-time maintenance response.

The parameters which could indicate a fault, deterioration, or damage of the elevator system were identified. The methodology embraced building and configuring an electronic monitoring device which comprises of the sensors, LED light, a voltage source, breadboard, jumper wires and an IoT microcontroller. The microcontroller is programmed to monitor temperature, 3 axial vibration, and acoustics parameters of the elevator system. Data and fault notifications are sent to a registered email for remote monitoring access on the cloud. The IoT devices and controller make use of any back up system which can be accessed in the cloud as a secondary storage system for the data being read by the sensors and notification updates. The back-up system used in this research is electronic mail. The read data from the machine was posted, together with the fault notification in cases of malfunctioning of the condition, to an email cloud server.

The results show that remote condition monitoring of the elevator system is a better maintenance approach as it reduces the downtime of the elevator system through just-in-time fault notification, trend monitoring for fault troubleshooting and also diagnosis of fault from historical events. This is indicated by a considerable reduced response time, (81%) as compared to the initial state of the system, with a total response time of 45.4 hours for the 6 fault notifications experienced during the condition monitoring unlike 240 hours for 4 breakdowns before modernising the maintenance approach. Five of the six breakdowns experience were indicated by both vibration and acoustics parameters which shows they are complimentary in fault diagnosis. An optimised limit for each parameter was also derived using control chart for variables analysis.

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List of acronyms

AEM Abnormal Event Management

CBM Condition Based Monitoring

CMS Condition Monitoring System

CPS Cyber Physical System

CS Control System

DPS Distributed Parameter System

EPF Enhanced Partial Filter

FDD Fault Detection and Diagnosis

FDP Fault Detection and Prediction

HMI Human Machine Interface

IDE Integrated Development Environment

IM Induction Machines

IoNT Internet of Nano Things

IoT Internet of Things

MCSA Motor Current Signature Analysis

MSB Modulation Signal Bi-Spectrum

NDT Non-Destructive Testing

OEE Overall Equipment Effectiveness

O&M Operation and Management

OSHA Occupational Safety and Health Administration

PDF Probability Density Function

PHB Process History Based

PM Predictive Maintenance

RFID Radio Frequency Identification

SCL Serial Data Line

SDA Serial Data

SEDA Small Enterprises Development Agency

WTC World Trade Center

Research Outputs

Articles submitted to journals for review:

I.O. Olalere, M. Dewa and B. Nleya,. *Early Fault Detection of Elevators Using Remote Condition Monitoring Through IoT Technology*. Submitted to: South African Journal of Industrial Engineers (SAJIE) 2018. (Accepted for publication).

Articles prepared for submission to journals for review:

I.O. Olalere, M. Dewa and B. Nleya,. *Artificial Neural Network Based Fault Detection of Elevators Using Time-Domain Features.* Prepared for submission to: Advances in Data Analysis and Classification. Springer Heidelberg 1862-5347, Germany, 2018.

Conference Papers/Abstracts Proceedings

Olalere, I.O., Dewa, M. and Nleya, B. 2017. Remote Condition Monitoring for Fault Indication in Elevators Using an IoT Technology for Improved Maintenance. *South African Institute of Industrial Engineering (SAIIE) 28th Conference. 25-28 October,2017, Vanderbijlpark, South Africa. Pp 33391-8*

Olalere, I.O., Dewa, M. and Nleya, B. 2018. Remote Condition Monitoring of Elevator's Vibration and Acoustics Parameters for Optimised Maintenance Using IoT Technology. *31st Annual IEEE Canadian Conference on Electrical and Computer Engineering (CCECE 2018). 13-16 May 2018, Quebec, Canada IEEE Pg 1-4.*

CHAPTER 1 : INTRODUCTION

1.1. Introduction

This chapter discusses the introduction to the research, the problem background, research aim and objectives, justification, scope of the project, structure of the report, and conclusion. The chapter discusses highlights on the current condition of the elevator system and the significance of the research.

The problem of fault detection in distributed parameter systems (DPSs) is formulated by maximising the power of a parametric hypothesis test that checks whether system parameters have nominal values. A lot of research has been done in terms of technological advancement towards reducing machine failures and faults in industrial systems. However, due to the complexity of these industrial systems, eliminating system failure still poses a great challenge in most industries. Faults and failures can be explained generally as deviation from normality to abnormality by a system, process, or component caused by varying working conditions and parameters. Wang *et al.* (2014), also define a fault as departure from an acceptable range of an observed variables or calculated parameters associated with a process.

Fault Detection and Diagnosis (FDD) is concerned with automating the processes of detecting faults on physical systems and diagnosing their causes. FDD is an area of investigation concerned with automating the processes of detecting faults (Srinivas and Michael 2005; Severson *et al.,* 2016; Shu *et al.,* 2016). This involves the timely detection of an abnormal event, diagnosing its causal origins and then taking appropriate supervisory control decisions and actions to bring the process back to a normal, safe, operating state. This entire activity has come to be called Abnormal Event Management (AEM), a key component of supervisory control (Costa, 2016). Modern industrial systems cannot exist without fault detection and diagnostics subsystems. (Dmitry *et al.,* 2009; Xiao *et al.* 2017). These therefore give rise to an important phenomenon which is the maintenance of elevators. If a manufacturing or service industry is to remain sustainable, there is a need for human and capital resource investment in the maintenance of its machinery.

1.2. Problem Background

Elevator systems faults often result in increased running costs and cost of production due to process or machine downtime as well as industrial accidents in some cases which may also lead to loss of several invested capitals. Failure analysis is a cross-disciplinary working area that combines diverse fields such as fractography, metallography, chemistry, mechanics, design issues, non-destructive testing (NDT), and others (Zerbst *et al*., 2015). Some cases of industrial machine faults or process failures may also result in industrial hazard and accidents. One instance is whereby a furnace worker was killed in an explosion when a boiler lid, 20 feet in diameter, flew off inside the TIMET titanium manufacturing plant on 900 Hemlock Road in Morgantown (Occupational Safety and Health Administration, 2015), is an example of process failure.

Another such incident happened on November 8, 2012 in Sherbrooke, Quebec, Canada, where two people died and 19 were injured after the failure of an industrial processing plant of a health-care products company, as reported by CBC news (2012). Presently, most maintenance decisions are mainly based on failure events and machine breakdowns. Nevertheless, in many cases and for many types of equipment, this event can rarely be seen or can happen after many years of utilisation (Mortada and Yacout 2011). This often results in loss of machine time and reduction in productivity of the industry due to the repair and restoration which requires special skills. Also, in a large process plant with several inter-dependent events whose output of one is the input to another, poses a great downtime to the whole process plant, thereby reducing the profit index of the company. Elevator systems considered in this research are located at the S block building of Durban University of Technology, Durban, South Africa.

There are four (4) elevator systems installed on the building with one accessible to only the staff, and other three (3) for public use. These elevators are installed and maintained by OTIS elevator company in 1982. The company play an important role in this research as the research is carried out under the supervision of one of the maintenance supervisor. The geared elevator system's average breakdown in a month is four (4) times when maintained immediately after breakdown, however, the downtime is usually longer due to the complexity of the system and the repair time. The other three (3) elevator systems have an average breakdown of two (2) to three (3) in a month. Due to the frequency of usage and the reliability of the gearless elevator system, one of the gearless elevator systems on S7 block was selected to be used for this research. The elevators are subjected to a monthly scheduled maintenance, while a reactive maintenance is adopted whenever there is breakdown in the system.

Table 1.1 One Month Downtime Table for the Elevator

	Response Time (hours)	Repair Time (hours)
1st Breakdown (27/02/18)	24	8
2nd Breakdown (16/03/18)	72	54
3rd Breakdown (24/03/18)	48	24
4th Breakdown (05/04/18)	96	96

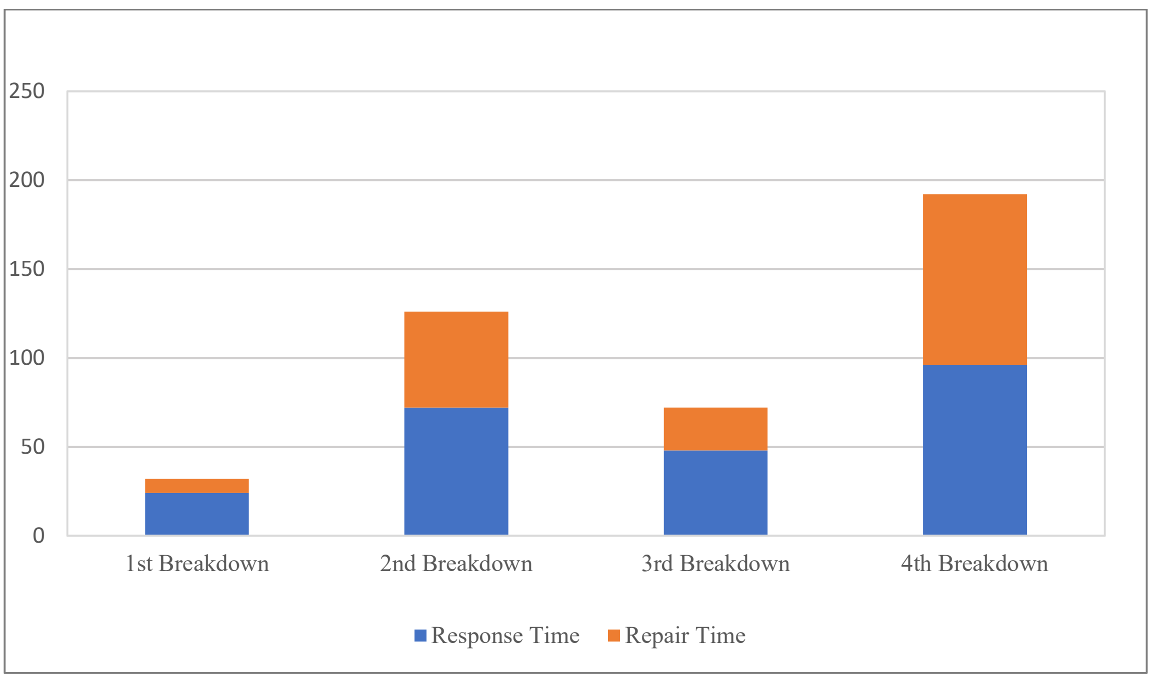

Figure 1.1: One Month Downtime Chart of an Elevator in DUT

(Source: DUT Maintenance Department)

Since the elevator system is not manned, therefore the breakdown in the system is not easily identified by the maintenance team. This scenario therefore leads to increased downtime of the elevator system. The chart in Figure 1.1 shows the downtime of the elevator system before the breakdown is noticed together with the downtime for the repair. It can be deduced from the chart and Table 1.1 that there is higher downtime due to the inability of the maintenance team to notice the breakdown of the elevator system on time. The bar chart in red colour also indicates the time to repair the system.

Therefore if the condition of the machine's significant components is assessed accurately, the mean effective life length of the component can be prolonged (Zhao *et al.,* 2016). This would improve the overall equipment effectiveness (OEE) and consequently result in higher company savings and enhanced competitiveness. It will also lower the hazard involved in process failure due to effective condition monitoring maintenance using an artificial intelligent method. In more detail, the CMS must be able to elaborate so-called 'deterioration patterns', obtained from fault related symptoms. CMS can be considered as a tool for 'process optimisation', achieved by upgrading the life span of critical components to match the time between periodical maintenance activities (Euro pump guide, 2012). A number of components with several varying parameters are monitored using this technique. The parameters may include, flow, pressure, power, speed, temperature, vibration, lubrication and wear, corrosion/erosion, and fracture amongst others.

1.3. Research Aim

The aim of this research is to enhance elevator efficiency by reducing the downtime of elevator systems or processes due to breakdown maintenance.

1.4. Research Objectives

The objectives of this research are as follows;

- To identify the distributed parameters which are major underlying factors for faults in elevator systems.
- To modernise maintenance routines through a remote monitoring technique for fault detection and notification.
- To diagnose the condition of machines for early detection of deterioration through assessment of the considered parameters.

1.5. Justification

CMS can be considered as a tool for 'process optimisation', achieved by upgrading the life span of critical components to match the time between periodical maintenance activities (Euro pump, 2012). When implemented correctly, a condition-based maintenance system will help to lower maintenance costs, increase machine availability and reliability, improve safety, enhance product quality and in many cases, extend the life of the equipment (Hamilton, 2005). A lot of model-based approaches have been applied across many research areas of condition monitoring, however, this project work employs a process history-based approach in fault detection and diagnosis in elevator systems. The issue of maintenance has been a very important one in the growth and survival of many industries. South Africa's international manufacturing output, at a percentage of total world manufacturing output, decreased from 0.61 per cent in 1990 to 0.5 per cent in 2010 (SEDA, 2012). This would indicate a downstream in SA's manufacturing/industrial sector of the economy and the need for this position to be strengthened. Maintenance can be considered a potential factor that could affect both the labour and running cost simultaneously, hence a great motivation and need for this research work.

Therefore, if fault detection and diagnosis approach in elevator systems is modernised into remote condition monitoring, then the downtime due to maintenance can be successfully lessened or reduced. This study therefore adopts the Internet of Things (IoT) for condition monitoring as a modernised mode of detecting and diagnosing elevators' faults. IoT of things approach is preferred because of the ability to access data on internet at any location in the world unlike using just one remote base stations. This would reduce device downtime through remote monitoring and support. This would give easy access to some elevators' components which are highly susceptible to failure but located at a remote position in the machinery or workstation. The condition can easily be transmitted and monitored on the internet which makes it easy monitoring and logging of machine history before any major catastrophic failure occurs. This could easily be achieved by using an IoT device which has an already built in circuitry sensor and internet transmitter. This also comes with a software platform for integration which makes the installation easy and user friendly. This allows authorised access to the condition of the machinery online by the maintenance team. Hence, the on-condition of the machine can be monitored remotely, and the history can also be used by the maintenance team for further prevention of failure.

1.6. Significance of the Study

This study tries to develop a maintenance approach that could reduce the overall downtime of the elevator system due to breakdown. This begins with identifying the parameters which could indicate malfunctioning of the elevator system, develop a remote monitoring device for this parameter, develop the severity level of the parameters based on expert knowledge and artificial intelligence and programming the device for early fault notification.

1.7. The Scope of the Research

This research focuses on a remote condition monitoring approach for elevator maintenance. Remote condition monitoring maintenance uses the intelligence approach of monitoring machines or process conditions, data capturing with fault notification. The data is used as the basis for preventive maintenance in diagnosing the condition of the machine in order to reduce the downtime of the elevator system due to delayed notification and troubleshooting of breakdown in the system. A key to condition monitoring preventive maintenance's effectiveness is knowing how many hours, miles, gallons, activations, or any other kinds of use have occurred before an item failed (Bayoumi and McCaslin, 2016). This research work optimises maintenance by adopting and using the approach of detecting and logging in of data with notification from the machine using Internet of Things (IoT) devices. IoT devices are a technological advancement in sensor technology which develops an approach of integrating data from the sensor instrument to the internet. Therefore, the data being monitored from the machine can be assessed and monitored, with fault notification, remotely on the internet, through the IoT devices.

The IoT devices are configured and installed at some locations on the machine where the needed parameters to be monitored are most likely to have significant impact and sensitivity. This approach gives a new dimension in condition monitoring which helps to overcome several limitations and challenges such as, but not limited to, high downtime, safety, and accessibility.

1.8. Structure of the thesis

Chapter 1: Introduction

This chapter focuses on the research area, the problem background, aim and objectives and justification of the study.

Chapter 2: Literature Review

This chapter consists of the survey of related literature and the summary of the previous research results.

Chapter 3: Methodology

This chapter discusses the available methods on maintenance policies, the choice of the method of this research (modernisation of fault detection and diagnosis routines in elevators) and details on how the research was carried out.

This chapter contains the design of the sensors network in the spatial location of the case study for the monitoring of the parameters considered. It also discusses the signal and data capturing by the sensors network, fault detection and diagnoses remotely which is the interest of this research work.

Chapter 4: Remote Device Design and Installation

This chapter consists of the design of a remote monitoring device and installation on the elevator system.

Chapter 5: Results and Discussion

This chapter contains the result of the development process, numerical data analysis from the data and instrumentation and the discussion of the findings.

Chapter 6: Conclusions and Recommendations

This chapter focuses on the discussion of research conclusions, recommendations, and further research to be done in this area.

1.9. Conclusion

This chapter gave some background information of the research area. The key areas of focus include the problem background of the research, which is the current situation and condition of the elevators on campus; the aim of the study which is to apply maintenance knowledge in increasing the efficiency of the system by reducing the downtime; as well as the objectives of the research, the justification and the scope of the research. The chapter also gave a highlight of the structure of the dissertation and an overview of its contents.

CHAPTER 2 : LITERATURE REVIEW

2.1. Introduction

This chapter discusses literatures on maintenance, breakdown maintenance, preventive maintenance, predictive maintenance, proactive maintenance, condition monitoring maintenance, overview of elevators, machine critical parameters, fault detection, fault diagnosis, Internet of Things, IoT application, maintenance practices on elevators, identification of parameters for fault detection, performance monitoring for severity and variation and conclusion. The literature explains each sub-heading as it relates to past research work and current efforts in this area.

So many challenges have been addressed in literature for manufacturing systems with diverse failure patterns and maintenance strategies. These have been aimed at ensuring that productivity is enhanced by cutting down machine downtime due to faults and failure, at a much-reduced cost of maintenance and bringing the system to a normal condition. The maintenance effort is called out of the competitive nature of the production-based economy where each industry seeks to edge out others in all ways. The down side in the maintenance policy of a company could impair its growth and ultimately lead to its collapse. Therefore, it is better that maintenance is put in place right from the onset of the production process, so that the deterioration pattern of the machine can be monitored, and breakdown prevented.

2.2. Maintenance

Maintenance is carried out in order to restore an industrial process or machine condition back to its normal state or working condition. According to the Longman Dictionary, maintenance is the effort that is required to keep something in good working condition (Longman Dictionary 2012). Maintenance is also defined as all technical, administrative, and managerial actions during the life cycle of an item intended to retain, or restore it to, a state in which it can perform the required function (Ben-Daya, Kumar and Murthy 2016).

The definitions therefore imply that maintenance are the actions taken to inhibit or prevent a component, device or machine from failing, or either to repair normal equipment degradation experienced with the operation of the device to keep it in proper working condition. The need for maintenance is predicated on actual or impending failure and ideally, maintenance is performed to keep equipment and systems running efficiently for at least design life of the components (O and

M Best Practices Guide 2015). Maintenance activity can reduce the breakdown rate with minor sacrifices in production time (Kaibiao and Hongxing 2010). The basic objectives of maintenance activity is to deploy the minimum resources required to ensure that components perform their intended functions properly, to ensure system reliability and to recover from breakdown (Márquez, 2007; Gulati, 2012; Niu, 2017). Maintenance provides critical support for heavy and capital-intensive industries by keeping the productivity performance of plants and machinery in a reliable and safe condition (Parida *et al*., 2015).

If proper planning and control is exercised for maintenance and repairs, it will cause and increase the useful life of machines, reduce maintenance and repair cost and reduce sudden downtime (Shiba *et al*., 2013). Proper maintenance practices can contribute to overall business performance through their impact on the quality, efficiency and effectiveness of a company's operations. Therefore, maintenance can enhance the company's competitiveness, i.e. productivity advantages, value advantages and long-term profitability (Alsyouf, 2009; Crespo Márquez *et al.,* 2014).

There are quite a few maintenance policies adopted to correct faults and failure in machines and processes which are:

- Breakdown maintenance
- Preventive maintenance
- Proactive maintenance
- Predictive maintenance

(Levitt, 2011; Faccio *et al.,* 2014; Lee *et al.,* 2016).

2.2.1. Breakdown/Reactive Maintenance

Breakdown/Reactive maintenance is basically a maintenance mode in which no action is taken until the machine stops working. In this mode of maintenance, nothing is done in terms of actions or effort in maintaining the facility until breakdown occurs. The breakdown of equipment occurs due to gradual wear and tear of the parts, which cannot be prevented (Ahamed-Mohideen and Ramachandran, 2014). This maintenance mode is a failure-based maintenance practice which has comparatively more disadvantages than advantages.

Breakdown/Reactive maintenance has a low cost of running because it minimises the amount of manpower to utilise as well as the cost of keeping the machines running (Couch, 2016). The disadvantage, however is unanticipated repair which in turn incurs high costs of repair, fluctuating production capacity, increased scrap out, and catastrophic failure which may endanger the machine operator or personnel (Apodaca, 2017).

Since machine breakdown will reduce production efficiency, maintenance as an important part in manufacturing systems is used to keep machines in good condition to decrease failures, which makes maintenance planning become more and more important in manufacturing processes. (Pan *et al*., 2012). Therefore, breakdown maintenance is only acceptable when a machine is redundant. Any machine with a higher maintenance cost than its replacement cost should be allowed to fail when it represents no risk to safety, production or product quality (Dennis, 2003; Campbell and Reyes-Picknell, 2015).

2.2.2. Preventive Maintenance

Preventive maintenance (PM) is a maintenance programme with activities initiated at predetermined intervals, or according to prescribed criteria, and intended to reduce the probability of failure, or the degradation of the functioning of an item (Shaomin and Zuo, 2010; Dienst *et al.,* 2015). Saumil *et al*., (2010) carried out a theoretical study of exponential machines with maintenance-reliability coupling, according to which the machine breakdown rate is inversely proportional to the rate of preventive. Preventive maintenance gives rise to an increased component life span, reduced failure of equipment and processes and allows for flexibility of maintenance with estimated 12 per cent to 18 per cent cost savings over reactive maintenance programmes (O and M Best Practices Guide b 2015). However, it leads to the increased cost of staff training and maintenance costs. Catastrophic failure may still occur, and frequent maintenance may also damage some good parts.

2.2.3. Predictive Maintenance

Predictive maintenance optimises the plant operation by using the actual current operating condition of the equipment or plant (Bevilacqua *et al.,* 2016). Predictive maintenance is a positive condition-based maintenance methodology that a machine's condition can be estimated and predicted through continuous monitoring (Fan *et al.,* 2011). Liao *et al.,* (2011) develop a data-driven machinery prognostics approach used in estimating a machine's health condition and machine degradation prediction based on statistical pattern recognition and on an auto-regressive moving average model. This offers a lot of advantages as maintenance is planned at a convenient time. The continuous assessment and prediction of a machine's performance can thus enable collaborative machine life cycle management, which conducts predictive maintenance to prevent unexpected machine failures and reduce unscheduled costly downtime (Kaiser and Gebraeel 2009; Jin *et al.,* 2016).

However, the cost of diagnostic equipment is high with increased overhead costs. Predictive maintenance or condition-based maintenance offers the highest economic efficiency, but also presents the largest challenge on how to ascertain whether a machine is working normally or abnormally i.e. in a fault condition or a condition requiring maintenance (Hackstein *et al.,* 2014).

2.2.4. Proactive Maintenance

Proactivity refers to the ability to avoid or eliminate undesired future events (Engel and Etzion, 2011; Bousdekis *et al.,* 2016). Proactivity is leveraged with novel information technologies that enable decision making and support human actions before a predicted critical event occurs (Bousdekis *et al*., 2015). Proactive-based maintenance is a systematic and holistic approach to building a maintenance system in such a way as to guarantee optimum safety, integrity and to approach failure-free operation (Mostafa, 2004; Abuhmida, Radhakrishnan and Wells, 2015). Hence, this maintenance mode tends to be optimised as compared to other maintenance methods. This is a very effective maintenance programme as it reduces frequent overhauls and increases the reliability of the component. It also reduces machine downtime as it prevents sudden equipment failure.

However, it could involve a high cost of implementation and savings are not easily noticed by the management. With proper planning of the maintenance activities, the shop can improve production efficiency and safety, resulting in increased productivity and heightened safety awareness (Bahr, 2014; Alayón *et al.,* 2017).

2.3. Condition Based Maintenance

The Condition-based maintenance (CBM) system provides raw platform data that is combined with other supporting and confirming information for analysis and action (Gulledge *et al.,* 2010;

Jantunen *et al.,* 2017). Recently, CBM policies are growing in popularity in industrial environments. Many of these policies are applied to decrease the cost of maintenance activities which are the largest part of any operational budget, so CBM is extensively used in the production environment (Safari and Sadjadi, 2011). The strategy is typically implemented by first identifying a reliability team that performs a qualitative assessment of plant process and machinery to determine the criticality of the assets (Parra *et al.,* 2016). Here, the decision to shut down the machine for maintenance is based on its condition which, with the currently available highly sophisticated instruments and equipment, can be determined very accurately, using a variety of on-line surveillance and condition monitoring techniques. The monitoring and fault prediction functions of a condition-based monitoring system is based on robot sensor equipment for continuous measurements, and this system performs online evaluation of characteristic fault indicators by use of modern digital signal processing methods (Nirosha *et al*., 2014). Chee *et al.,* (2014) uses a transition-based autoregressive moving average model and an enhanced particle filter (EPF) to predict probability density function (PDF) and breakdown time of unobservable degradation processes.

Xinhua *et al*., (2015) uses the condition monitoring approach for monitoring a machine tool process using thermoelectric module to harvest the waste heat being monitored from the spindle units of a machine tool using wireless sensor stable, thermal structure design, and optimisation of the thermoelectric module. Many condition monitoring techniques have been developed to detect and diagnose abnormalities of wind turbines with the goal of improving gearbox reliability and increasing turbine availability, thereby reducing operation and maintenance cost (Sheng and Veers 2011). Condition monitoring, which is part of predictive maintenance (PM), uses predictive techniques to measure output from specialised instruments that signal the level of equipment deterioration (Davies, 2012).

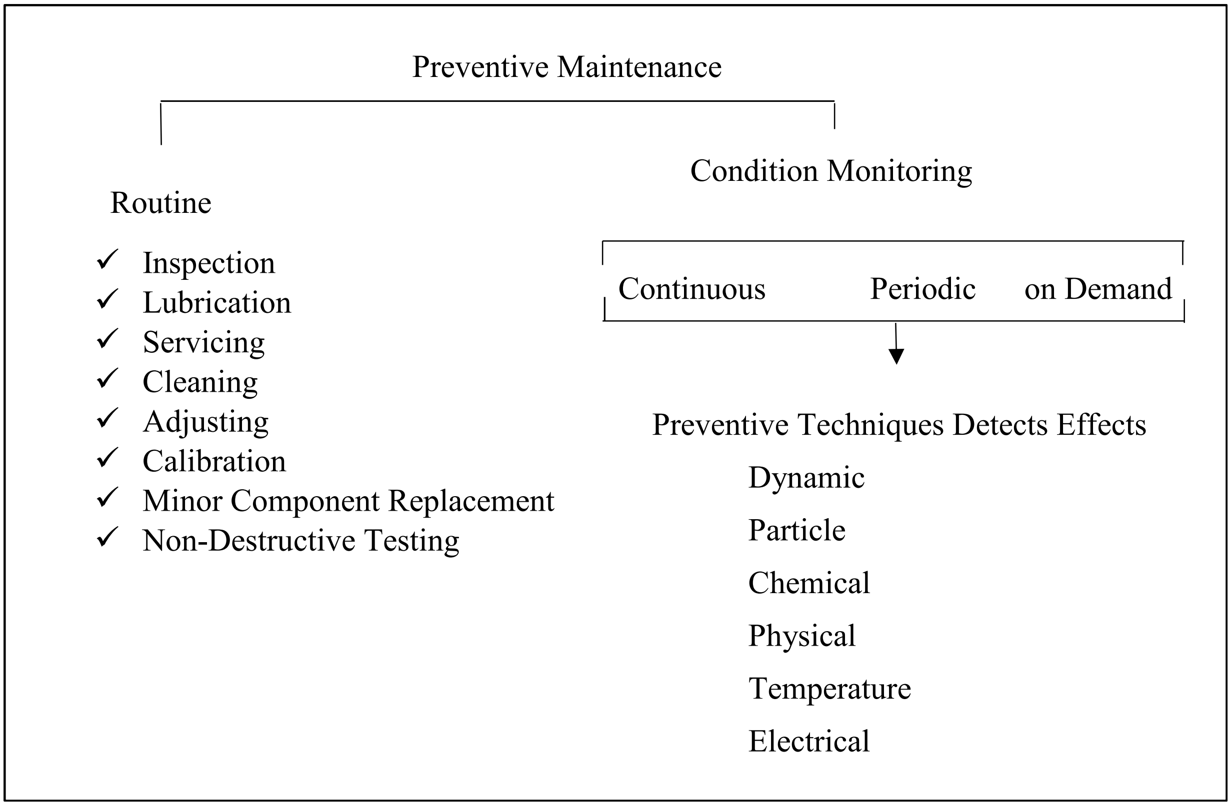

Figure 2.1: Preventive Maintenance Technique

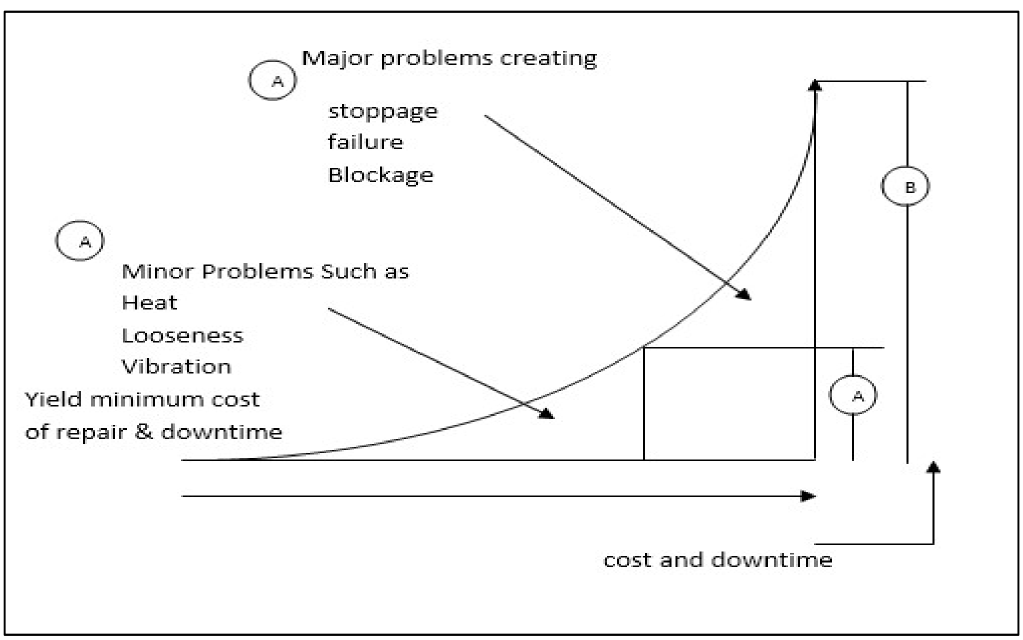

Figure 2.2: Chart of the Equipment Deterioration Against Repair Cost and Deterioration

(Tomlingson, 2007)

Figure 2.1 and Figure 2.2 (Tomlingson, 2007) illustrate that the greater the degree of equipment deterioration, the greater the repair costs and duration of downtime to make the repair. A CBM programme, if precisely done and efficiently employed, can significantly decline the maintenance cost by decreasing the number of needless scheduled PM activities (Ehram and Sayed, 2011). Machine condition monitoring is the most preferred predictive maintenance tools in various industries as through various condition monitoring methods, a monitoring professional can detect, predict and prevent a wide array of machines and equipment failure as reported by global trends and forecast 2020 (ReportBuyer, 2015).

2.4. Overview of Elevators

Elevators have successfully made the possibility of high rise buildings visible as its operation has become essential to any high rise building (Barney and Al-Sharif, 2015). The elevators transport human beings and goods vertically upward, helping to overcome the work done by gravity. Without the elevators, downtown skyscrapers and high rise buildings in city life would become an idea that cannot be conceived (Bernard, 2014). Therefore, the use of elevators has continuously grown as there are more than seven billion elevator journeys taken in buildings all over the world (Al-Kodmany, 2015). Elevators require effective inspection frequently in order to draw the appropriate maintenance strategy and to sustain its functional operation (Kalligeros, 2012). Elevators generally consist of three principal mechanical parts, a traction machine which is composed of traction motor, a main sheave and breaker, the cage and the counterweight which is used to balance the cage and connected to the second sheave of the traction machine through a moving pulley (Park and Yang, 2010). Some of these parts are peculiar to some industrial machines which makes the research replicable to the industrial machines adopting the same approach. There are several classifications of elevators based on the characteristics being considered or the principle of operation. Otis (2013) classifies elevators as: Hydraulic, Screw and Motor driven elevators.

Hydraulic elevators are used preferably in elevators where large payloads need to be carried and it makes use of a direct-acting arrangement or side-acting hydraulic cylinders (Engineering, 2009). A hydraulic elevator includes a car engaged with a first hydraulic ram, a counterweight engaged with a second hydraulic ram, and a pump to transfer hydraulic fluid between the hydraulic arms (Matthews *et al.,* 2016).

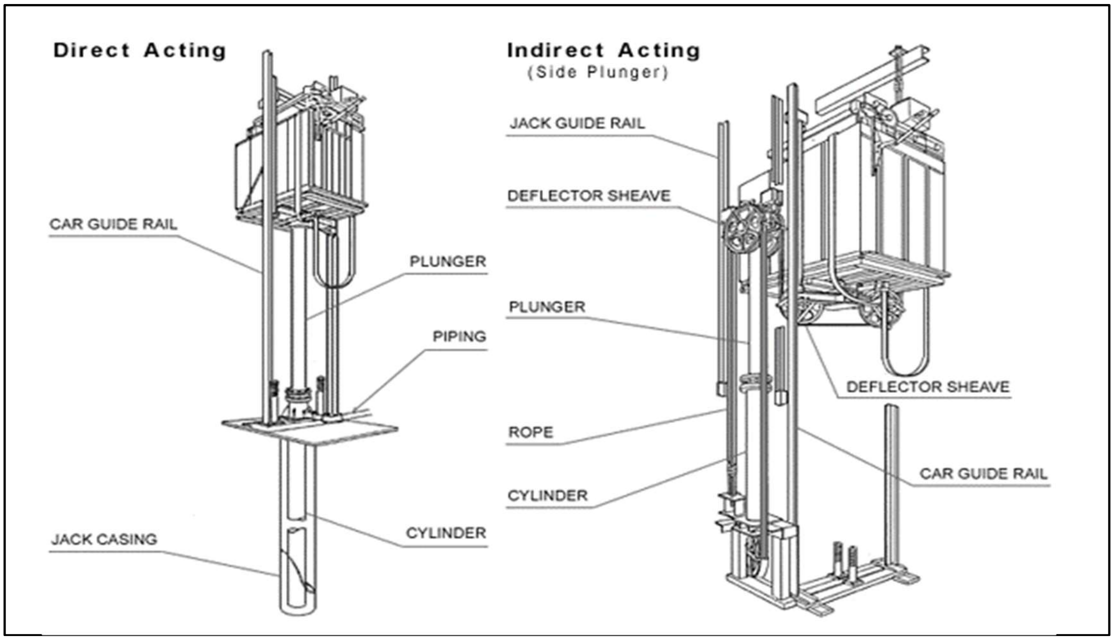

Figure 2.3: Side Acting Arrangements with two Cylinders in Hydraulic Elevators

(Source: *https://www.mitsubishielevator.com/products/elevators/hydraulic*)

Figure 2.3 illustrated by Mitsubishi Electric (2016) gives the drawings of the two (2) types of hydraulic elevators; the sides acting which has the plungers on the side of the elevator car; and the direct acting, which has the plungers underneath the elevator car. They require a pit and machine room which must be built before installation and also require more maintenance than other elevator drive systems (FUJIHD News, 2016).

Helical screw driven elevators have a screw drive system which propels the elevator car vertically up and down (Buehl, 2010). The helical driven lift also requires a lift pit that houses the drive system for the lift and elevators. The lift pit of 1.85m deep, is needed for a bottom-drive lift while a lift pit 1m deep for the top-drive lift mostly operates at a maximum speed of about 0.63m/s (Department of Public Works, 2007).

Elevators that work with cables and wheels are referred to as traction elevators because it involves a motor pulling on the car and the counterweight as explained by Toshi (2016). The traction elevators are classified into two types which are the geared elevators and the gearless elevator type as shown in Figure 2.4 and Figure 2.5 respectively.

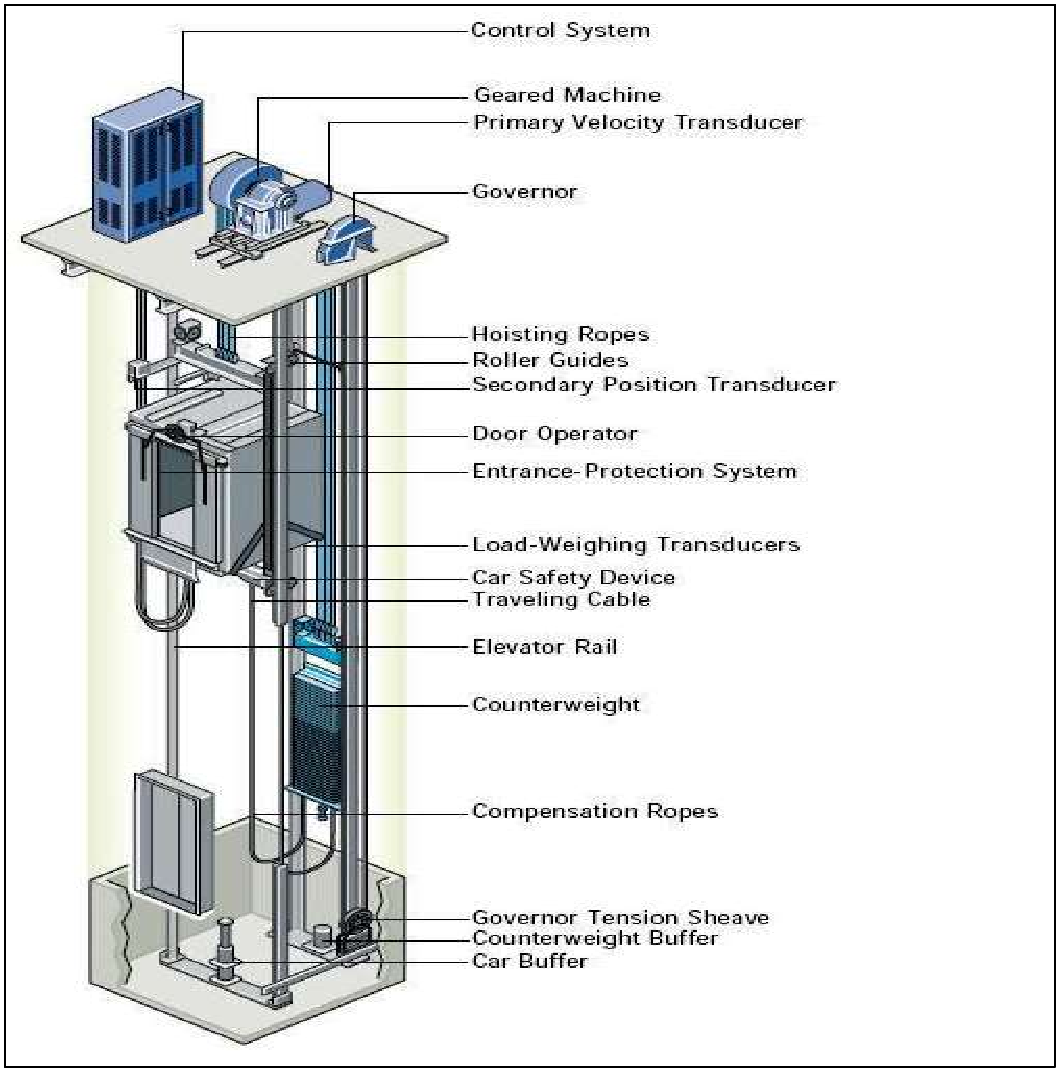

Figure 2.4: Geared Traction Elevators

(Source: http://www.electrical-knowhow.com/2012/04/basic-elevator-components-part-one.html)

In order for the load on the motor to be reduced, the counterweight is calculated to match the weight of the car and a half-load of passengers such that as the car rises, the counterweight descends, balancing the load (OTIS, 2016). Elevators may also be categorised as the following:

- Gearless Machine: The gearless machine drive is used in high rise applications. This driving machine has the drive motion and drive sheave connected in line on a common shaft, without any mechanical speed reduction unit located between the drive motor and drive sheave. Gearless machines are used for high speed lifts between 2.5 m/s to

10 m/s and they can also be used for linear speeds for special applications (http://www.electrical-knowhow.com/2012/04/basic-elevator-components-part-one.html). Figure 2.6 shows the engineering drawing for the gearless machine as illustrated by Djibring (2016).

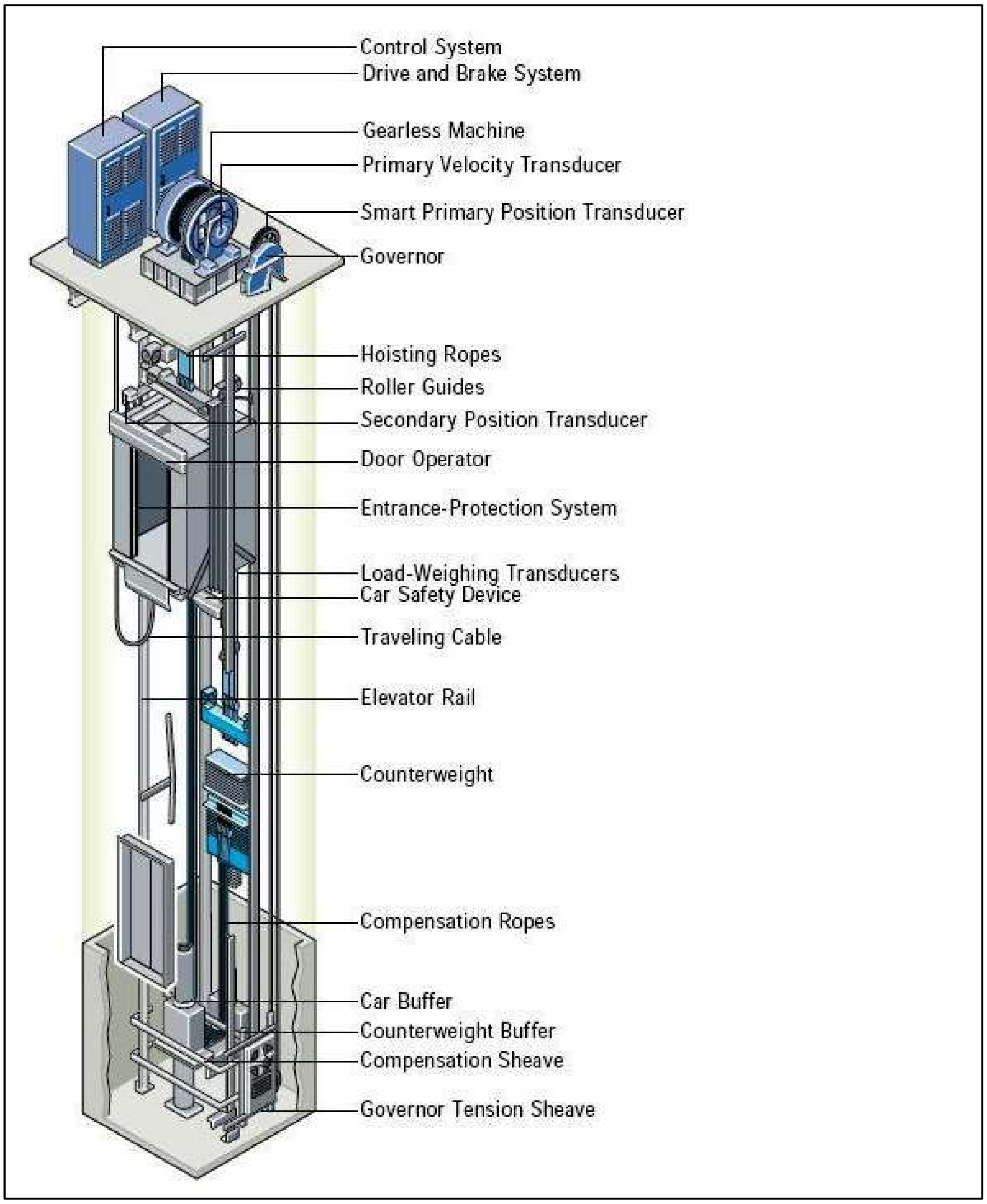

Figure 2.5: Gear-less Traction Elevator

(Source: http://www.electrical-knowhow.com/2012/04/basic-elevator-components-part-one.html)

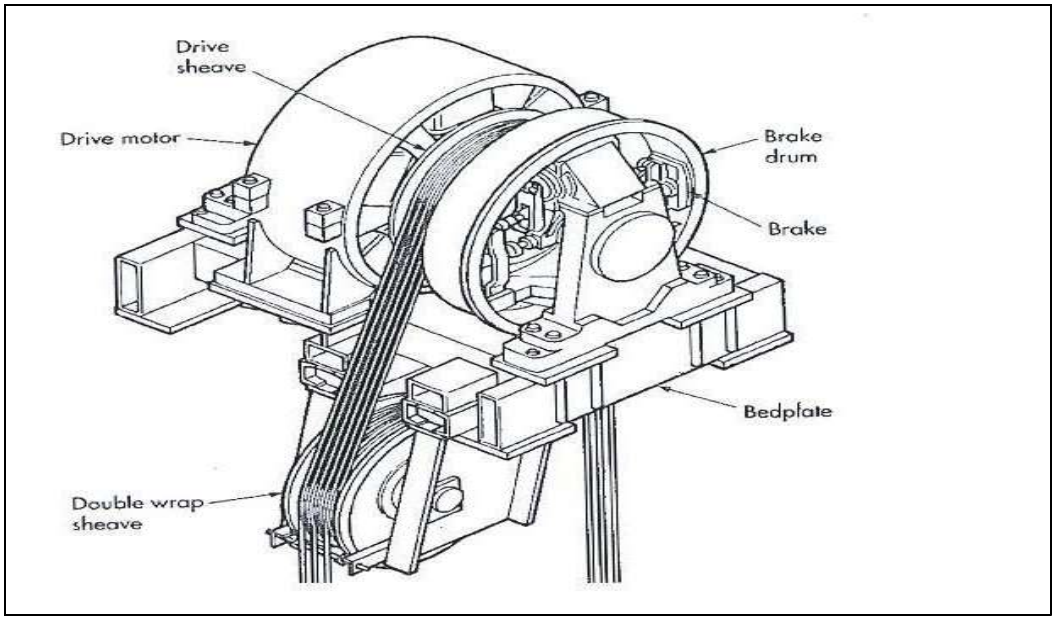

Figure 2.6: Gear-less Drive Traction Elevator

(Source: http://www.electrical-knowhow.com/2012/04/basic-elevator-components-part-one.html)

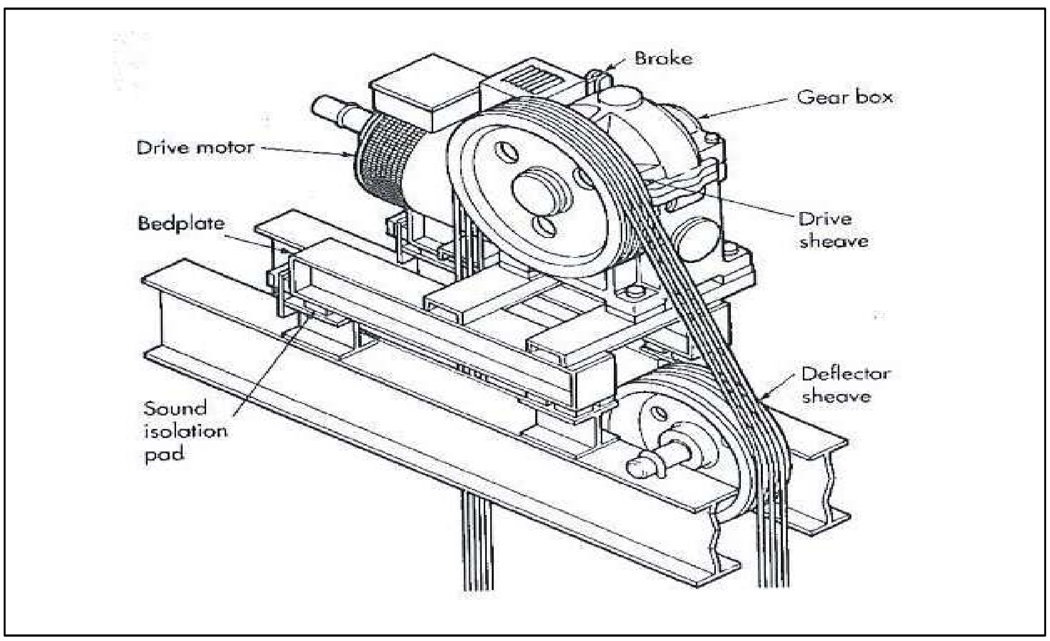

Figure 2.7: Gear Drive Traction Elevator

(Source: http://www.electrical-knowhow.com/2012/04/basic-elevator-components-part-one.html).

- Geared Machine: This type of machine is used in low and mid-rise buildings and applications. This design makes use of a mechanical speed reduction gear set that reduces the rpm of the drive motor (Input Speed) to suit the required speed of the drive sheave and elevator (output speed) (Mostafa *et al.* 2015). A geared machine is suitable for higher loads and is meant to operate at a lower speed. The engineering drawing is illustrated in Figure 2.7.

2.5. Machine Critical Parameter

The condition of some components of an elevator system is of critical importance to the health condition or wellness of the machine. Machine health prognosis is crucial to reduce unexpected downtime, maintenance costs, and safety hazards in industrial systems. Pang *et al.*, (2014) proposed a novel methodology to predict probability density function (PDF) and breakdown time of unobservable degradation processes. Motor current signal analysis (MCSA) has become the reference method for the diagnosis of induction motors (IMs) which is a non-invasive method, requiring just a current sensor to capture the stator current, and it can identify a wide variety of motor faults using just a single measurement (Sapena-Bano *et al*., 2014). Kar and Mohanty (2008) identified loss of lubrication, crack initiation, and propagation, surface wear, surface fatigue, and structural fatigue as the five (5) failure mechanisms in gearbox. Cibulka *et al.*'s (2012) work on bearing failure showed that larger deformation causes an increased level of noise and vibration and leads to a feel of wear and corrosion, providing a significant contribution to the total material loss. Zipp (2010), and Annamdas *et al.,* (2016) introduced an intelligent vibration monitoring for wind plants, which is a vibration data acquisition system consisting of embedded accelerometers, high speed digital signal converts, and a wireless network. Any deviation from the nominal values of these conditions could indicate an impending damage initiation on the machine.

Konrad *et al*., (2015) monitored parameters such as vibration analysis, oil monitoring and analysis, acoustic emission, ultrasonic testing techniques, strain measurement, process performance, radiographic and thermography, in order to detect and diagnose abnormalities of wind turbines using condition monitoring techniques. Vibration is often given less importance but can be a symptom of a malfunctioning process or machine and is frequently a signal of danger (Genta, 2012; Duan *et al.,* 2016). The simplest and most commonly used method for detecting the presence of faults using vibration analysis involves the comparison of different signals against a machine working under healthy conditions (Ruiz-Cárcel *et al.,* 2016). Due to a slight imperfection in the manufacture of the worm gear of the hoisting motor, vibrations were transmitted to the sheave shaft which were taken up by the hoisting ropes, which in turn transmitted them to the frame work and elevator cab (Kenany *et al.,* 2016).

Weinberger (2015) also developed a sound pick-up device installed at a point in the shaft of the counterweight roller to detect the elevator deterioration indicated by vibration over time due to the progressive ageing process of the bearing of the counterweight support roller causing the functional failure of the bearing (Clark *et al.,*). Stranieri and Mangini (2010); and Smith (2016) invented a noise management device for attenuating noise from the machine room that houses a drive such as geared machine or electric motor, that generates periodic sound waves and mechanical vibration.

Table 2.1: Parameters for Occurrence of Faulty Conditions on a Rotating Machine

Parameter Measure Detected Condition	**Temperature of Machine**	**Pressure of Process fluid**	**Flow of Fluid**	**Oil Analysis**	**Spike Energy of Bearing**	**Vibration of Machine**
Out-of-Balance						X
Misalignment	X					X
Bent Shaft	X					X
Ball-Bearing Damage	X			X	X	X
Journal-Bearing Damage	X	X	X	X		X
Gear Damage				X		X
Mechanical Looseness						X
Mechanical Rubbing					X	X
Noise						X
Cracking						X

Mingfeng (2012) also developed an elevator safety detector whose feedback and diagnosis is based on characteristic signals, comprising of a signals detection unit connected sequentially to a vibration and noise information for signals and data acquisition unit of the Microprocessor. Therefore, during the running progress of an elevator, the useful signals of vibration of the elevation car present low-frequency signals and noise signals with high frequency (Qifeng *et al.,*, 2016). The higher the precision level in measuring the parameters which indicates the online condition of the machine, the closer we are at identifying the initiation of deterioration in the machine condition. Hence, this apparently avoids the phenomenon known as damage as maintenance of the machine can be scheduled earlier, therefore reducing machine downtime due to maintenance in a great deal while prolonging the life time of the machine as well.

The information in Table 2.1 by Ugechi *et al.,* (2009), indicates the occurrence of faulty conditions and the likely parameters that could probably indicate the fault. It also shows that some more parameters can indicate a condition.

2.6. Fault Detection

Most currently used damage identification methods are included in one of the following categories: visual or localised experimental methods such as acoustic or ultrasonic methods, magnetic field methods, radiography, eddy-current methods or thermal field methods (Zhang *et al.,* 2016; Balageas *et al.,* 2016). The fault detection method or technique is determined by the type of maintenance that is adopted by an industry. Maintenance optimisation is a paramount issue for industries that utilise physical assets due to its impact on cost, risk, and performance (Andrewus *et al.,* 2007; Zhang *et al.,* 2017). In modern industry, the maintenance strategies have so far changed from the age-old corrective and preventive ones to the condition-based maintenance (CBM) due to innovation and developments of sensing technology (Zhang *et al.,* 2013). This recent trend has given rise to better machine and system effectiveness as the downtime of machines is reduced. This has also eased the debugging and diagnosis process in most systems and machines as the on-condition state and the deterioration pattern can be monitored and easily identified.

Detection of machine faults like mass imbalance, rotor rub, shaft misalignment, gear failure, and bearing defects is possible by comparing the vibration signals of a machine operating with and without faulty conditions. Accelerometers, eddy-current proximity sensors, and velocity seismic transducers are enabling the techniques of motion, position, and expansion analysis to be increasingly applied to large numbers of rotating equipment (Agrawal, 2017). These signals can also be used to detect the incipient failures of the machine components through online monitoring systems, reducing the possibility of catastrophic damage (Samhouri *et al.,* 2009). Chandrashekhar and Ganguli (2016); Pedram *et al.,* (2017) developed a damaged detection method using the sensitivity of modal frequency changes. Ibrahim *et al.,* (2014) presented a new approach to detection and diagnosis of bearing fault severity based on vibration analysis using a Modulation Signal Bi-Spectrum (MSB). The results show that MSB has a better and reliable performance in extracting small changes from the faulty bearing for accurate fault severity.

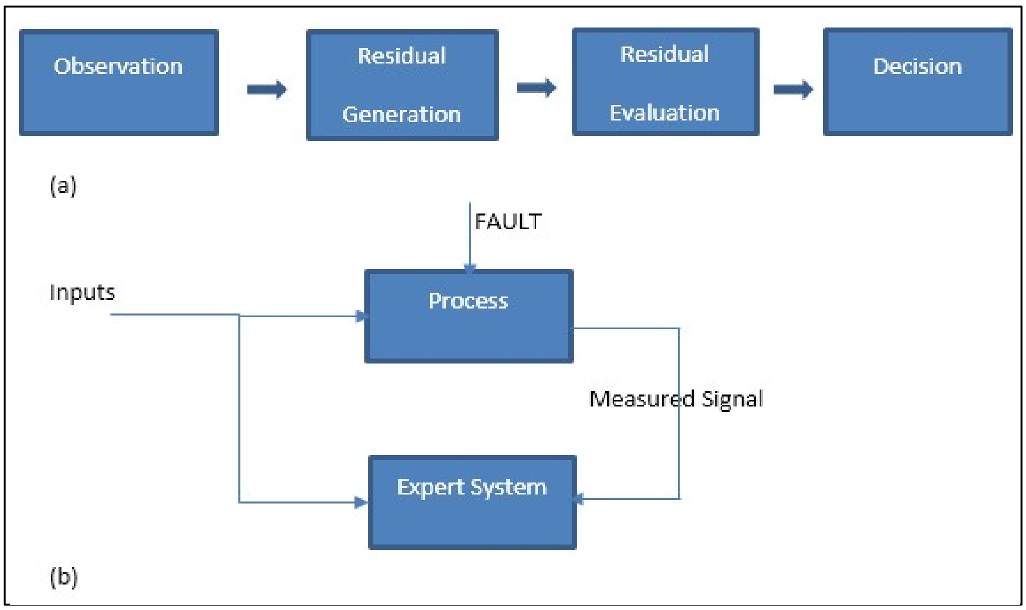

Figure 2.8: The Model Based Method for Fault Detection

(Source: Hammed *et al.,* 2009)

Machine faults are gradually being detected using artificial intelligence methods because of its increased accuracy, robustness, and avoidance of some subjective human errors. The part labelled 'a' in Figure 2.8 illustrates the general idea of the model-based methods while the part labelled 'b' shows an expert system approach which can be used to generate residuals and allow detection of changes in the system behaviour and leads to fault detection and possible diagnosis (Hameed *et al.,* 2009).

2.7. Fault Diagnosis

The aim of diagnostics is to detect faults or failure and to determine the type, location, and severity of them, based on analysis of the existing data, including the data obtained by monitoring as well as design data and historical data and even user knowledge (Kenneth *et al.,* 2005; Lingmei *et al.,* 2017). The two fundamental ways to address fault diagnosis tasks necessary to perform a predictive maintenance are rule-based techniques and the machine learning technique (Patents Researcher, 2015). Tribology knowledge is of a major importance in understanding many failure mechanisms and their symptoms (Roylance, 2003; Kenneth *et al.,* 2005; Wolff, 2017).

Tribo-knowledge deals with understanding the principles, mechanisms, and operating conditions of a machine in order to help with tribo-diagnosis of the failure mechanism. Nadakath *et al.,* (2008) identified problems such as unbalance, bent shafts, mis-alignment, oil whirls, mechanical looseness, resonance bearing problems, coupling problems, earth faults in windings, turn to turn faults in windings, broken windings, displacement of stator conductors, electrical activity in bearings and seals using an artificial intelligence approach on plant maintenance. Wan *et al.* (2015) applied vibration signals of various elevator functions, their energy characteristics and time domains in diagnosing deviated shapes of guide rail shoes, erroneous rope grooves of traction sheaves. Parameters were monitored during the operation of the machine to be monitored, in such a way that a change in the machine, was deduced when at least one monitored machine parameter reached sits limit value (Patents Researcher, 2015).

2.8. Internet of Things (IoT)

IoT refers to the networked interconnection of everyday objects, which are often equipped with ubiquitous intelligence (Feng, 2012). Chen *et al.,* (2014) also defines IoT as an intelligence network which connects all things to the internet for the purpose of exchanging information and communicating through the information sensing devices in accordance with agreed protocol. Out of many emerging technologies, Internet of Things (IoT), also known as machine-to-machine (M2M) (where smart devices that collect data, relay information to one another, process the information collaboratively, and take action automatically) is a new paradigm offering both challenges and opportunities (Yen-Kuang 2012).

From a conceptual standpoint, the IoT builds on three pillars, related to the ability of smart objects to: (i) be identifiable (*anything identifies itself*), (ii) to communicate (*anything communicates*) and (iii) to interact (*anything interacts*) – either among themselves, building networks of interconnected objects, or with end-users or other entities in the network. Developing technologies and solutions for enabling such a vision is the main challenge ahead of us (Miorandi *et al.,* 2012). Scalability, modularity, extensibility, and interoperability among heterogeneous things and their environments are the key design requirements for IoT (Bandyopadhyay and Sen, 2011; Sotiriadis *et al.,* 2017).

There are a variety of things or objects – such as Radio-Frequency Identification (RFID) tags, sensors, actuators, mobile phones, etc. – which, through unique addressing schemes, are able to interact with each other and cooperate with their neighbours to reach common goals (Giusto *et al.,* 2010). Specifically, the integration of sensors/actuators, RFID tags, and communication technologies serves as the foundation of IoT and explains how a variety of physical objects and devices around the society can be associated to the Internet and allow these objects and devices to cooperate and communicate with one another to reach common goals (Van-Kranenburg, 2011). Through embedding short range mobile transceivers into some other array of additional devices and items, enabling new forms of communication between people and things and between things themselves, the IoT would add a new dimension to the world of information and communication (Debasis and Jaydip, 2011; Maria de Fátima and Radwan, 2017).

2.9. IoT Applications

A number of industrial IoT projects have been conducted in areas such as agriculture, the food processing industry, environmental monitoring, security surveillance, and others (Li *et al.,* 2014). Based on current technological trends, one can readily imagine a time in the near future when your routine physical examination is preceded by a two to three days' period of continuous physiological monitoring using inexpensive wearable sensors that record signals correlated with your key physiological parameters and which relay the resulting data to a database linked with your health record (Moeen *et al.,* 2015).

IoT-aided robotics solutions perfectly match the needs of industrial plants and smart areas. It has been observed that robotics-driven activities are more important as long as tasks are executed in areas forbidden to people (i.e. as inside a machine, within as furnace, or in a room filled of lethal gas and liquids). Moreover, they can provide valid support in outdoor scenarios (like smart grids and energy plants) (Grieco *et al.,* 2014). With the capabilities of decision-making and autonomous control, the machine-to-machine (M2M) system can be upgraded to a cyber-physical system (CPS) which is an evolution of M2M by the introduction of more intelligent and interactive operations, under the architecture of the Internet of Things (Chen *et al.,* 2012; Kim, 2017).

Abu-Ali and Abu-Elklu (2015) identified the architectural requirements necessary for IoT-based healthcare applications, and the networking requirements for those applications. IoT connected devices have the unique capability to tell the current state to other connected devices in the surrounding, i.e. it facilitates better communication flow between human and machines (Singh and Singh, 2015). In addition, the innovation of the services through the definition of cloud computing, online services, and ubiquitous access to information is combined in order to make feasible the connection to the Internet of all the objects which are found around us, within the so-called IoT (Atzori, 2010; Molano *et al.,* 2017). These processing solutions carry out different inference steps, the conversion of the data into meaningful knowledge, involving several research fields and being the basis for the future of Internet of Things (IoT) (Castro *et al.,* 2012).

2.10. Maintenance Practises on Elevators

An elevator system has a number of maintenance practices carried out on a time to time basis to keep the elevator in a good condition at all times. Friedrich *et al.,* (2016) developed a maintenance module that combines all of the maintenance tasks, which include for example, a visual inspection of the elevator cabin, the elevator shaft, the control cabinet, and the cable and towing rope. Other maintenance modules could be overlaid which conceivably may be the drive module (greasing, cleaning, and examining hardware components of the drive), the door module, the shaft module (encompassing all hardware components of the shaft like, guide rails, cables, switches, drive head guides, counterweight guides) and the electric module. Siti *et al.,* (2018) theoretically improved the knowledge base of maintainability of elevator system by identifying operational defects on travelling performance, machine room, hoistway and elevator pit, elevator car and elevator lobby. Zhang *et al.,* (2008) tested the friction on the slide guide in an elevator system and th experiment showed frictional behaviours including pre-sliding/gross-sliding regimes, transition behaviour between them,time lag and velocity dependence. Besides comfort, elevator facility must be able to function well relative to the air conditioning system and ventilation in the elevator car (Janipha *et al.* 2018).

The temperature of the machine room also calls for the maintenance of the controls and electronic components of the system. Piper (2006) and Krarti (2017) suggest the installation of a dedicated cooling system for the elevator equipment room as the best solution for the problem of overheating of the drive and control system of an elevator. Song *et al.* (2014) designed a mechanical ventilation in the elevator shaft space to mitigate the stack effect as a result of the heat but which may not completely be eliminated.

2.11. Identification of Parameters for Fault Detection

This section addresses the first objective of the study which is to identify the parameters which are the underlying factors for fault detection on the elevators. There are several motivations for parameters considered in the elevator systems. Some of these have been taken care of by the manufacturer at the design stage of the machine. Firstly, it was assumed that the system or machine was not overloaded during use to avoid deterioration of conditions due to overloading. It is desirable that the monitoring system operates asynchronously to the payload system so that the system's throughput does not suffer due to the checking overhead (Khanna *et al.,* 2015; Monir, 2017). Secondly, it was assumed that the components of the elevator are functioning properly at installation of the monitoring system and devices. This was to ensure that the system was in a normal working state or condition at the commencement of data monitoring in order to detect the deterioration pattern of the components of the machine. Thirdly, the lift or elevators considered in this research study were the types which are installed with machine rooms. This houses the controls and the drive system of the elevators; hence the monitoring device are installed inside. Fourthly, in determining the parameters which were monitored, expert knowledge, case studies, system requirements, mode of operations and principal components were taken into consideration.

All the four assumptions were factored in as considerations in the implementation of the research. Hence, the following parameters were considered for the purpose of this study but may also be extended beyond this in the future.

2.11.1. Temperature

In the type of elevator considered where a lift pit is required, the temperature of the machine room and hoistway is a very important phenomenon in maintenance of the machine. Elevator manufacturers mostly specify temperature limits for the machine room which is typically in the 85 to 95^0F (30 to 35^0C) range and must be maintained in the controller cabinets for proper functioning of the solid state devices used in the control system (Marchitto, 2016). The controls for the elevators are situated in the machine room or on the elevator roof in the hoistway which is mostly characterised with poor ventilation design.

Adequate natural and mechanical ventilation for machinery and control equipment has to be provided in order to avoid overheating of the electrical equipment and to ascertain the safe and normal operation of the elevator as stated by A17.1 Safety Code for elevators and escalators (Grondzik and Kwok 2014). The design of the pit, due to its nature, will not accommodate the vent and therefore, this raises the level of heat or room temperature experienced in the lift pit. The effect of this is the failure of the controllers. At a level of temperature, there is a high chance of malfunctioning of the controls.

The National Elevator Industry Inc. (2013) states that at high temperature conditions, there is insulation and electronic components life reduction, erratic operation and equipment shutdown, while lower temperature causes icing, congealed lubricant hardened switch gears, erratic operation and equipment shutdown. When this happens, the elevator car might get stacked or broken down and considering some climatic conditions during summer where there could be an excessive increase in the intensity of the Sun, this would raise the atmospheric temperature and in turn the room temperature of the machine room.

Therefore, the machine room temperature is identified as one of the parameters for fault detection in elevators and can be monitored remotely to prevent failure due to excessive machine room temperature, and also to be able to diagnose if the failure was caused by increased machine room temperature.

2.11.2. Vibration

Vibration monitoring is an important method for the on-condition evaluation and monitoring of machines and civil structures (Morshed and El-Sayed, 2016). This is an important parameter which could tell the condition of the elevator. Vibration is an important phenomenon in any machinery with rotating components and drives. It is usually the indication of malfunction or severity in any system in motion. According to ISO-18738-1:2012 (2012), the major signals defining the key performance indicators of elevators and its ride quality is the definition, measurement and expression of its vibration and noise signals (Esteban *et al.,* 2016). Jiang and Rui (2015) categorises the causes of elevator vibration into two based on the mechanism source, which are mechanical vibration, caused by poor design, bad manufacturer, installable quality, weighing, suspension; and electronic vibration which includes motor, drive and control system.

Vibration could indicate a deviation in normality of conditions such as misalignment, bearing damage, mechanical looseness, gear damage, friction, noise etc. These machine faults would easily give signal for abnormality. The collection and analysis of vibration signal can be used to judge the degree and type of mechanical fault, which can provide the effective evidence for detection of the running state and fault diagnosis of elevators (Qifeng *et al.,* 2016).Therefore, friction in the gearbox would be indicated by vibration of the gearbox, drive motor, drive sheave, bed plate etc. which invariably indicates the need for lubrication of the gearbox, replacement of damaged components or parts or overhauling of the whole system as the case may be.

Aside from the lubrication of the drive system, the friction on the rollers on the guide rail could also result in wear and tear along the guide rail which may cause excessive vibration of the elevator car. This also affects the alignment of the elevator’s floor to the floor level of the building. Therefore, vibration is another parameter identified for fault detection in elevator systems.

2.11.3. Acoustics

This is another very important parameter that could indicate a faulty component or part in the elevator system. In most machines, most of the energy is converted from electrical energy to mechanical energy, however, a portion of the energy is also converted to sound energy. The sound energy reduces the efficiency of the machine as the lost energy is meant for the visible mechanical work done. In a rotating machine component, there is high tendency of some form of energy being converted to sound, this is due to the friction between two rotating components.

Kwangyoun and Hanseok (2011) recognised the acoustic events in an elevator and further sorted and classified the acoustic state as being either normal or abnormal. An extreme handrail chain tension generates an abnormal sound by the chain touching the truss, causing the abrasion of the sprocket, jumping and cutting of the chain and stopping the handrail (Hiroyuki *et al.,* 2007). This is therefore reduced by the lubrication of the rotating components such as the bearings, gear box, rollers etc.

Ingold (2009) highlights tonal noise from traction elevator hoist machinery, tonal noise from switchgears for traction elevators, transient noise from poorly adjusted elevator car guide rollers or bumps in rails, elevator doors and doors enunciators as the sources of noise from the elevators which could be monitored and used for maintenance and diagnostic purposes. A broken gear tooth, damaged rollers, as well as bearings will be signalled by an increase in the sound energy in the system. Failure in the elevator door is indicated by arbitrary noise produced during its operations which clearly indicate the need for maintenance (Perälä *et al.,* 2005). If the decibel of the sound is picked up at the damage initiation, the severity of the condition could be avoided, and the system can be prevented from total breakdown.

2.12. Performance Monitoring for Severity

The performance of any machine or system is measured by the efficiency of the machine/system. Machine efficiency is a major factor that is most often neglected by the management and thereby results in losses and reduced operating life (Ahuja and Khamba, 2008; Kluczek, 2017). Machine performance entails monitoring the behaviour of a machine adaptively in order to generate an early warning of possible faults (Ridwan *et al.,* 2012). The condition monitoring approach for maintenance is poised towards reducing the downtime of the machine while increasing the efficiency. Through machine performance assessment, and prediction of remaining useful life, leading to a proactive maintenance strategy to minimise the machine downtime during production activities, the efficiency of operation and manufacturing can also be increased (Yan *et al.,* 2007; Ylipää *et al.,* 2017). This will generally optimise the productivity of any industry or company. The parameters monitored remotely in this case study were vibration, temperature and sound for variations in values. The range of operations of an elevator during a normal working condition is stated as 65 ±3 dB for the door sound level, 75 dB for the hoistway, 10 ± 3mg for lateral vibration,15 ± 5mg for vertical vibration (Information on noise and vibration 2008). Variation in the monitored parameters values were as a result of the change in the working condition of the machine.

Torres Pérez (2016) explained the severity value as severity of deviation when the individual peak condition of the machine exceeds the alarm limit envelope, which is the level above which a peak in the machine condition is considered abnormal. Sarangapani and Rangarajan (2002); Pourbabaee *et al.,* (2016) determined the severity level by finding the weight value of the proposed data from the monitoring system at both the normal operating condition and at the typical failure trend condition, while comparing it with a predetermined typical severity profile value and identifying the problem with the current events or conditions in order to determine the root cause for the severity.

Coss *et al.,* (2007) adopted a method of detecting faults associated with a processing tool based on the fault severity level. Severity level of prominent conditions of most machines are stated by the manufacturer in order to prevent a total breakdown of the equipment and facility. Ogura *et al.* (2006) also developed an on-condition machine failure diagnosis method which monitors severity in machine conditions by transmitting and receiving signals through communication devices provided at the working machine and at an information centre or base station. This study adopted a monitoring system configured to pick up the on-condition parameters of the machine and analyse these against the severity level. This enabled early detection of deterioration in the machine normal condition hence preventing the total machine breakdown at the severity level. Detection required data gathering, comparison to standards, comparison to limits set in plant for specific equipment, and trending over time, while diagnosis entailed recognising the type of fault developing and determining the severity of given faults once detected and diagnosed. (Khazraei, 2011).

2.13. Remote Condition-Based Device Development and Discussion of Gap

Lee, Kao and Yang (2014), designed a remote prognostic device for control and decission making of machine operations for equipment vehicles in a mining industry. The equipment vehicles transport materials and equipment from one work station to another consisting of both horizontal and vertical motions which makes this a little similar to the elevator system. Lee, Bagheri and Kao (2015) further developed a self-aware, self-predict, self-compare, up-time device for condition-based monitoring and diagnostics in machine which works with a unified system framework for machine performance adopting cyber-physical systems. Yang *et. al.,* (2015) also designed a unified frame work and platform of cloud-based machine health monitoring and manufacturing system. Cloud-based machine condition monitoring explores the ability of monitoring the condition of a system on the cloud using a web based application. Xia *et al.* (2016) also proposed a closed-loop design evolution of engineering system using condition monitoring through interest of things and cloud computing. This introduces a device with a multi-domain system with dynamic interactions between the system and the domain for conditing monitoring and fault detection.

Several literature have addressed condition mintoring through developed device for fault detection in several applications, in the mining , construction industry but more needs to be done in developing a unified system that monitors the cooonditions and carries out a self -check between the system using a dynamic IoT capability for fault notification. Al-Kodmany (2015) explained the elevator maintenance system at one World Trade Centre (WTC) using microsoft Azure Intelligent System which responds to faults proactively by sending service engineers real-time data so that total breakdown of the elevator can be avoided by feeding the data into a dynamic prediction mode. Mourtzis *et al.* 2016 also developed a product service system comprising of sensors network and controller with monitoring service that provide preventive remote maintenance through automatic monitoring of condition of the system for assessment by the maintenance department. This system also do not provide fault notification based on artificial intelligent system because every system is unique and dynamic in its own way.

Al-kodmany (2015) explained the elevator maintenance system at one World Trade Center (WTC) using Microsoft Azure Intelligent system which responds to faults proactively by sending service engineers real-time data so that total breakdown of the elevator can be prevented by feeding the data into a dynamic predictive model. Mehta *et al.,* (2015) developed a condition based systems which uploads data to website for remote viewing for the machine's major component through artificial intelligence using Bayelsian Classification and sensor fussion. This system however only allows for condition monitoring on the website by the monitoring team, however, this research effort identifies the parameters for fault diagnosis, develops the severity level of each parameter through artificial intelligence adopting neural network clustering tool and programing the fault notification using the trained data outcome for severity condition level for the system.

2.14. Conclusion

This chapter discussed the relevant literature review on maintenance of elevators. The chapter included the review of literature on machine maintenance and the different types of maintenance policies which are breakdown, preventive, proactive, condition monitoring maintenance policy and remote condition-based maintenance device development and discussion of gap. The chapter also reviewed literature on elevator systems and its maintenance, fault detection and diagnosis of the elevator system. The chapter also reviewed available literature on internet of things (IoT) devices and its applications, however, this has not been applied to maintenance and monitoring of elevator system.

CHAPTER 3 : METHODOLOGY

3.1. Introduction

This chapter discusses the research methodology used for the study. The current state of the elevator system is looked into and considered together with the maintenance practice on the system. The common problems encountered by the elevator system are also considered and discussed giving considerations to some few surveys on the elevator systems around. The research approach of modernising the current system of maintenance from breakdown maintenance system to remote condition monitoring for fault detection is also discussed in this chapter. The design and development of the remote monitoring device and implementation of the monitoring system on the elevator is also covered in this chapter. This addresses the second objective of the research which is to modernise the maintenance routine through a remote monitoring technique for fault detection.

3.2. Research Approach and Method

Elevators are generally susceptible to high downtime during a breakdown of the system. This is firstly due to absence of an operator during its operation as most elevators are not manned during operation. The downtime of the machine whenever there is a breakdown is a function of how soon the users communicate with the maintenance team which is usually not instant, except when there is an emergency. The elevator being considered in this study often suffers longer downtime due to delays in communicating a breakdown to the maintenance team as a result of other alternative elevators around. This therefore results in hours and days of downtime before being checked by the maintenance team.

Hence, this study optimises the maintenance routine from scheduled maintenance to remote monitoring for fault detection and notification in order to reduce the downtime in the system. This is realised by installing a remote monitoring device on the elevator facility to monitor the condition and the fault signals on the elevator. In order to do this, official permission in Appendix 1 was sought so as not to compromise the ethics and safety standards of operation of the machine. The research is to be carried out with the help and guidance of the maintenance team to keep the integrity of the elevator system intact.

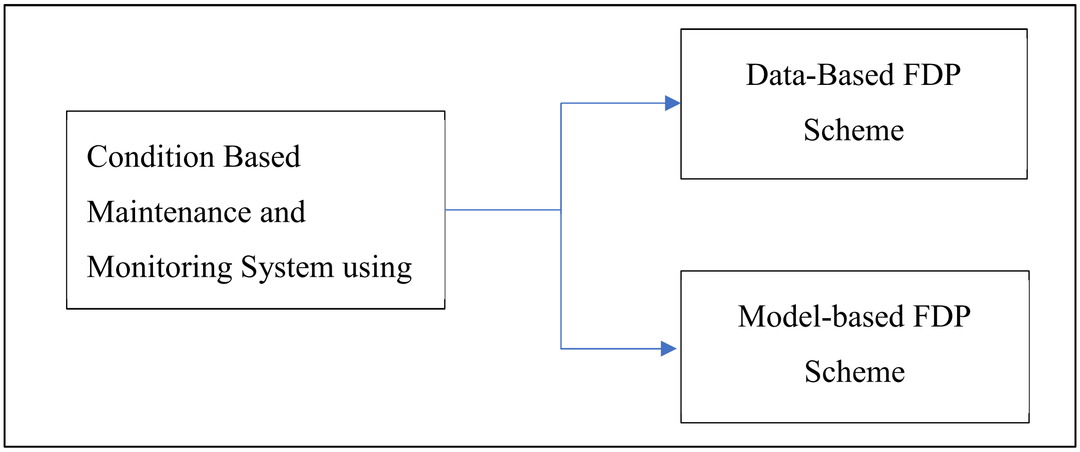

Figure 3.1: Condition Based Maintenance Approach

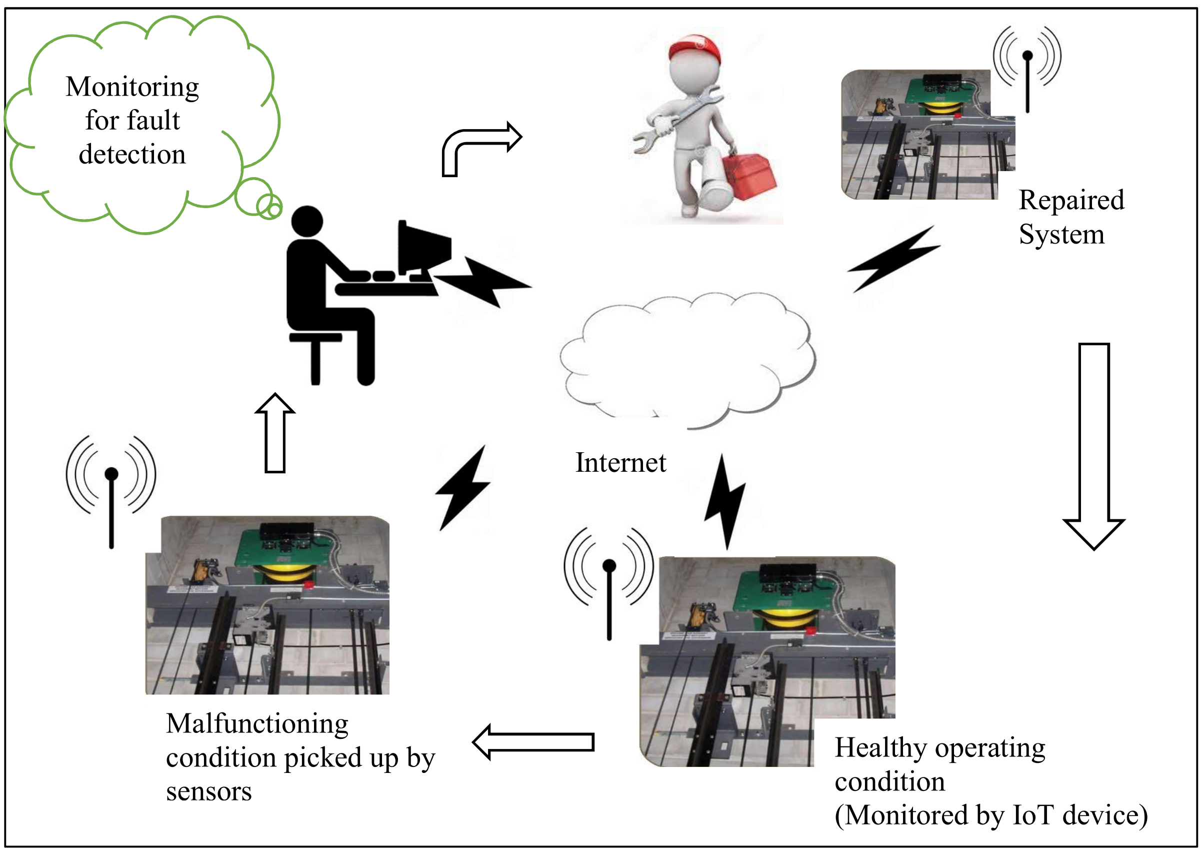

Figure 3.2: Graphic Representation of the Research Methodology

(Designed by the author)

Fault detection and prediction (FDP) schemes currently used are either one of the following; data-based or model based as indicated in Figure 3.1. The data-based approach adopts a real-time data monitoring technique which collects the data on machine condition, analyses and predicts the current machine condition.

This research however adopts a data-based approach for fault detection for diagnosis on machines. The parameters which indicate a signal for maintenance are monitored by installation of some intelligent devices for remote data monitoring and fault notification. The data from the machine is monitored, collected, and analysed for fault detection and fault notification is sent at every deviation from the normal conditions of the parameters. This research also adopts a Process History Based (PHB) approach for data analysis which analyses the data using a statistical approach of data comparison against a set value (severity limits). Figure 3.2 is a graphic illustration and representation of the idea of the research work.

Parameters which are critical to the condition of the elevator system was monitored. The sensors were installed on the spatial domain of the machine being used as a case study and connected to the configured Internet of Things device. The data was monitored, recorded and saved through cloud computing so that it could be accessed remotely at any location in the world. This was achieved through the Internet of Things (IoT) devices and cloud server programming.

3.3. Overview of Elevator's Problem

The maintenance approach adopted by most elevator companies focuses on reducing the downtime of the elevator system due to maintenance as well as ensuring the safety of both the users and the goods or loads. A general survey of the problems associated with elevators and escalators installed in facilities and malls in Durban is carried out to have a wider view of the peculiar problems and maintenance carried out on the systems. The survey was extended to cover the escalators because elevators and escalators share some principles of operation in common which include the transmission along the guide rail and the controls housing. Therefore, since accessibility to the guide rail of the elevator may not be easy during the survey due to access to the hoistway, the escalator was used as a close study to the elevator system. A telephone interview granted with a maintenance engineer of an elevator company in Durban clearly pointed out that routine maintenance is carried out monthly on the elevator system to make sure that the controls and the entire components and accessories are in a proper functioning condition. It was explained that basically, maintenance of elevators focuses on some specific functional parts which include the drive system, braking system, the elevator car and landing doors and guide rail. He further explained that the controls are majorly located in the machine room and are basically challenged by the temperature of the room, which if high enough, could cause a major malfunctioning of the controls and even a total breakdown of the elevator system. An example is the escalator image in Figure 3.3 which broke down due to a faulty control.

Figure 3.3: Faulty Escalator Control

(Image Captured at Berea Mall)

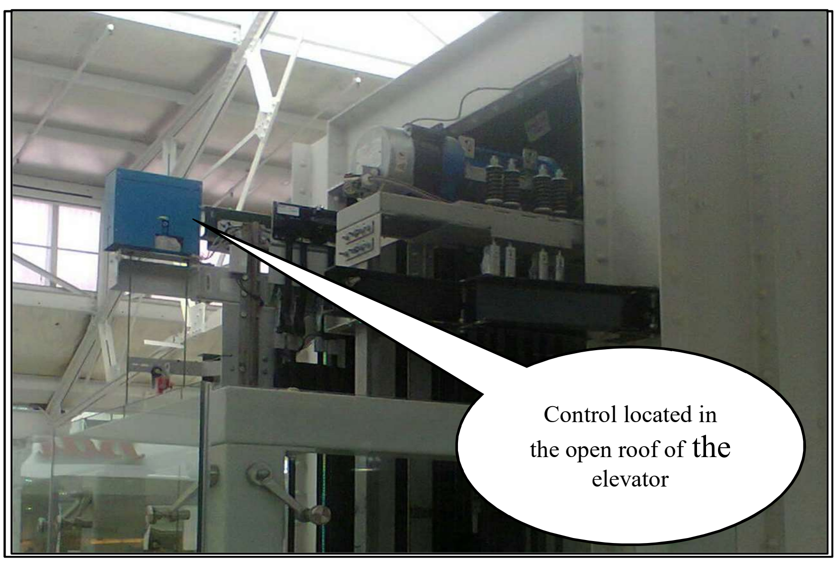

Figure 3.4: Elevator with Controls Located in The Open Air

(Image Captured at Musgrave)

Some elevator systems try to overcome the challenges of malfunctioning of the controls due to increased room temperature by having their controls located in the open air on the elevator car, but majority still have them located in the machine room. The image in Figure 3.4, shows an elevator system captured with the controls located on the elevator car. This mostly avoids the problem possessed through malfunctioning of the controls of the elevator system through rises in the temperature of the machine or control room.

Kariya (2012) also indicates that the hoistway out of plump and damaged rollers or guide rails are part of the turn backs for maintenance of the elevator systems. An interview with another elevator maintenance engineer via telephone on 23rd February 2017, (Otis Elevator Staff) also reiterates this problem as one of the problems or breakdowns experienced by the elevator systems. A survey conducted indicated that a damaged roller and guide rails as well as the hoistway out of the plump also contribute to breakdowns in elevator systems and escalators. This can be shown in Figure 3.5, which shows an elevator that had problems with the rollers and guide rail at China mall.

It is evident that once there is partial damage or complete damage of the rollers which mostly bear the weight of the passengers and support it to the guide rails, the elevator system may wobble and breakdown.

Figure 3.5: Damaged Guide Rail of an Escalator

(Image Captured at China Mall)

Figure 3.6: Damaged Roller and Guide Rails of an Escalator

(Image Captured at China Mall)

Figure 3.6 also shows the damaged escalator as a result of faulty rollers and guide rails. The fault affects the performance of the elevator, by increasing the vibration of the stairs in the case of the escalators while increasing the vibration of the elevator car in the elevator system.

In addition, the brake system is another very important component of the elevator system that needs regular maintenance. The brake drum or disk is directly coupled to the elevator drive shaft. The maintenance is carried out on the brake system by checking the brake shoe for wear and tear, crushing or pinching. A faulty braking system of an elevator might apart from endangering the life of the users, also reflect on the performance of the elevator systems by creating an uneven level between the elevator car and the building floor. This can be seen from Figure 3.7, which was taken from a building in the CBD of Durban.

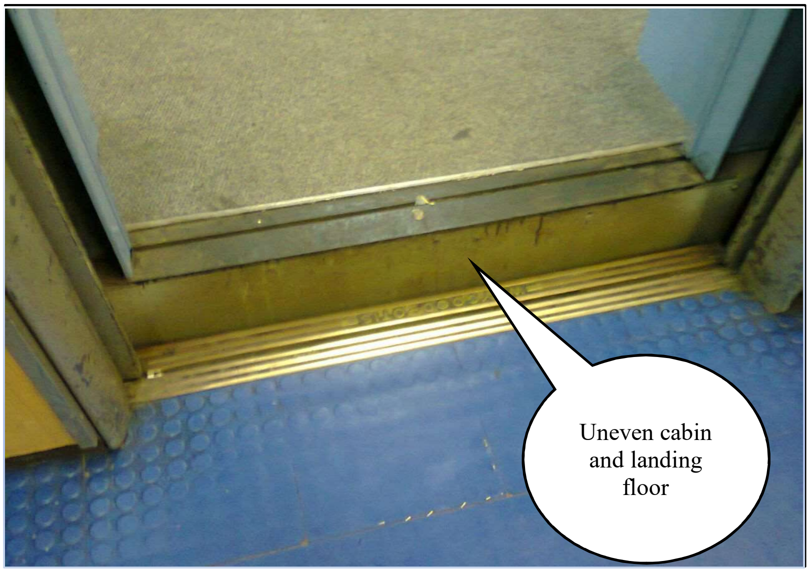

Figure 3.7: Unlevelled Lift Car and Floor

(Image from a Building in Durban)

It was also pointed out by the maintenance engineer that the maintenance of the brake system must always be carried out on a monthly basis.

This research is based on the cable type of elevator as a case study. A cable elevator type was chosen because of the popularity in usage. It is worth noting that most elevator systems that we use in public places, residential houses, etc. are mostly a cable type of elevator, hence the reason for using it in this research. However, it can also be adapted for other types of elevators.

3.4. Elevator Case Study

This research adopts the elevator as a case study and optimises the maintenance routine from the on-site condition monitoring for fault detection and diagnosis to remote on-condition monitoring for fault detection and diagnosis and remote fault notification of malfunctioning. On-condition monitoring maintenance of the elevators is very important because of the safety of the life of the users, hence the reason for creating a regulatory law for installation and maintenance by the department of labour in its Gazette. Section 44 of the Act is as stated below:

> 'Inspections and Test: The user shall ensure that every lift, escalator or passenger conveyor is inspected and tested in accordance with the relevant health and safety standards incorporated into these regulations under section 44 of the Act;

a) After any modification, has been effected, or;
b) After any failure, has occurred, or;
c) Whenever there has been a change in the competent lift service provider and
d) At intervals not exceeding 12 months thereafter, or at shorter intervals according to in-house risk assessments, by an inspector service provider who shall complete a comprehensive report separately for each lift, escalator or passenger conveyor so inspected and tested, and such inspection service provider shall date and sign such report and submit it within 30 days to the user who shall keep the report in a safe place and a copy of the report in the machine compartment' (Department of Labour, 2015).

This case study therefore provides a situation where the data from the machine cannot only be monitored remotely and notified of fault but can also be printed out in the form of a report and provided the researchers with the privilege of having the process history data stored up for maintenance and reference purposes. The access to the remote monitoring system could be granted to the outsourced maintenance team prior to the on-site visit and the condition could be diagnosed and maintenance instructions passed on to the machine maintenance team.

3.5. Hardware Installation and Remote Data Capturing

Optimising a maintenance routine from breakdown maintenance to remote condition monitoring for fault detection involves the development of a remote monitoring device for capturing the conditions of the elevator. This section therefore addresses the second objective of this research which is to optimise maintenance routines through remote monitoring techniques for fault detection. The hardware was configured to monitor the conditions (parameters considered) of the elevator system, log it on the cloud (internet) for remote access and send fault notification. The spatial domain of the case study, which is the elevator system was installed with the instruments for the parameters measuring, the temperature of the machine room or hoistway, the vibration of the drive systems and acoustics from the rollers on the guide rail and drives.

The components and devices for the remote monitoring system consist of mainly electronic devices which were configured and connected, to form a remote monitoring system. The inter-connected devices and network system formed the Remote Condition Monitoring System (RCMS). The hardware for the remote monitoring system could be categorised into three (3) categories based on their designed functions. They are;

- Sensors – Data/Signal capturing
- Controller for Data/Signal logging and transmission and
- Device connectors.

3.5.1. Sensors

These are highly sensitive devices that capture signals and data from a monitored event or condition in a machine. The sensors used for the monitoring device are highly sensitive and portable sensors so that it can be accommodated for space in the domain and also for small deviations in measuring conditions. The parameters monitored have one or two sensors installed for effective data capturing of the conditions of the machine. The sensors were chosen based on their work requirement, sensitivity and robustness in usage and compatibility with Internet of Things devices.

3.5.1.1. Temperature Sensor

There are different types of temperature sensors based on the usage. In this research, the room temperature of the hoistway or the machine room was monitored, meaning the required type of temperature sensor was the type which measures ambient temperature. Another consideration given to the choice of the temperature sensor type was the temperature range to be measured. Since the temperature measured was the room temperature, the sensitivity of the temperature sensor of choice was within a room temperature range with some allowance given for variation in the temperature (5 ^oC – 70 ^oC). An image of different temperature sensors is shown in Figure 3.8.

Figure 3.8: Room Temperature Sensors

(www.intorobotics.com)

The machine room temperature condition was important for proper functioning of the control system of the elevator system. This was the most pronounced cause of control system breakdown in the human elevator system.

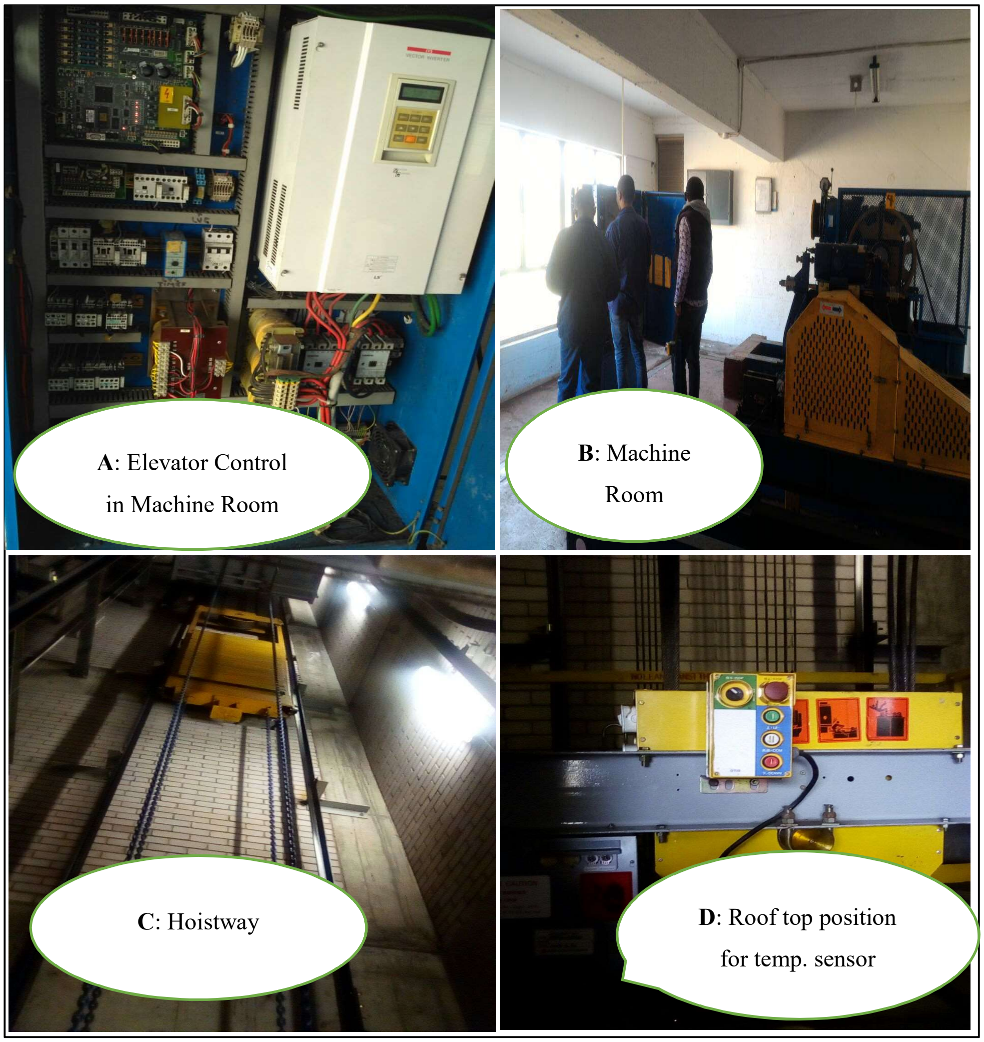

Figure 3.9: Position of Installation of Temperature Sensor in the Hoistway

(Image Captured by Author)

The temperature sensor was installed on the elevator roof top along the hoistway of the elevator for high sensitivity. The room temperature and the residual temperature of the control unit of the elevator was accurately picked by the sensors due to the proximity. LM35 temperature sensors as described in Figure 3.9 are used in the configuration in monitoring the room temperature of the machine room. The sensor consists of three legs, which are the power pin, VCC for reading the data, and GND for connecting to the ground. The power leg is connected to the 5V power source of the micro-controller board, while the VCC is connected to the analog pin on the micro-controller and the GND leg is connected to the ground rail of the breadboard while the ground of the board is connected to the rail of the breadboard.

3.5.1.2. Vibration

The vibration parameter is a very important parameter that could diagnose or indicate the condition of a machine with rotating components. Vibration could indicate many mechanical faults on elevator systems such as mechanical looseness, wear and tear, friction, abrasion etc. Different components of the elevator could signal fault or deterioration by increases in the vibration parameter. Faults or deterioration in the elevator's condition can be monitored and picked-up by monitoring the vibration parameter of some components such as the elevator drive shaft, drive sheave, bedplate, elevator car and gear box. Any deviation in the normality of the vibration parameter of the monitored components will show that there is deterioration in the condition of the system, and the system alerts the appropriate centre and the history of the condition of the machine is accessed remotely by the repair team before dispatching the mechanics to repair and restore the system to normality. The vibration sensors are of different types based on the requirements and sensitivity. They are;

- Accelerometers (Piezoelectric)
- Velocity Sensors
- Proximity probes (Capacitance or eddy current) and

Velocity sensors typically work by measuring the motion of a small, body entrained in the acoustic field (Williams *et al.* 2017). Mata-Contreras, Herrojo and Martín (2017) stated that velocity sensorsare mostly suited for measuring angular displacement and velocity of reactions. Proximity probes sensors are also used to obtain 'orbit plot' or 'Lissajous figure' of a shaft motion which works based on capacitance probe(Goyal and Pabla 2016). The accelerometer sensor was chosen for this study because it has been proposed for measurement involving monitoring and analysis of the integrity of structures and machinery where a set time, statistical, frequency domain features is taken from 3-dimensional axis. It is therefore used to measure the vibration of the lift system with much focus on the elevator car, shaft of the motor, drive sheave or the bedplate of the elevator drive system. This type of sensor is applicable to this system parameter measurement as it is mounted on the elevator car so as to measure the vibration of the whole system based on the motion of the elevator car on the guide rail. The different types of vibration sensors are shown in Figure 3.10.

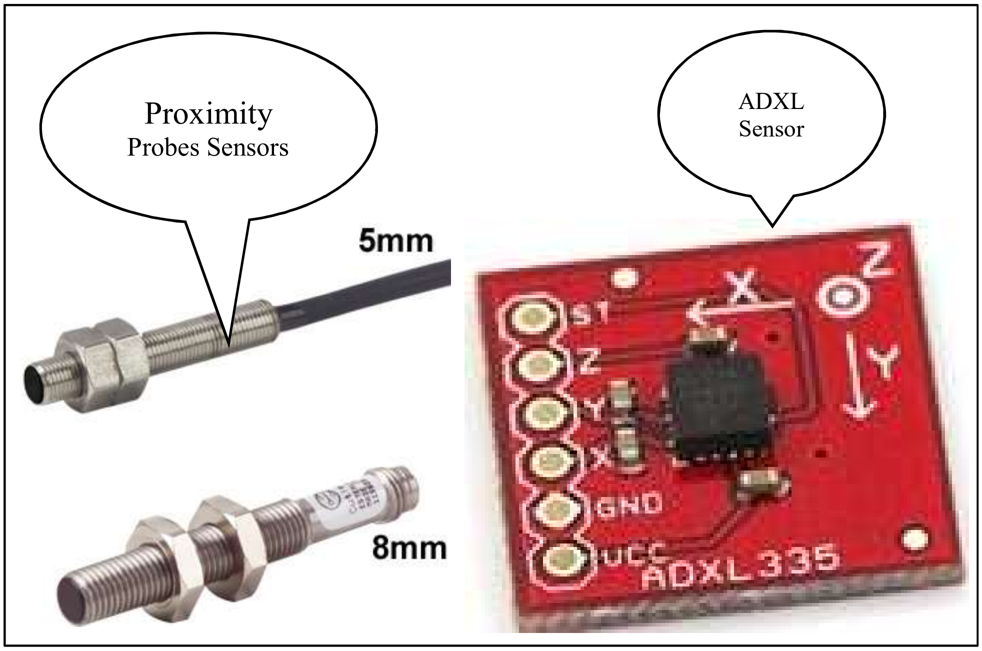

Figure 3.10: Vibration Sensors

The Spark Fun 3-Axis Accelerometer ADXL335BD sensor shown in Figure 3.10 was mounted close to the drive sheave and the drives for the elevator doors to pick the vibration of both the elevator car and the bedplate of the drive system. The sensor which is highly sensitive with +- 5g error was connected with other configured devices and placed on the elevator car roof as shown in Figure 3.11.

The vibration parameter monitoring was aimed at diagnosing the bearing faults or mal-functioning, mechanical looseness, misalignment, faulty brake assembly sheave looseness. Spark Fun 3-Axis Accelerometer ADXL335BD sensor was chosen amongst other type because of it high sensitivity of ± 5g and the ability to measure vibration on three axes. The deviation in the normal functional condition of the system can be pre-informed by the change in the vibration parameter of the machine condition.

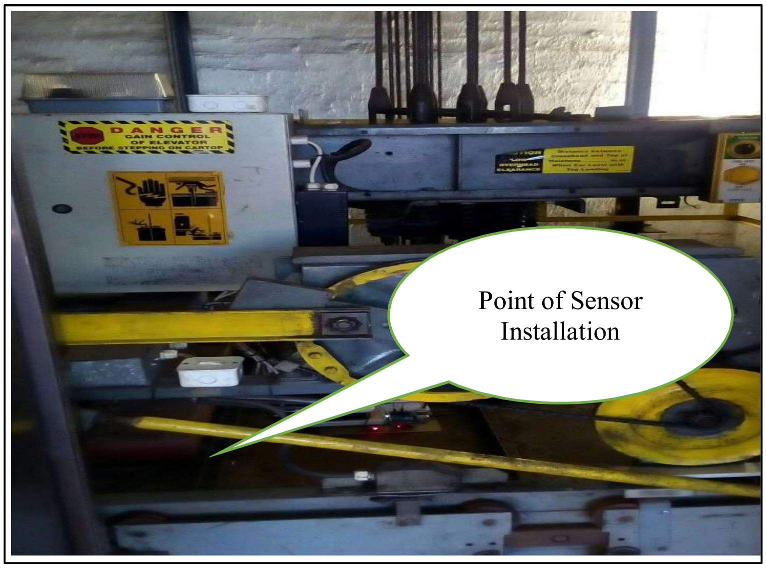

Figure 3.11: Mounting Position for Vibration Sensor

3.5.1.3. Acoustics

This parameter measures some energy in the form of sound energy which was unwanted in the system. The system was installed with acoustic sensors to monitor sound from the drive system and the elevator car doors drive system, as well as the rollers on the guide rails in the hoistway. Abnormality in any of the units or components of the elevator, indicate the need for proactive maintenance before total breakdown of the system. An image of the sound sensor is shown in Figure 3.12.

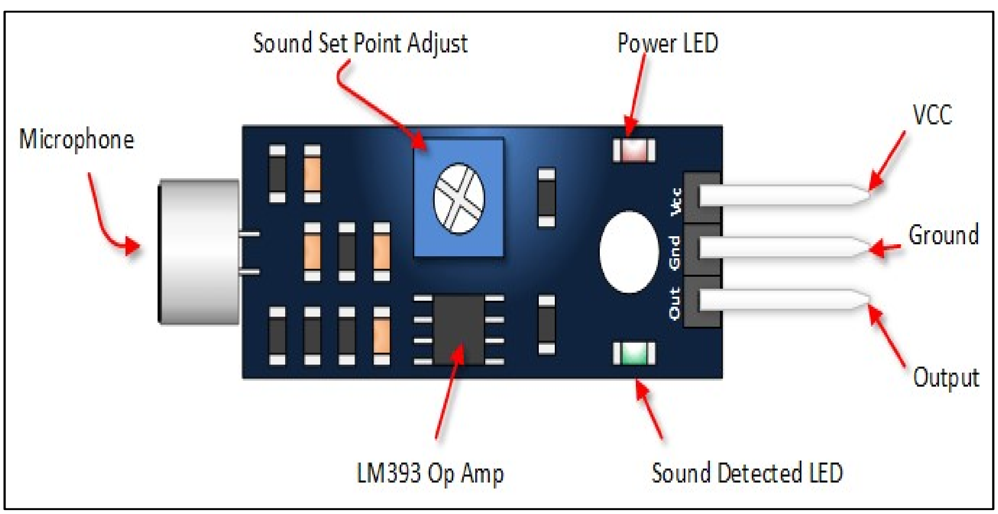

Figure 3.12: Acoustics Sensor

The sensor was installed on the elevator roof in the hoist way to pick up any abnormality in the sound of the drive system. The sensor at the spatial location of the system, picks up any acoustic excitation from the brake system as well as the bearings on the shaft and the drive sheave of the electric motor driving the system and the drive chains of the doors. Severe noise from the elevator door is also picked up by the sensor as well. Any deviation from the normal condition of these components is indicated at the severity level.

3.5.2. Controller for Data/Signal Logging and Transmission

The controller is a very important device in the construction of the monitoring system. This device is the main component of the monitoring device as it coordinates the configuration of the input devices such as the sensors as well as the output devices which may be the actuators or output data and determines what happens to the data picked up from the elevator system. The type of controller used in this research is a micro-controller known as Arduino Yun, which is used in the configuration of the sensors for data capturing, and logging in the data captured by the sensors through a set of instructions to the cloud or internet devices together with fault notification. The ability of the micro-controller to post data to the cloud makes it an IoT device. The Arduino Yun micro-controller used in this research did two major tasks, namely:

- Hardware configuration for data capturing and
- Data logging and transmission.

The data capturing is the interpretation of the signals from the sensors from a high-level machine language to a low-level language which can be understood by the operator. The micro-controller collects data as input from the sensors as signals, processes the signals, and outputs the instructions to the Human Machine Interface (HMI) for visuals by the operator or the actuators (drive devices). HMIs are the screens or output devices which display the conditions of the machine for the machine operator, and they also act as an input device for the operators to set instructions for the machines. In this research, the HMI is limited to the Integrated Development Environment (IDE), of the installed Arduino Yun micro-controller and the email address interface, as no specialised HMI is used.

The Arduino IDE is the programme software whose platform is used in configuring all the sensors and the output instructions based on the monitored data. The serial monitor of the IDE is used as the HMI as it displays the read data from the micro-controllers. Data logging and transmission is the process of reading the values from the sensors and relaying the data to an output device. Some digital sensors have an HMI screen to read out the sensed signals, however many sensors, most of which are analog, have the sensed values read, logged and processed by the micro-controllers.

This study used a recently built IoT compliant micro-controller type by Arduino called ARDUINO YUN. This type of micro-controller is unique in all sense of controllers because of its ability to transmit data to and from the internet using wireless fidelity (Wi-Fi) connection as compared to the existing cable connectors. It captures the signals from the sensors, interprets the data and executes a set of instructions programmed into it. It transmits the read signal in the form of data to the cloud (internet) for remote access. The Wi-Fi connection accessory makes this device robust and unique as it makes the application wider than other controller types. The device is a micro device which makes it handy and compact in application. Hence, the controller can be installed in a very small spatial domain of any system as it covers a very small area. The connection to the internet is through wireless fidelity making it a robust device as it reduces the spatial domain for running wired connections. Wireless sensors can also be connected to this controller making its application wider. The image of the Internet of Things device, Arduino Yun (2017), is shown in Figure 3.13.

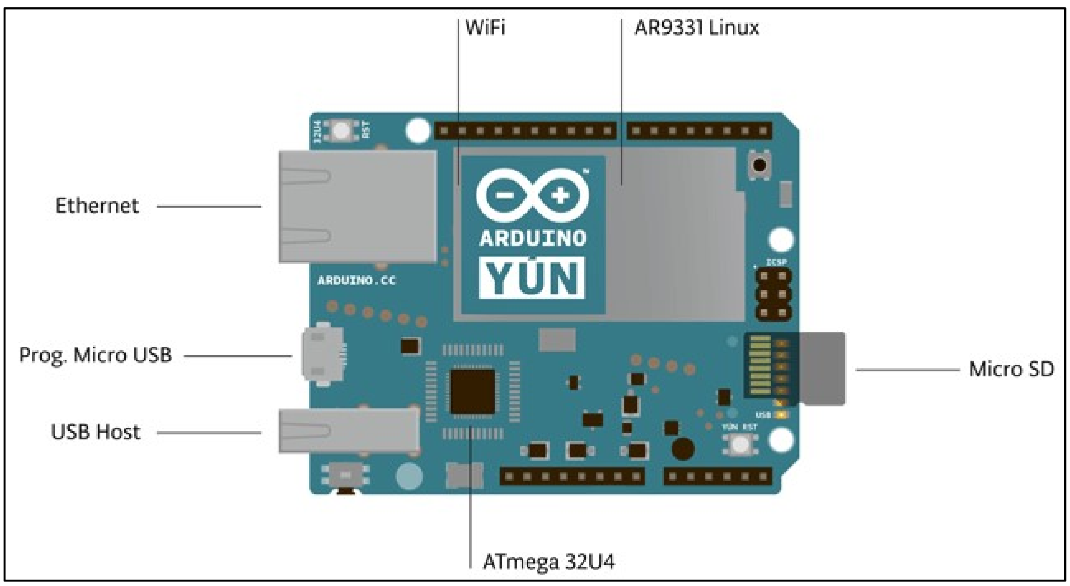

Figure 3.13: Arduino Yun Micro-controller

(Source: www.arduino.com)

The three (3) sensors are connected to the Arduino Yun controller for data capturing and transmission to the cloud. The connections are wired using jumper wires and breadboard, while the controller is programmed for data logging, fault notification and transmission to the cloud. This is carried out through a third-party programme called tembo which helps in the connection of the IoT devices to the internet. tembo has numerous cloud applications (choreos) of data to the micro-controller which includes emailing, tweeting, Google spreadsheets, Dropbox, and many more. This research, however applied the use of the email choreo which had the data sent to the email address for remote cloud access to the data. Email alerts were also used in cases of severity of the monitored conditions by indicating when any of the parameters reached the severity level. This was a form of an alert system given to the operator remotely in order to alert an impending damage or fault initiation. The condition of the machine can then be accessed from any remote location and proactive maintenance decisions taken.

3.5.3. Device Connection

The Remote Monitoring System (RMS) comprises of electronic devices and components connected and configured together to work together as a single system. It includes all the sensors, the connectors, the micro-controller (Arduino Yun), the DC power source, the breadboard and the resistors. The connections start by powering the micro-controller with a 5V power source. This is connected to the USB power port of the micro-controller. This automatically brings up the red LED light on the micro-controller which indicates that it has been powered. The sensors are connected to the breadboard and then wired to the micro-controller through the jumper wires. The power (5V) pin is connected to the power rail of the breadboard and the ground of the microcontroller is also connected to the ground rail of the breadboard. The power pin of the sensors and ground pins are then connected to both the power and ground rail of the breadboard respectively.

The circuit was built with breadboard for multiple connections of some components such as the resistor, LED, push buttons to the controllers, while the sensors as well are connected to the breadboard and to the controllers. The schematic drawing of the breadboard and the controllers is shown in Figure 3.14. The led light indicates severity in any of the monitored parameters when the circuit is on and the button on the power bank source is used to power the circuit. The sensors are also connected to the controller and the controller is powered through a source, which is a 5V battery. The controller has both a Wi-Fi port and an Ethernet for connection to the internet.

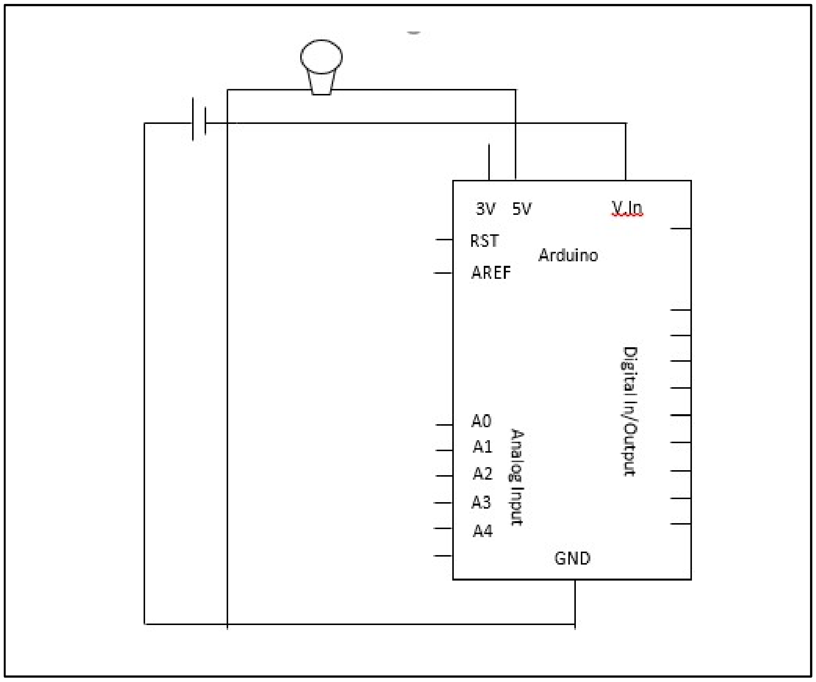

Figure 3.14: Connection of the Controller to the Led Indicator

The Arduino Yun controller was connected to the Wi-Fi network around the domain of the elevator being used as the case study and the log-in details for the board were changed from the default setting to ensure the security of the device. The Arduino Yun board also has the ports for an analogue connection for the sensor chips using male-to-male cable connectors, and it could also connect to it wirelessly. The sensors were connected to the analogue port of the controller using the male to male cable.

3.6. Software Programme for Data Monitoring

The software end of the Remote Condition Monitoring (RCM) system is equally as important as the device hardware configuration. This includes the programming of the controllers for reading the signals from the sensors, the conversion of the voltage signal in bytes to meaningful values. The software required was installed on the PC for both the code development, configuration of the devices and managing the data output and sending to the email. The initial configuration of the Arduino Yun micro-controller was done on the Arduino website. Other further coding of the controller was done on the Arduino IDE (Integrated Development Environment) which is the coding environment for writing, running, testing and deploying codes on the Arduino hardware. The latest Arduino IDE, Arduino 1.5.6-r2, was downloaded and installed on the PC.

Python and Note++ software was also installed on the PC which works with the microcontroller for the development of the server for the remote access online. However, since the output data in this research was not displayed in a special website, only the IDE and third-party web-platform was used in sending the data to the email. The software development of the monitoring system was sub-divided into two (2) parts.

- Coding of the controller and
- Coding for the cloud server

3.6.1. Configuring the Controller

The Arduino Yun microcontroller uses Wi-Fi in connecting to the network and most of the configuration is done online via the internet using the Arduino IDE. The first task is powering the microcontroller through a 5V power source, which turns on the red LED light on the Arduino board as indicated in Figure 3.15.

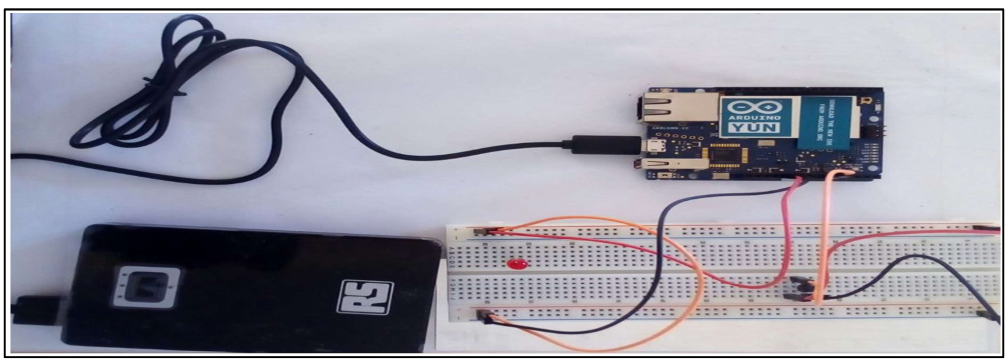

Figure 3.15: Arduino Board Powered by a 5V Battery Source

The red LED light indicates that the board's Wi-Fi has been turned on, which can then be detected by any smart mobile device and PC installed with Wi-Fi network card in the domain of the microcontroller. This makes the network open for accessibility and can be controlled from anywhere by anyone, hence, the need for configuration of the board. Configuration of the board is needed for both the functionality of the device for its use and also for the security of the network. Therefore, the Wi-Fi network is searched on any mobile devices such as tablet or PC, and the Wi-Fi address which starts with Arduino name and the mac address is connected to it. Once the PC or tablet is connected, the Arduino IP address 192.168.240.1 (http://arduino.local) is entered on the web browser and it opened the configuration page in Figure 3.16.

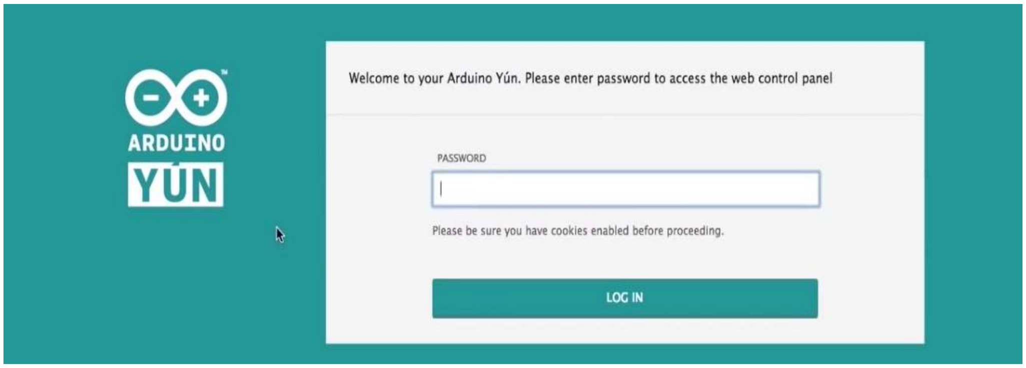

Figure 3.16: The First Configuration Page for the Board (Arduino)

The password, Arduino, is entered which is the default password and then logged in. This opens the configuration page and the settings such as the device name, password, time zone location, which are all configured on the device, and once this it is done, the device assumes the configured settings.

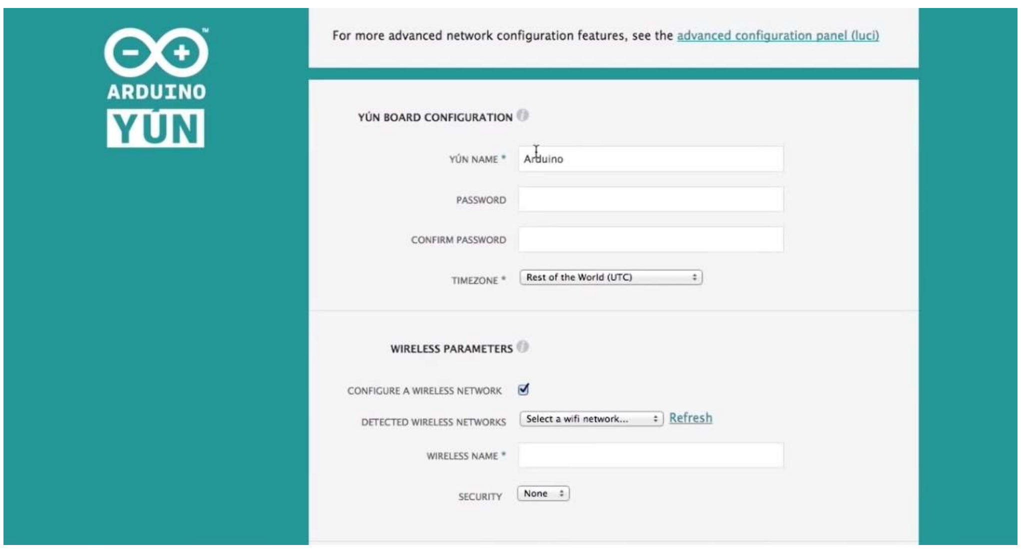

Figure 3.17: Configuration Settings

The default settings were changed as in Figure 3.17, to protect the monitoring device against security compromise and the setting is saved. The board is re-started, which successfully has the board ready for inputting code for monitoring. The controller can also be reset into the default settings by just pressing the reset button on the board. This helps in clearing the prior information that had been configured on the controller and starting afresh.

3.6.2. Coding for the Controller

The microcontroller which is the intelligent device in the whole set-up cannot control or take decisions unless being programmed by uploading as set of instructions into it through codes. The device has been configured to be programmed in C++ code language, hence, the microcontroller is programmed in C++ language.

The coding is done in sequence depending on the action to be executed at a point in time. The first lines of code declare the variables being used:

3.6.2.1. Declaration of Variables

These variables accept input from the sensors network while the Float command ensures that the values are numbers in decimal and not a rounded-up number.

Step 1: Declaring the variables *tempC* for temperature*,* VibC for vibration and SoundD for sound. Int dmsg = 'Checkthe system for fault'.

Step 2*:* Introduce the float command to give a whole number; *Float tempC; Float VibM; Float SoundD;*

Step 3*:* Opening the bridge, and console port for communication on the controller (*#include* <Console.h> *#include* <Bridge.h>).

Bridge allows for communication between the micro controller board and the PC on the serial monitor of the IDE using the console port.

Console opens the port for communication in accessing the data being monitored by the board on the PC from the serial monitor end.

Step 4: Declaring the third-party account, temboo (*#include <Tembo.h> #include "TembooAccount.h").*

Temboo sets up account information which helps in sending data from the sensors to the email remotely.

3.6.2.2. Assigning the Sensors to Analogue Pins

The analogue pins on the microcontroller need to be assigned to the sensors pin through codes.

Int tempPin = 0; // Temperature sensor plugged into analogue pin 0.

Const Int VibPinX = A1; // Vibration sensor plugged into analog Pin 1.

Const Int VibPinY = A2; // Vibration sensor for Y axis plugged into Pin 2

Const Int VibPinZ = A3; // Vibration sensor for Z axis plugged into Pin3

Int SoundPin = 4; // Sound Sensor plugged into analogue Pin 4

Int led = 13; // led light is plugged into pin 13 which has a built-in resistor on the board.

The sets of code above assign each of the sensor pins to the analog pin of the micro controller board for connection. Most analogue sensors come with three (3) different pins for connection, the power-in, power-out and the ground. The power-in pin is connected to the power source of the 5V from the microcontroller. The power source from the microcontroller is extended to multiple ports by connecting a male to male jumper wire from the 5V power port on the microcontroller board to the power rail on the solderless breadboard. The ground pin of the sensor is also connected to the ground port of the micro controller. The ground port on the micro controller is connected to the ground rail of the breadboard to allow for multiple connection of devices to the microcontroller ground port. The sensors are connected to the breadboard and the male to male jumper wire was used to connect the power-pin to the power rail of the breadboard and the ground pin to the ground rail on the breadboard while the middle pin is connected to the assigned port on the microcontroller. The power-out pin of the temperature sensor, which is the middle pin is connected with the male-male jumper wire to port 0 on the microcontroller, while for the vibration sensor, it is connected to port 1 and for the sound sensor it is connected to port 2 of the micro controller.

3.6.2.3. Opening of the serial Port for Communication

The code for opening the serial port for communication between the board and to other devices and programmes is given below:

Step 1: Read in the value from each parameter pin (analogRead (tempPin); analogRead (VibPin); analogRead (SoundPin))

Step 2: Print out the parameters values (Console.print((byte) tempC); Console.print (analogRead (Xpin)); Console.print (analogRead (Ypin)); Console.print (analogRead (Zpin)); Console.print (analogRead (SoundPin)).

Step 3: Indicate when the current values exceed the severity limit by turning the LED light on and sending fault notification.

If $\overline{X} - 5mg \geq X \geq \overline{X} + 5mg$ OR

$\overline{Y} - 5mg \geq Y \geq \overline{Y} + 5mg$ OR

$\overline{Z} - 5mg \geq Z \geq \overline{Z} + 5mg$ OR

$tempString > 35^{o}$ C OR

$SoundPin > 70dB$

Then

TembooChoereo SendEmailChoreo;

SendEmailChoreo.addInput (“MessageBody”, dmsg)

Else

End If

Delay (3000);

The above lines of code open the serial port of the microcontroller for the conversion of the analog signals from the sensors to digital. The variables are set to read the values from the pins of the sensors while the values are assigned with another variable which converts the signal to digital values. Conditional statements are then introduced for decision making by the microcontroller. The mean value of the vibration parameter is determined from the data collected at the initial stage of the commencement of the remote condition monitoring system. The severity level of each parameter is set based on the expert knowledge from the machine manufacturer and the analysis from the data read from the installed sensors on the machine domain. The code for the comparison of the current measured value of the machine parameters against the severity limits is added. Hence, at damage initiation when the condition of the parameters reaches the severity limit, the microcontroller sends a fault notification to the programmed maintenance email for precautions to circumvent the situation and avert critical breakdown of the machine. The microcontroller triggers the condition of a LED light as high to indicate abnormality and a feedback notification is initiated by sending an email across to the maintenance department for proactive maintenance of the machine.

3.6.3. Coding for the Cloud (Email Choreo)

There are several cloud servers which could be used to remotely access the condition of the elevator system. These cloud servers are available through a third-party web service called

TEMBOO and had been programmed to work synchronously with the Arduino microcontroller. Temboo web-service assists in connecting Arduino microcontrollers and Arduino-compactible devices to a vast array of web-based resources and services. The web-based applications, which are programmed for Arduino and could be used for remote access of the monitored parameters include, Facebook, Amazon, Dropbox, Bitly, Google, Gmail, LinkedIn, Twitter, Yahoo, Youtube, websites etc. All these and many more are the web-services which make it possible to connect the monitoring device to the cloud server.

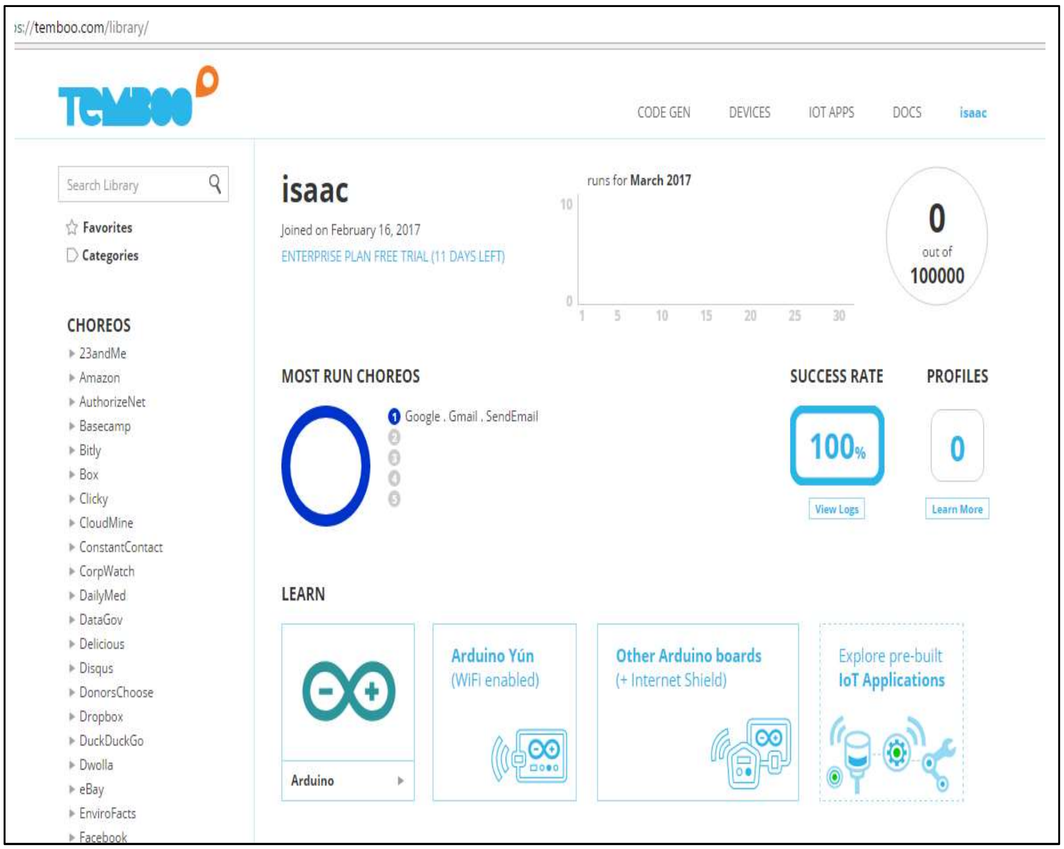

Figure 3.18: Temboo Third Party IoT Web Page GUI

This research, however, considers one choreo for accessing the data remotely on the internet as indicated in Figure 3.18. The email choreo is adopted for the remote data monitoring online for two major reasons:

- Easy access to the monitoring teams and prompt email notification,
- It is less stressful and cumbersome, unlike a webpage, and also allows for multiple email notifications and data updates.

The graphical user interface (GUI) of the Temboo web-application is shown in Figure 3.18, which has the different choreo displayed on the landing page. The first step in setting up an email choreo is to first create a new Gmail account for capturing the monitored data. The username for the mail is *elevatordatamonitoring@gmail.com* and the password is set for the access. The most important settings for the Gmail account to connect to the Temboo web-account is to get the App specific password. This is particular to an individual email account. To get the App specific password, there is a need to activate the 2-step verification by turning it on. Thereafter, an account is opened on Temboo web-app with the username as Isaac, registered with the email address formally created.

The Gmail choreo is clicked on the landing page of Temboo after logging into the page. The google option is chosen and then the send email option chosen as well. On the same page, the board type is selected which is Arduino Yun, the App specific password of the email is entered on the Temboo choreo account set-up and the run button is clicked. This automatically generates some lines of code which is copied and pasted on the Arduino IDE. The automatically generated lines of code from Arduino have some data called the Temboo-data (ltji wzlr xppy xnwk). The code or sketch also has some input variables such as the data to be sent to the mail, and the email address to be sent to and the variable declaration and inclusion. Figure 3.19 shows some of the required fields generated by Temboo. The email address, username, password, and message-body were replaced with the information peculiar to this research, the email created, username and Temboo-data password generated. Another generated sketch or code aside from the main sketch for the email is the Header file sketch. This sketch consists of Temboo account information such as the account name, App key and a few lines of code. Figure 3.20 shows the account information generated as the header file for this work which is copied and pasted in a separate new window of the Arduino IDE.

```
{
  digitalWrite(ledPin,LOW);
}
delay(10000);
  if (calls <= maxCalls) {
    Console.println("Running SendEmail - Run #" + String(calls++));

    TembooChoreo SendEmailChoreo;

    // Invoke the Temboo client
    SendEmailChoreo.begin();

    // Set Temboo account credentials
    SendEmailChoreo.setAccountName(TEMBOO_ACCOUNT);
    SendEmailChoreo.setAppKeyName(TEMBOO_APP_KEY_NAME);
    SendEmailChoreo.setAppKey(TEMBOO_APP_KEY);

    // Set Choreo inputs
    SendEmailChoreo.addInput("FromAddress", "opeyemiisaac1@gmail.com");
    SendEmailChoreo.addInput("Username", "opeyemiisaac1@gmail.com");
    SendEmailChoreo.addInput("Subject", "Remote Sensor Data");
    SendEmailChoreo.addInput("ToAddress", "opeyemiisaac1@gmail.com");
    SendEmailChoreo.addInput("Password", "ltjiwzlrxppyxnwk");
    SendEmailChoreo.addInput("MessageBody", tempString+ "C");


    // Identify the Choreo to run
    SendEmailChoreo.setChoreo("/Library/Google/Gmail/SendEmail");

    // Run the Choreo; when results are available, print them to serial
    SendEmailChoreo.run();

    while(SendEmailChoreo.available()) {
      char c = SendEmailChoreo.read();
      Console.print(c);
    }
```

Figure 3.19: Temboo Generated Code for Email

```
*/

#define TEMBOO_ACCOUNT "isaac"  // Your Temboo account name
#define TEMBOO_APP_KEY_NAME "myFirstApp"  // Your Temboo app key name
#define TEMBOO_APP_KEY "roR9shrSSHPQGsFDgLHRLjOGZWeel9sf"  // Your Temboo app key

#if TEMBOO_LIBRARY_VERSION < 2
#error "Your Temboo library is not up to date. You can update it using the Arduino lib
#endif

/*
```

Figure 3.20: Temboo Generated Header File Sketch

The two sketches are compiled on the IDE and the Temboo library of the IDE is ensured to be up to date and then uploaded to the board. This setup is installed on the elevator and the machine room temperature, acoustics as well as the vibration of the system is monitored.

3.7. Data Capturing

The data for the monitored conditions are read and recorded from the email. Brittain (2004) designed a data capturing engine with automatic target data location, extraction and storage at an interval of fifteen (15) minutes. Similarly, the device is configured to capture and send the data to the email at an interval of ten (10) minutes, which means that six sets of data are sent in an hour if the conditions are normal. The data is captured for a period of 53 days and recorded. The severity level for each of the parameters, which are temperature, vibration, and sound/acoustic is calculated based on manufacturer's specification for the machine (elevator). The level is determined based on the limits of excitation from the mean parameter value stated by the machine manufacturer or from the data.

The data from the machine is monitored and logged by the IoT device configured and analysed against the severity level. The data is captured as signal for the elevator system's condition, fault diagnosis, notification, and sent to the cloud (email) for remote access. The data from the monitored machine can be displayed in a chart and analysed. Different statistical charts and software can also be used to represent the data being capture by the controllers remotely for easy analysis of the data. The data are plotted in graph using MATLAB for easy interpretation of each parameter against the severity level. This makes analysis for remote monitoring maintenance possible and likewise, proactive maintenance and expert knowledge is possible from the machine manufacturer. These three monitored parameters are configured and programmed to avoid breakdown maintenance due to failure of controls as a result of hoistway temperature, wearing of the roller bearings on the guide rails, failure or inefficient brake system, and floor level allowances or gapping. Severity in any of the monitored parameters indicates a signal to a failure and need for proactive maintenance.

The data logged from the monitoring device is used as diagnostic for fault detection by analysing the severity levels of the machine under different conditions. Deviation in the proper working condition of the machine is a signal of some deterioration in some machine components and parts.

Table 3.1: Elevator Failure Mode and Effect

No	Failure/Fault	Effect	Analysis
1	Faulty Brake system or Brake shoe.	Increased sound or noise; Unlevelled cabin and building floor, increased vibration.	Worn out brake pad or shoe Brake shoe check.
2	Friction on guide rail.	Increased sound from the guide rails. Increased vibration gradually to severity.	Worn out rollers, Lubrication needed.
3	Control System Shutdown.	Sudden stoppage or shutdown of the cabin.	High machine room temperature, Power Surge.
4	Shock and vibration at regular interval	Increased vibration of cabin, floor imbalance, long time of travel.	Wearied hoist cable and wear.
5	Faulty drive assembly (pulley or drive chains).	Increased shock, sharp displacement or wobbling of the elevator car.	Increased vibration.
6	Jamming of the gear box.	Increased vibration, Increased noise from the gear box.	Increased vibration, Increased sound.

Table 3.1 illustrates the likely failure mode and effect analysis in the diagnosis of the probable problem with the machine condition.

3.8. Conclusion

This chapter addressed the second objective of the research which is to optimise maintenance routine from the current breakdown maintenance to remote condition monitoring for fault detection and notification. Optimising maintenance of machines using a remote condition monitoring approach offers two major advantages. The first is to optimise the system by reducing the downtime and catastrophic breakdown of the elevator system, which increases the productivity and efficiency of the elevator system. The inability of the maintenance team to detect a breakdown of the system in time is eliminated through this approach. Secondly, it offers the possibility of remote manning of the elevator system and critical components, which may not have been safe or possible for the machine operator. Remote condition monitoring approach using IoT technology uses the privilege of monitoring the conditions of a machine and some components of the machine located remotely and in a hazardous environment. Since physical presence is not needed to monitor the condition of a system, the safety of the operator is ensured as well as the users because of early detection of faults which prevents accidents. In cases where there is an operator, less exposure to hazard is possible through this technology.

In some instances of industrial accidents where explosion of facilities and machines are possible, remote condition monitoring provides the possibility of access to the machine conditions before the damage as the parameters are available remotely on the cloud. Several cloud computing applications could also be adopted for remote data monitoring of machine and process conditions. A very robust application is developing a web application that displays the monitored data in form of a GUI from the device. The web-application display gives the privilege of a multi-complex display of several data for remote monitoring however, requires a lot of detailed and complex programming in order to achieve, hence the email remote monitoring is adopted in this research.

This chapter therefore discussed the approach and development of the remote monitoring device for remote condition monitoring of the elevator's conditions, which takes care of the second objective of the research.

CHAPTER 4 : REMOTE DEVICE DESIGN AND INSTALLATION

4.1. Introduction

This chapter discusses the design, development and installation of the remote monitoring device on the elevator system. It gives more highlights on the construction of the remote monitoring device and its individual components. The components connected to develop the remote monitoring device are individually analysed and explained. The connections and the installation of the device on the elevator system was also explained in this chapter. This further gives a grasp of the second objective of the research which is to optimise maintenance through a remote monitoring technique.

The remote monitoring device comprises of the powered configured components which together captures signals and sends these as data to the remote internet access. A remote sensing device includes a remote sensing component, a network module such as a web application server, and a database (Gaw 2016). The configured device comprises of:

- The sensors,
- The microcontroller,
- The power source,
- The internet router,
- Connectors.

4.2. System Architecture for the Remote Machine Condition Monitoring

System architecture for remote machine condition monitoring accomplishes the requirement of monitoring and measuring the condition of machines, processing the data from the instrument and accessing the conditions remotely without physical presence. The approach in this research makes use of micro-controller enabled sensors for measuring the parameters of the elevator, the powered IoT compliant microcontroller for controlling the whole system connection as well as the data transmission from the sensor and to the cloud database which in this case is the emailing choreo. The microcontroller work as the CU, thereby carrying out some logical reasoning and arithmetic on the read sensor data. The platform is therefore categorized into three layers, which are the Sensors layers for data capturing, the API/Data transmission layer and the web application client.

Figure 4.1 illustrates the system architecture for the remote condition monitoring maintenance for a machine using the IoT technology.

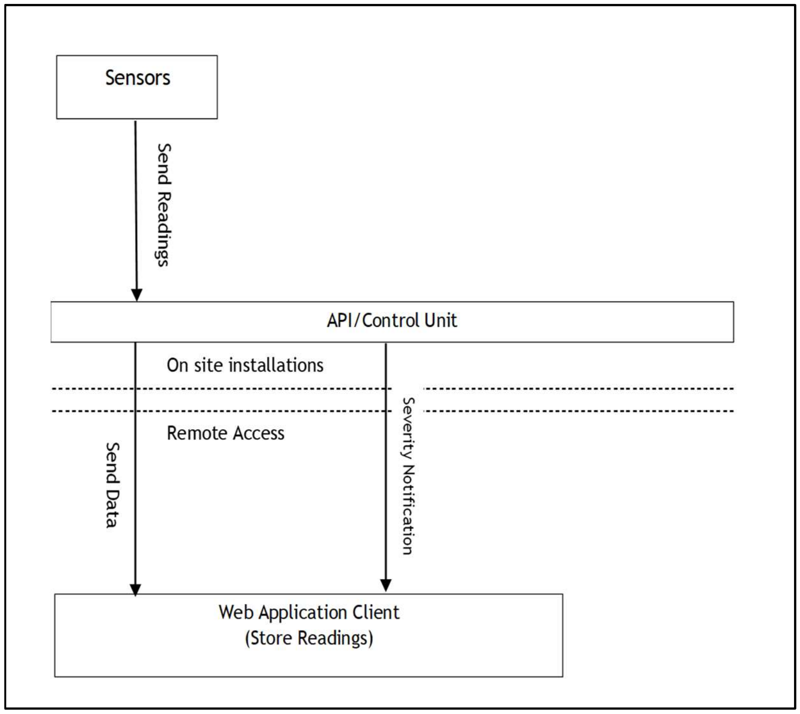

Figure 4.1: System Architecture for Machine Remote Condition Monitoring

Microcontroller-enabled sensors: These measures the conditions of the machines for both the vibration parameter and the machine room temperature parameter.

API/Control Unit: This unit monitors the sensed signal from the sensor, converts it to digital value which are readable to the operator.

Cloud Services/Web Application: This is the Internet end of the whole set-up that provides the remote link for the data being monitored by the device. This serves as the database for storing the data from the sensors as well as a remote access for the data and medium of event notifications.

4.2.1. Sensors

The sensor network comprises of three different sensors connected to the microcontroller to sense three different parameters; vibration, acoustics and temperature. The temperature sensor used is LM35 which is connected to the breadboard as indicated in Figure 4.2.

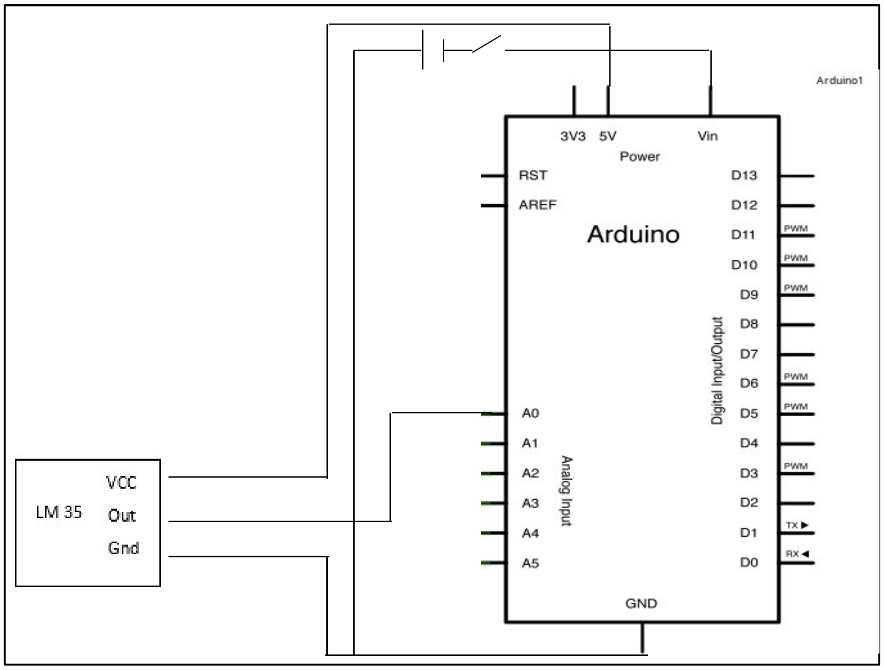

Figure 4.2: Temperature Sensor Connection

The ground pin is connected to the ground rail of the breadboard and the power pin to the power rail while the output signal is connected to the analog input zero (0) on the microcontroller. The sound sensor used is Sparkfun Sound detector LMV 324, which has the ground terminal connected to the ground rail on the board, the power connected to the power rail and the signal terminal indicated as envelope connected to the analog input pin 2 on the microcontroller. Figure 4.2 shows the diagram for the connection and Figure 4.3 shows the image of the connection.

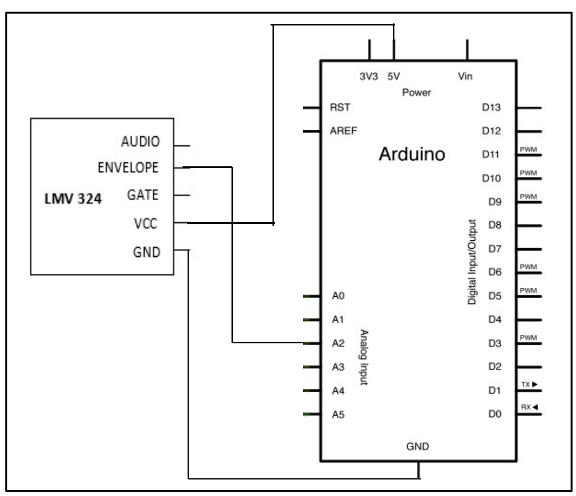

Figure 4.3: Sound Sensor Block Diagram

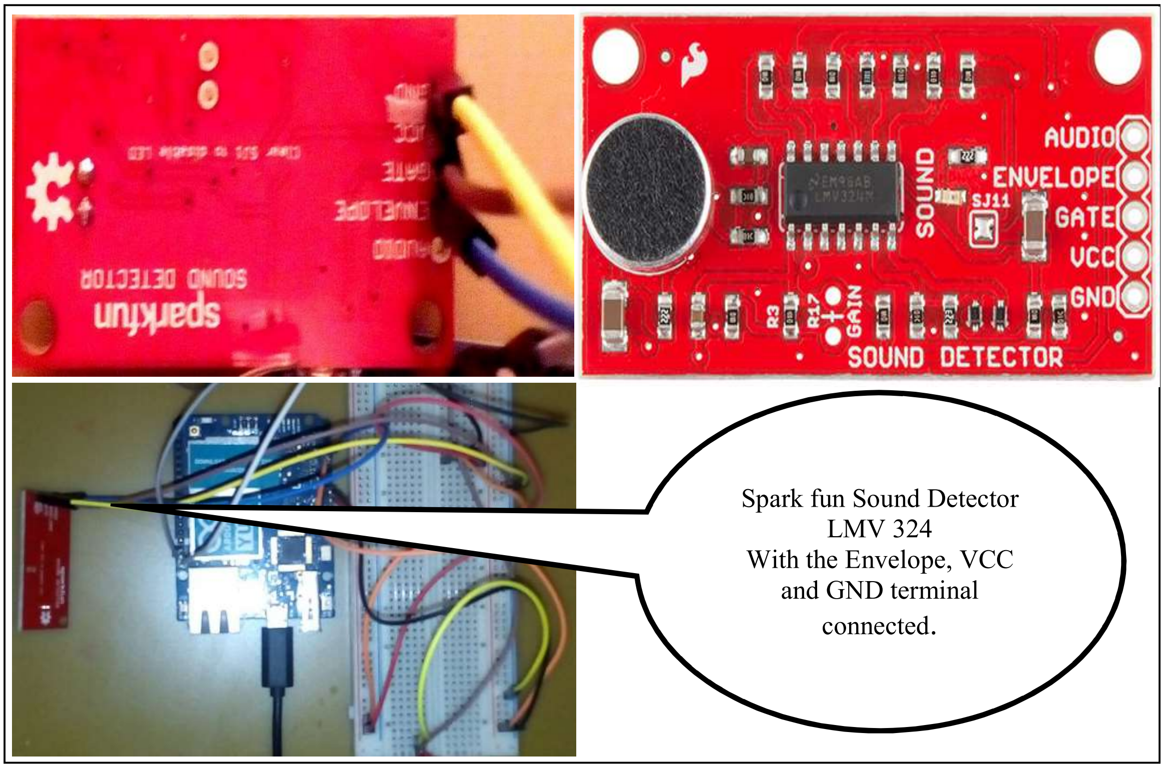

Figure 4.4: Sound Sensor Connection

The terminals are soldered to a male to male jumper wire and then connected to the breadboard and the envelope to the microcontroller. An ADXL 345 vibration sensor was used in picking the three axial axes of vibration of the system being monitored. The vibration sensor has ten pins with five pins on one end and five pins on the other end. This vibration sensors senses the vibration of the system on three-axial space (i.e. *x, y* and *z* axes). The vibration sensor is connected using only five pins out of the ten pins available on the sensor module, three pins on one end and two pins on the other end of the sensor. The power pin on the sensor is connected to the power rail on the breadboard, the ground to the ground rail and the Control Systems (CS) pin to the power rail as well. The Serial Clock Line (SCL) pin and Serial Data (SDA) pin on the sensor module are to be connected the SCL and SDA pin on the microcontroller, however they have to be bridged to the power rail using the resistor. Hence, they are both connected to separate rails on the breadboard, then the rail connected to the respective point on the microcontroller while the rail also has the resistor connecting it to the power rail on the breadboard. The connection of the vibration sensor can be seen as shown in Figure 4.5.

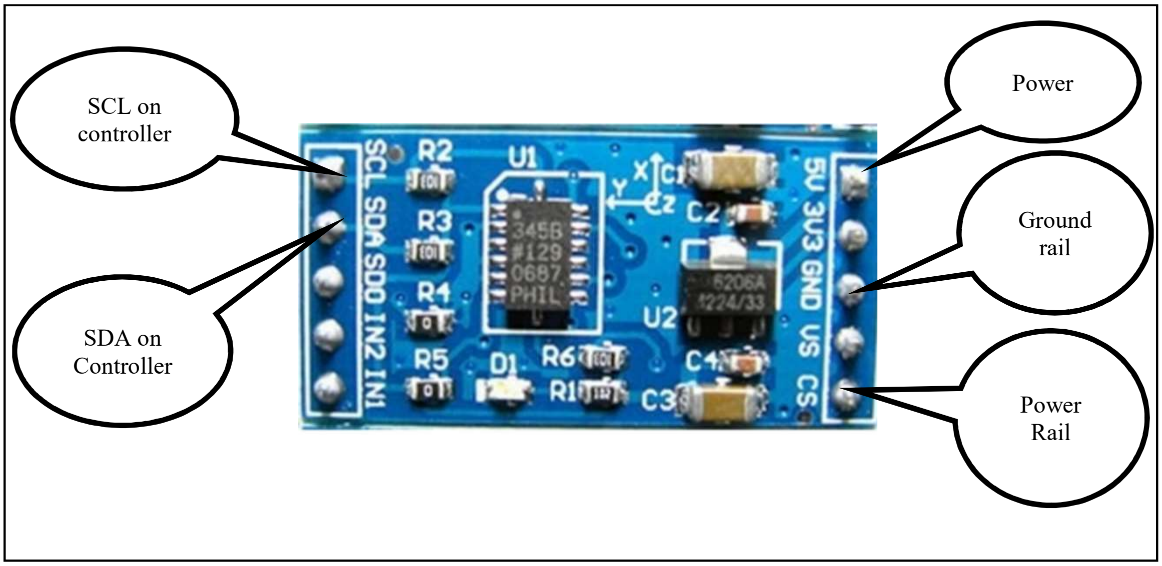

Figure 4.5: ADXL345 Vibration Sensor

Figure 4.5 also illustrates the diagram of the connection to the controller and the breadboard.

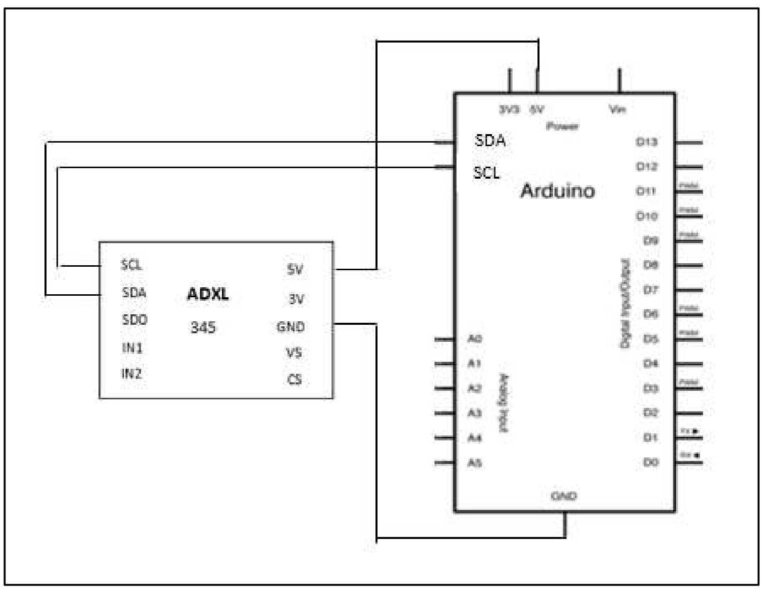

Figure 4.6: Connection of Vibration Sensor Module

4.2.2. Microcontroller

The microcontroller used for the device construction is Arduino Yun controller which is an IoT enabled controller with wireless facility. It is powered using a 5V battery source and also connected to the internet via the Wi-Fi facility. The microcontroller is one of the principal components of the remote monitoring set-up as it connects the three sensors, interprets the signals from the sensors and also transmits the data to a remote internet base. The microcontroller has both the digital input ports and the analog and both the temperature and sound sensor are both connected to the analog input port on the microcontroller. The vibration sensor module is connected to the digital input port of the controller. The connection can be seen in the Figure 4.6.

4.2.3. Power Source

The whole set up is powered by a 5V battery source. The battery is directly connected to the microcontroller and all other devices, which are mainly sensors powered by the power rail of the microcontroller. To extend the power life of the source, two power sources, being power banks, were connected. Figure 4.6 illustrates the image of the power source, 500mAh power bank for the remote monitoring device.

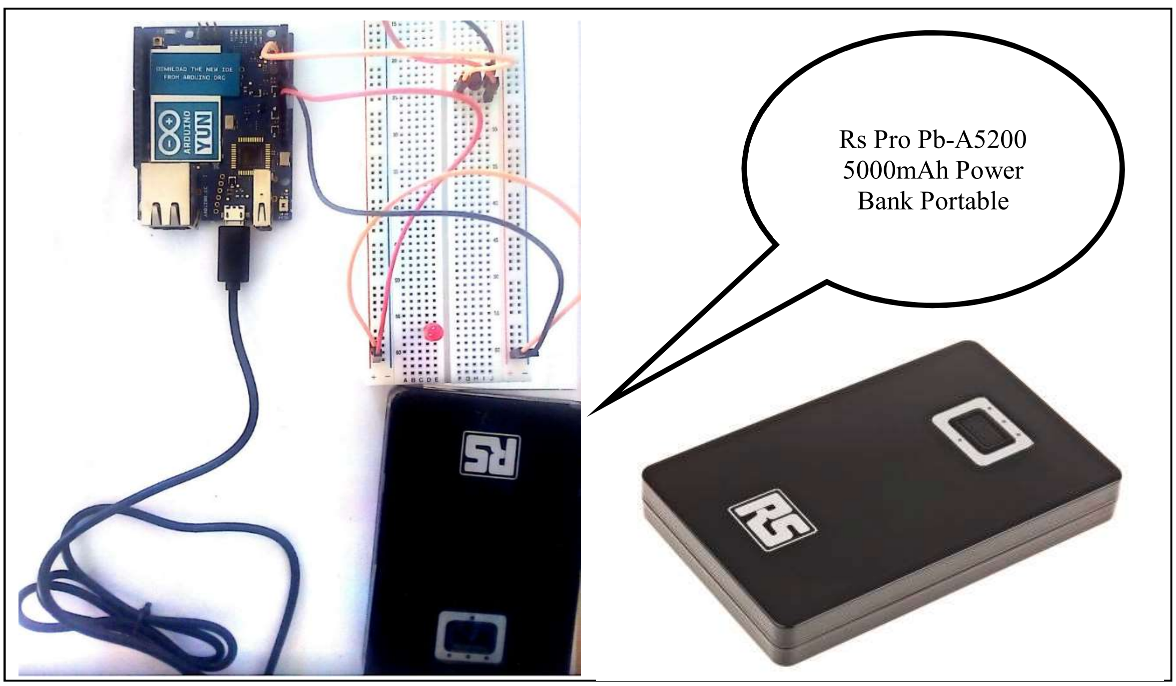

Figure 4.7: Power Bank for Power Source for Controller

4.2.4. Router

The router is the internet source device for the microcontroller. The microcontroller is connected to the internet via Wi-Fi to the router and the Wi-Fi settings of the router are configured on the microcontroller. The router in Figure 4.7 is a stand-alone device which is powered by an in-built battery which is re-chargeable. Therefore, it was connected to the power bank source in order to extend its power life.

Figure 4.8: The Mobile Potable Router

4.2.5. Connectors

These components consist of the connecting devices between each component in order to link for communication. The connectors include the male to male jumper wire, male to female jumper wire, and the breadboard. The jumper wires are used to connect the pin terminals of the sensors to the power rail on the breadboard and the ground rail on the breadboard. It also connects the data/signal pin to the microcontroller input port. The breadboard is a multi-face port that allows for multiple connection of devices and sensors to the power, ground port and the input pin of the microcontroller.

4.3. Set-Up and Installation

The whole monitoring device is constructed and configured to work as a system installed on the machine for real time data monitoring. The three parameters are remotely monitored and sent to the cloud via email choreo by the remote monitoring system. The circuit diagram in Figure 4.9 shows the configured components block diagram for the monitoring device for the conditions of the system. The device was installed on the roof of the elevator cab to get a more precise data of the conditions of the drive system and to avoid obstructions by the users. The position of installation was chosen so as to deliver a high signal reception from the car drive system, car door and landing door drive system and the brake system of the elevator.

The vibration and sound of the car along the guide rails as it travels up and down, the braking of the car and the drives of the car and landing doors and locks were the major focus of the device being installed on the car.

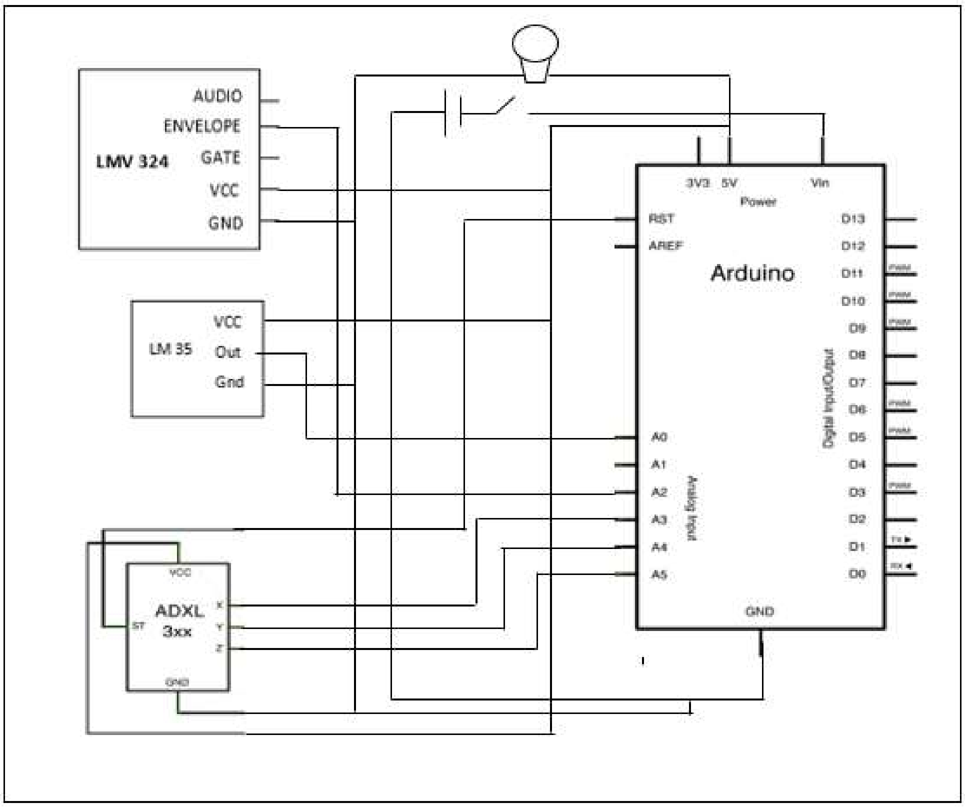

Figure 4.9: Remote Monitoring Device Block Diagram

Temperature threshold helps to monitor likely malfunctioning of the controls from the machine room. The device was therefore installed on the system by sending the car to a level below the top level from where the landing door was opened for access to the outer top of the car roof. Figure 4.10 shows the installation of the device on the system.

The device was fastened to the point of installation using a recommended adhesive so as to avoid resonance vibration from the system or drifting of the device on the roof, which could affect the accuracy of the data read by the sensors. Access to the roof top of the elevator car was gained by sending the car a level below the last floor and opening up the landing door using the lock key Figure 4.10 shows the installed point on the elevator roof top of the car.

Figure 4.10: Device Installation

The conditions monitored by the device are to give some diagnostic information for the abnormality of the system. The controls are troubleshot in the machine room to detect malfunctioning of the controls. Figure 4.10 shows the support of the elevator car on the guide rail by means of the rollers. Any faulty roller or drive cable is indicated through increased vibration of the system. A faulty braking system could easily be indicated by increased acoustics and vibrations of the elevator car. Any fault indication from the drive system for both the car and the landing door was also picked up by the monitoring device.

The position of the remote monitoring device was therefore, carefully selected in order to have a good sensitivity of any malfunctioning of the elevator system. Any malfunctioning components of the system is therefore picked up as malfunctioning of the system.

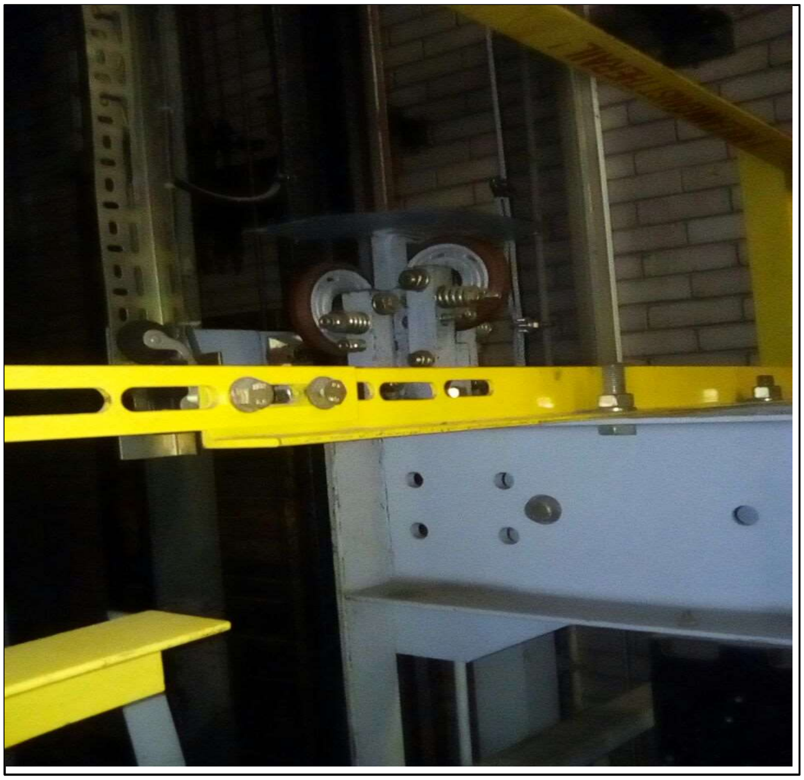

Figure 4.11: Elevator's Support on Guide Rail

4.4. Conclusion

This chapter discussed the design and installation of the remote condition monitoring device for remote monitoring maintenance of the conditions of an elevator system. The critical components/parts of the elevator system were discussed and subsequent parameters, which were indicative of fault initiation in the system were identified. The sensor network configuration was carefully designed and configured to capture the current condition of the elevator system as well as send the data and fault notification to a remote location for data monitoring for fault detection. The remote monitoring device was therefore installed at the outer car roof such that it could capture the data from those critical components accurately and send to the remote location via the IoT configured device embedded on the system.

CHAPTER 5 : RESULTS AND DISCUSSION

5.1. Introduction

This chapter presents analysis of the remotely captured data on the internet via email and the discussion of the results. The chapter discusses the data presentation, graphical presentation and analysis of data for fault detection, temperature graphical presentation, acoustics graphical presentation, vibration graphical presentation, assessment of parameters for fault diagnosis and discussion, Optimising the monitoring system by adopting control charts for variables, and conclusion. The collected data was used to diagnose the condition of the elevator system for fault detection and deterioration during the working condition. This chapter therefore addresses the last objective of the research which is to diagnose the elevator's condition from the remotely captured data for early detection of faults for a modernised maintenance routine. The maintenance routine is optimised from the breakdown maintenance policy to remote condition monitoring for fault notification, detection and diagnosis of deterioration in elevator condition.

The possibility of detecting faults on the elevator system remotely through the remote monitoring device and responding immediately to any deterioration in condition (proactive maintenance) optimises the system from the current breakdown maintenance policy. The optimised maintenance routine from remote condition monitoring is presented in this chapter by analysing the captured data for early detection of fault in the elevator system, identifying the possible faults in the system, and adopting proactive maintenance to bring the system back to its normal working condition. The data are evaluated against the severity limit conditions, considering their range of excitation from the mean value, and the graph of each parameter is plotted using MATLAB programming software.

5.2. Data Presentation

Data capturing from the elevator system entails sending the temperature, vibration and acoustic data from the remote monitoring device installed on the elevator system to the internet application used. The data were sent to the email on the code programmed into the microcontroller board of the remote monitoring device installed on the elevator system. The data were therefore sent instantaneously at an interval of 10 minutes and then recorded in tabular form for better presentation and analysis. The data from the elevator system is presented in Appendix 2, consisting of the monitored parameters, temperature, vibration and sound/acoustics as well as the given time interval between each captured data. The data captured during the system's breakdown were discarded as it is not significant in diagnosing fault and malfunctioning of the system since the system is not working. The data in Appendix 2 were therefore captured from the email address registered on the IoT device and put in the table format.

5.3. Graphical Presentation and Analysis of Data for Fault Detection

The data for each parameter were plotted against time with the MATLAB software tool for better presentation and analysis. The individual parameters, temperature, acoustic and the vibration, was plotted individually against the time so that the condition of the system can be evaluated through comparison of effects and reconciling the values to the mean value, based on the historical data. To have a good graphical presentation, the data are plotted against the time duration of the commencement of the data capturing and operations. Furthermore, the data set captured during the breakdown of the elevator system is discarded as the elevator is not functioning, therefore the data is inconsequential to the condition of the elevator system.

5.3.1. Temperature Graphical Presentation

The temperature time graph indicates that the atmospheric temperature conditions were within the permissible range, which is 30° to 35°C as stated by Marchitto, (2016), for the proper functioning of the elevator controls in the machine room as well as the hoistway. The graph in Figure 5.1 shows that the peak temperature during the period of the remote monitoring was 27^0C and the lower limit for the condition is 22^0C . The atmospheric temperatures were within the normal range and therefore, may not impose any adverse effect on the controls of the system. This would imply that temperature parameter may not be a factor for fault or malfunctioning of the system during this period.

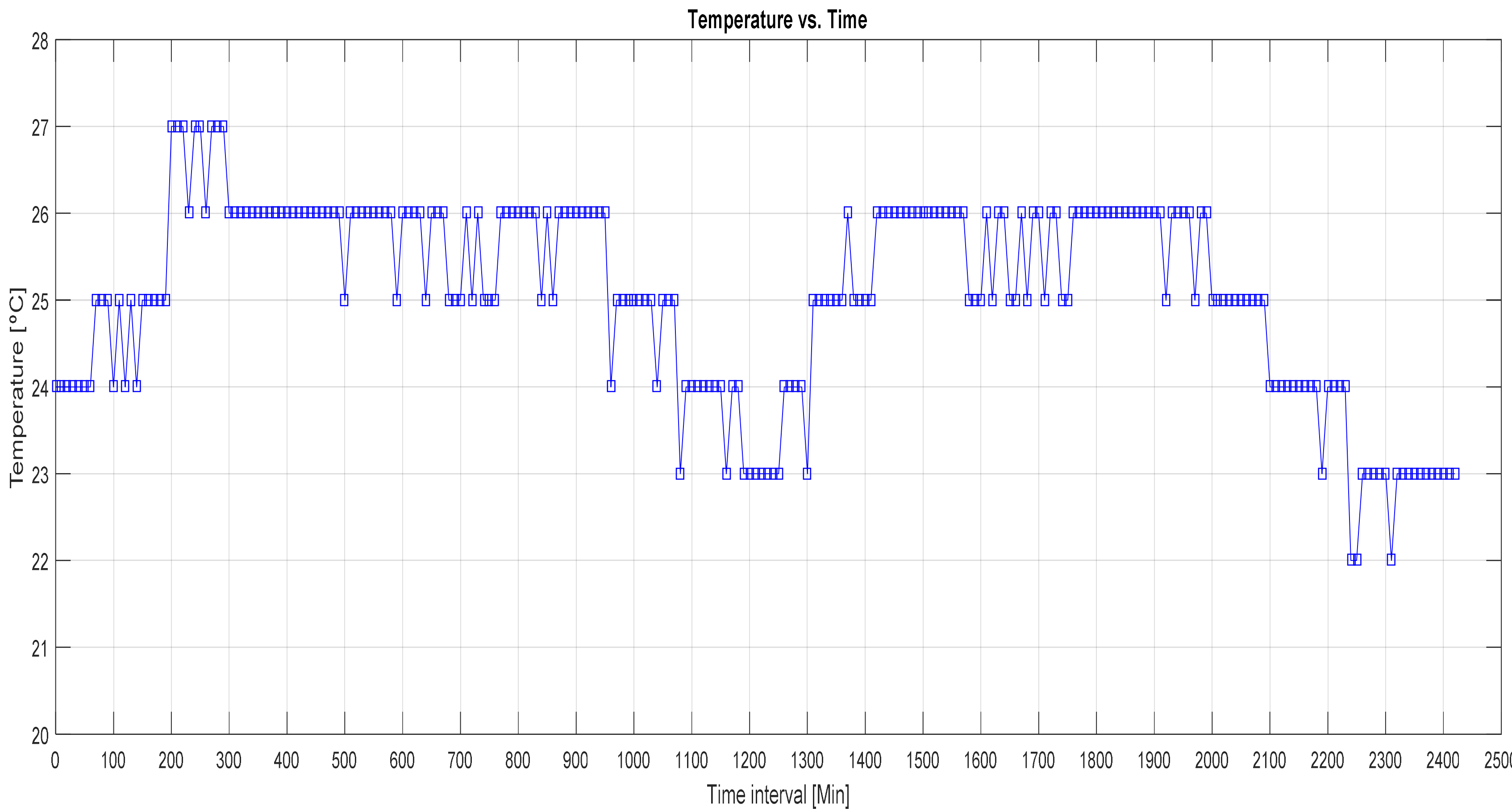

Figure 5.1: Temperature Against Time Graph

5.3.2. Acoustics Graphical Presentation

Figure 5.2 shows the graph of the sound parameter against the time duration measurement of the system. The sound sensor module measures the sound intensity by converting the output voltage from the sensor to sound intensity in decibels. The conversion is done by evaluating the output voltage relative to the reference input voltage of the sensor by using the formula below:

$$I\ (dB) = 10\ log_{10}\ (\frac{I_{Sound}}{I_{ref.}}) = 20\ log_{10}\ (\frac{V_{Sound}}{V_{reference}}) = 20\ log_{10}\ (\frac{P_{Sound}}{P_o}) \quad \text{.........................} \ (1)$$

The sound intensity level, I, in decibels can be derived as ten times the logarithm of the ratio of the intensity of a sound wave to a reference intensity. The ratio could be expressed in voltage and can also be expressed as a function of the instantaneous sound pressure, P_{Sound}, to the reference pressure which is 20 Pa. The acoustic signature shows that there are events that happened during the operation of the machine which show irregularity in the operating conditions. These were noted as an indication of malfunctioning of the system as a fault notification were received at these instances and discussed in section 5.4. The graph indicates that there were five (5) different times of abnormality in the condition of the system which fault indications were sent, with the first abnormality occurring at 100minutes, and the second at 650minutes, the third at 950 minutes, the fourth at 950 minutes and the fifth at 1500 minutes, and. The applicable standard VDI 2555-2:2004 for acoustic design for lifts specifies a maximum sound pressure level in the hoistway as 75 dB, the door as 65 dB and the relay switching as 55 dB (Schindler, 2017). A tolerance of 5dB is considered for the system due to depreciation and duration of usage of the system.

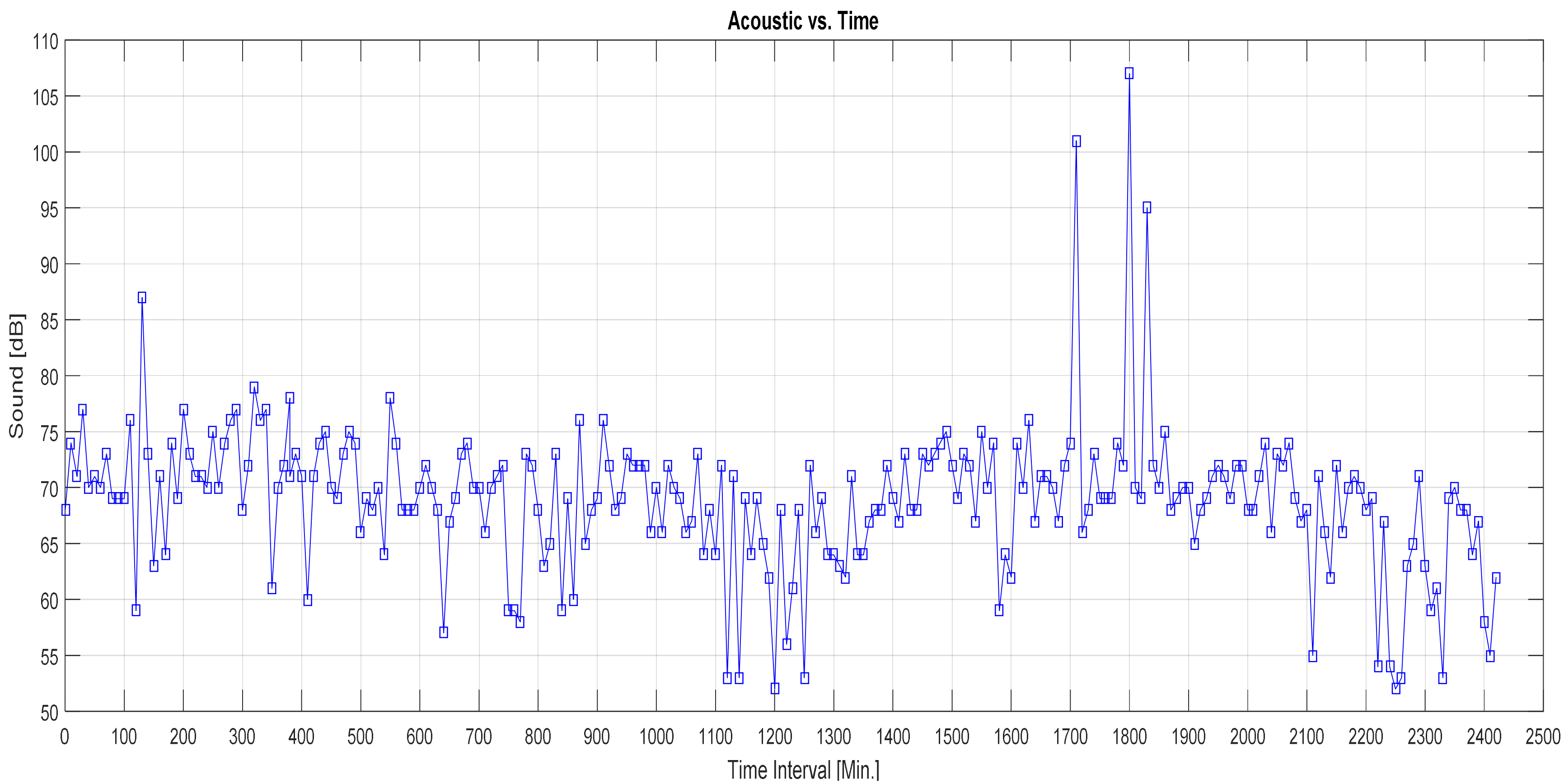

Figure 5.2: Acoustic Against Time Graph

The lower limit of the condition may also be considered as severe and an indication of deviation from normality to abnormality of the system. Since the least sound pressure level of the system's components is 50 dB, then giving a tolerance level of 5 dB, we can take the lower level of the acoustic parameter to be 45 dB. At this level of condition, it shows that the system was no longer in a running condition, hence, it indicates a breakdown of the elevator system. Therefore, there were five notifications of fault generated from the acoustics which can also be noted on the graph that there are five points above the critical level of acoustic condition which demanded proactive maintenance before breakdown. The analysis of the cause at each notification is discussed in section 5.4.

5.3.3. Vibration Graphical Presentation

The vibration parameter is an important parameter for condition-based maintenance of a machine. The three-axial vibration sensor gave a better analysis of the condition of the elevator system as the system's axial vibration can be reconciled against each other. Figure 5.3 presents the graph of the vibration in 'mg' of the elevator car in the y-axis. Schindler elevator manufacturer states that the vibration of the elevator car should be ±5 mg to its mean vibration. With reference to Figure 5.3, which is the y-axial vibration parameter, the mean vibration on this axis from the graph is 10mg and the normal condition is therefore expected to be within the limit of 15mg and 5mg. The points from 120 minutes to 180 minutes are outside this region are clear indication of abnormality in the condition of the elevator system. The z-axial vibration graph is presented in Figure 5.4 and it shows that the control limits of vibration on the z axis is between 0 – 5 mg. The z-axial vibration data is presented in Appendix 2. The limits of vibration on the z-axis for a normal working condition considering the allowance as stated earlier, would be between -5 mg to 5 mg. The graph of z-axial vibration shows that there were some points outside the bearable limits of condition. These points are an indication of abnormality of the condition of the system, which calls for proactive maintenance or a routine check to salvage the situation before critical breakdown. Figure 5.5 shows the graphical representation of the x-axial vibration parameter of the elevator system.

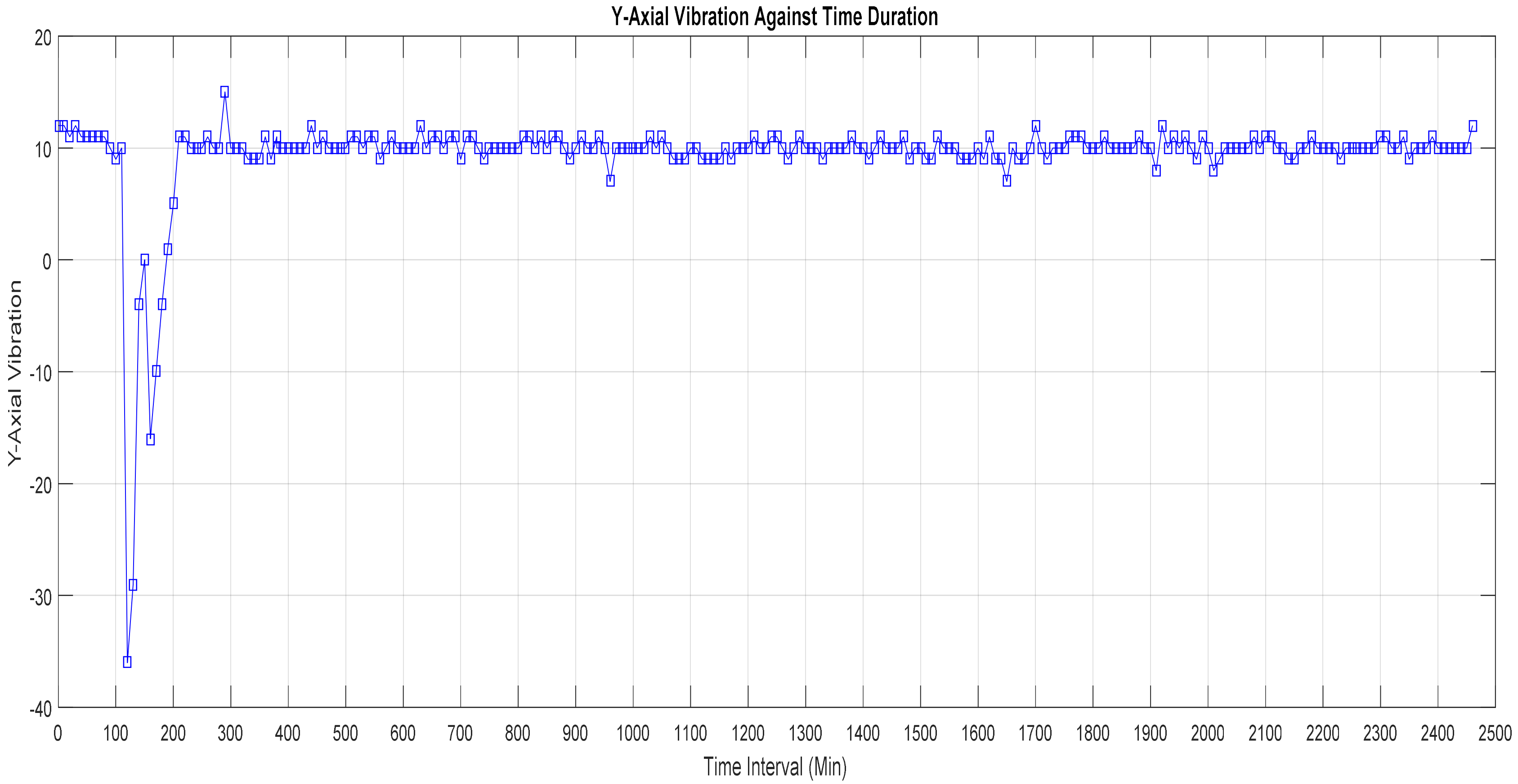

Figure 5.3: Y-Axial Vibration Against Time Graph

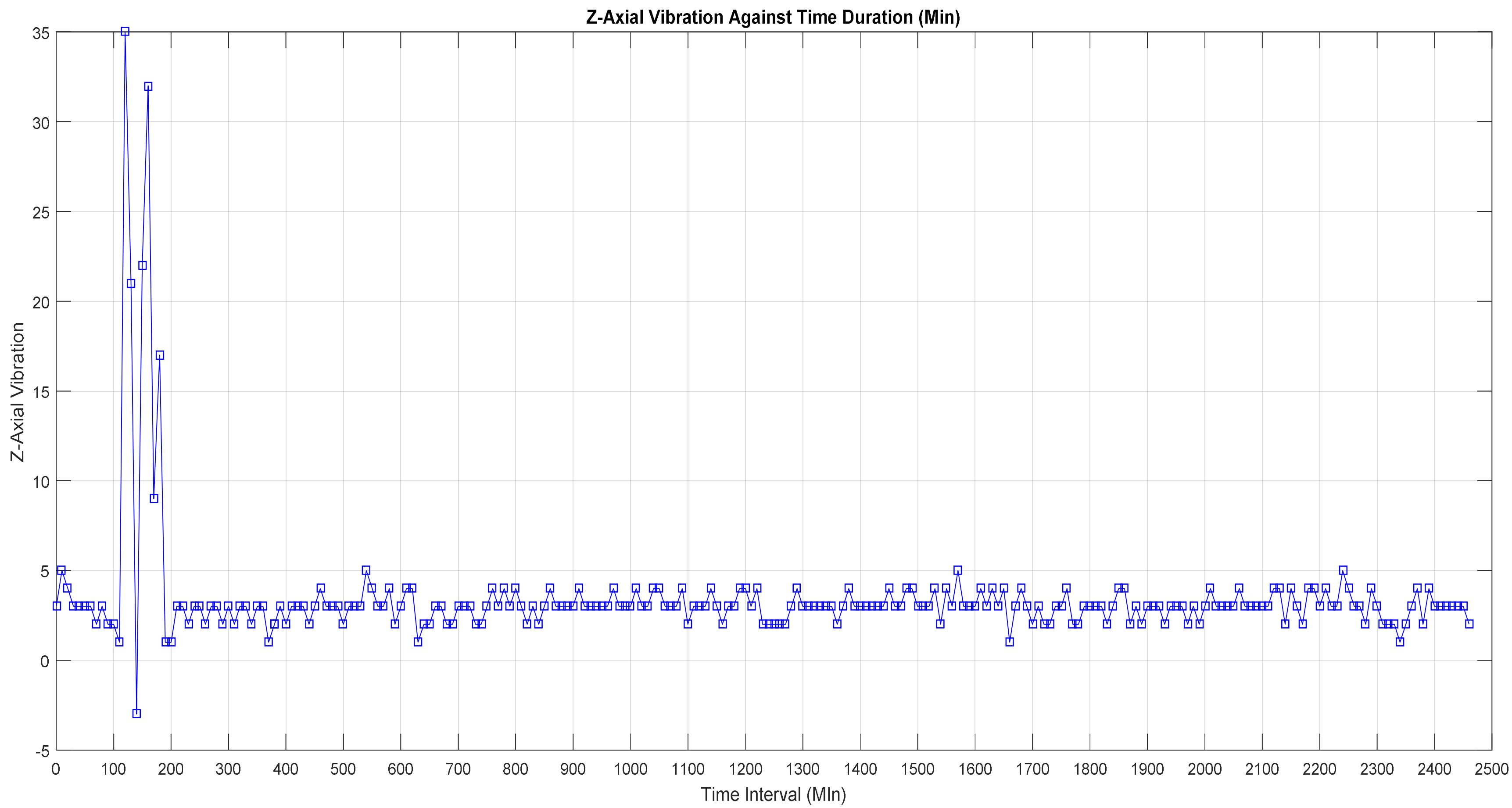

Figure 5.4: Z-Axial Vibration Against Time Graph

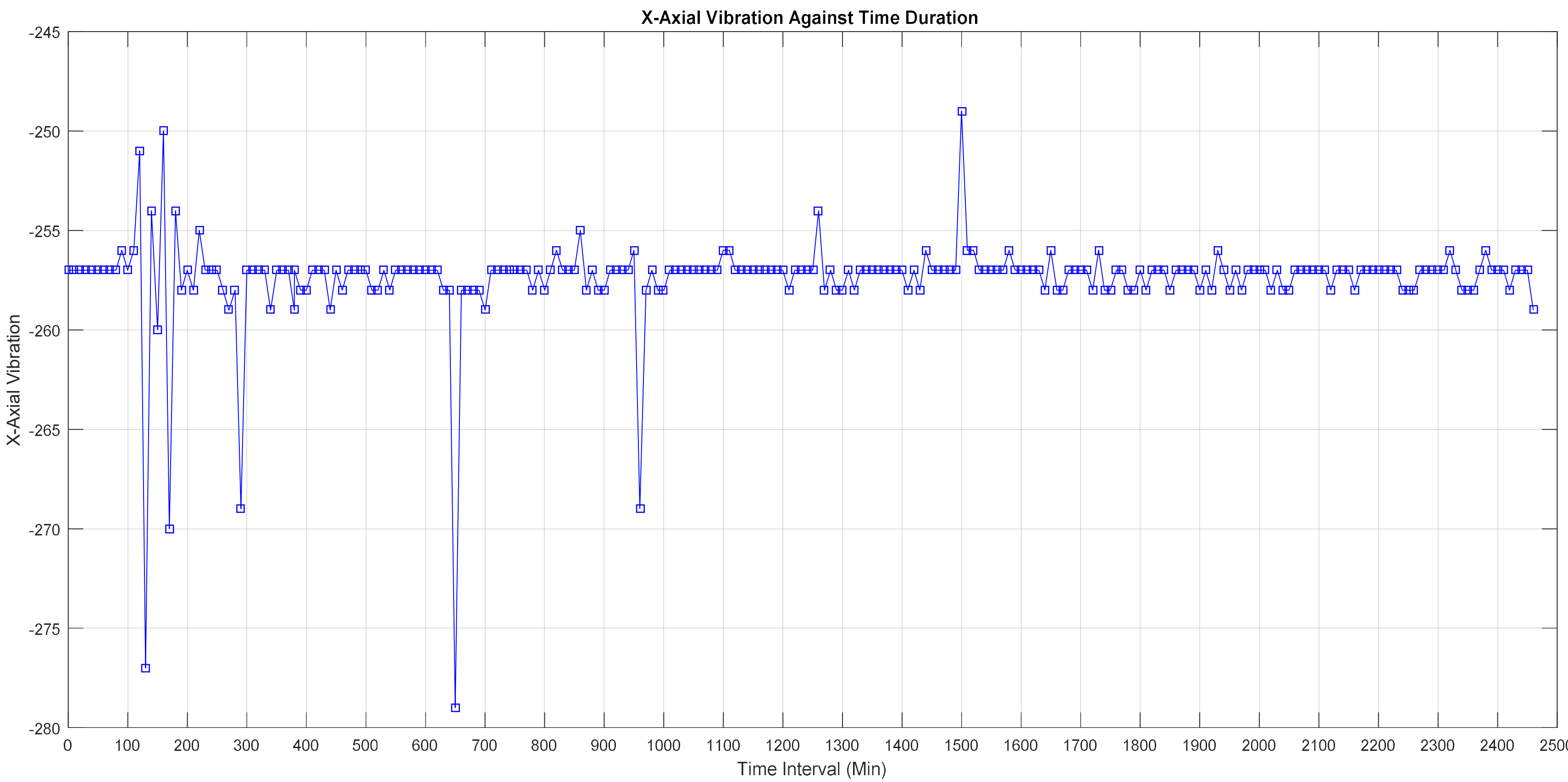

Figure 5.5: X-Axial Vibration Against Time Graph

The graphical representation of the vibration signature helps in determining the mean vibration of the system and also in determining the range of severity of the system. The data presented by Figure 5.5 shows that the normal condition of the system is between the limits of -260 mg and -255 mg. The points outside these limits on the graph would indicate an abnormal condition in the system or interruption in the normal working condition. The three axial vibrations is analysed in section 5.4 to give more information on the excitation of the system.

The three parameters; temperature, acoustics and vibrations, are indicative of a fault and malfunctioning of the elevator system and the bases for fault notification. The acoustic and vibration parameters therefore indicate faults at points outside the range of normalcy in the condition of the elevator system. Acoustic and vibration parameters would give more information on the deterioration of the condition of the system when reconciled together, therefore, this is presented in the next section for assessment of the elevator's condition. The signals were used in diagnosing the condition of the machine remotely to assess whether the condition is normal or not.

5.4. Assessment of Parameters for Fault Diagnosis and Discussion

This section addresses the third objective of this research which is to diagnose the condition of the elevator system for early detection of faults and condition deterioration. The remotely captured parameters were used for diagnosing the current condition of the elevator system being monitored for maintenance purposes. The data was therefore constantly checked as the parameters values were sent to the email. The temperature data shows that the room temperature is within the specified normal condition limits, 30° to 35°C as stated by Marchitto, (2016). The condition monitoring system was conducted from June till August 2017 which falls during the winter period of the year, hence the reason for the temperature range captured by the monitoring device. Figure 5.1 clearly shows that the limits of the temperature captured during the condition monitoring process are 22^0C and 27^0C. The functioning of the controls would therefore not be adversely affected by the atmospheric or room temperature.

The acoustic parameter is a very important tool in diagnosing the state of the system before breakdown and at the initiation of malfunctioning of the system. Figure 5.2 shows the acoustic graph of the remotely monitored data from the elevator system. The first sets of fault notification on the email was received between the 100 minutes and 200 minutes of the monitoring. This immediately called for examination of the data from the system remotely to diagnose the system's working condition. The acoustics limit for the system is first noted which is 75 dB as earlier stated. The first excitation outside the bearable limit occurs between the first 100 minutes and 200 minutes of the data monitoring. Fault notification was sent at this instant to the email. The maximum sound level expected from the drive system during operational mode of the elevator is not supposed to exceed 75 dB.

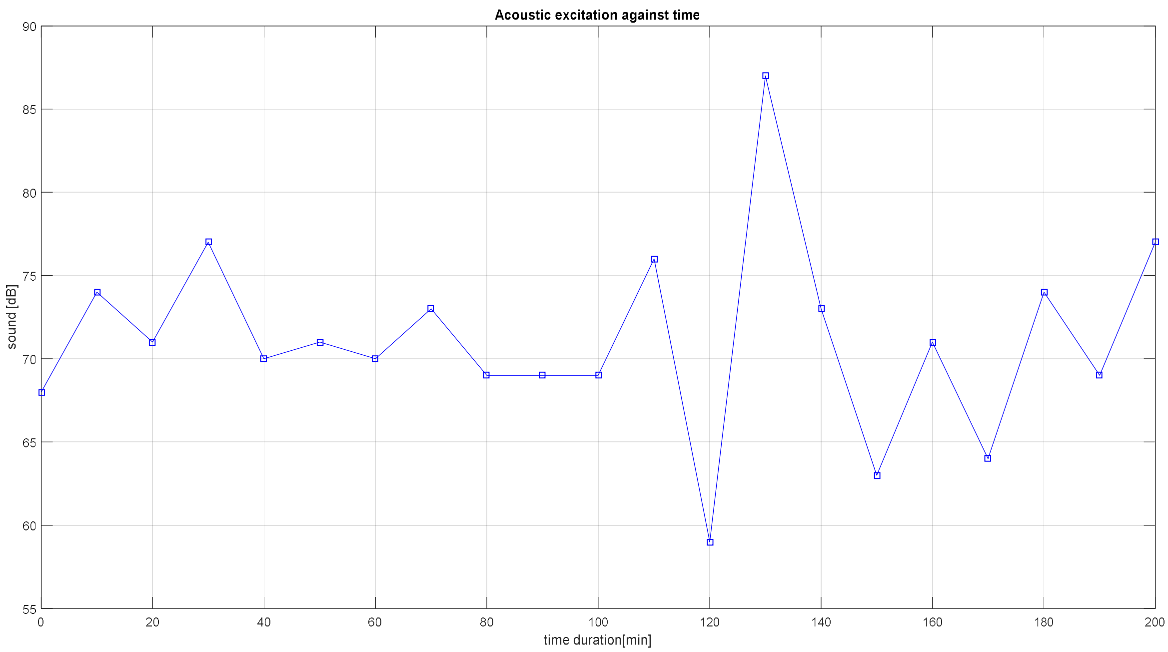

Figure 5.6: Acoustics Excitation

Figure 5.6 shows a detailed graph of the first excited region of Figure 5.3 so that the periods in which the abnormality in the condition started can easily be identified. There were four (4) points on the graph where the sound level was abnormal during the operation of the system. The data in the shaded region of Table 5.1 shows the data within the set time frame of abnormality in the sound parameter, so that the exact time and its value can be noted. The excitation of the sound parameter above the severity level which is 75 dB are indicated on Table 5.1.

The two points 76 dB and 87 dB, occurring at 110minutes and 130minutes, indicate that there is a malfunctioning of the elevator system. To further diagnose the condition of the elevator system at this moment, the vibration parameter was also considered. The graph of the vibration parameter at this instant was plotted as in Figure 5.7 to diagnose the state of the elevator system. The X-axial vibration graph also shows that there was an excitation at the range of time of excitation of the acoustic parameter.

Table 5.1: Data Indicating Severity in Condition

Temp (°C)	Vibration (g-force, mg)			Sound (dB)	Time (Minutes)
	x	y	z		
44	-257	12	3	68	00
44	-257	12	5	74	10
44	-257	11	4	71	20
44	-257	12	3	77	30
44	-257	11	3	70	40
44	-257	11	3	71	50
44	-257	11	3	70	60
45	-257	11	2	73	70
45	-257	11	3	69	80
45	-256	10	2	69	90
44	-257	9	2	69	100
45	-256	10	1	76	110
44	-251	-36	35	59	120
45	-277	-29	21	87	130
44	-254	-4	-3	73	140
45	-260	0	22	63	150
45	-250	-16	32	71	160
45	-270	-10	9	64	170
45	-254	-4	17	74	180
45	-258	1	1	69	190
47	-257	5	1	77	200

At the instant of excitation of the sound parameter of the elevator system beyond the normal condition limit which was 87 dB, there was a corresponding high excitation in the vibration parameter of the system which was -277 mg.

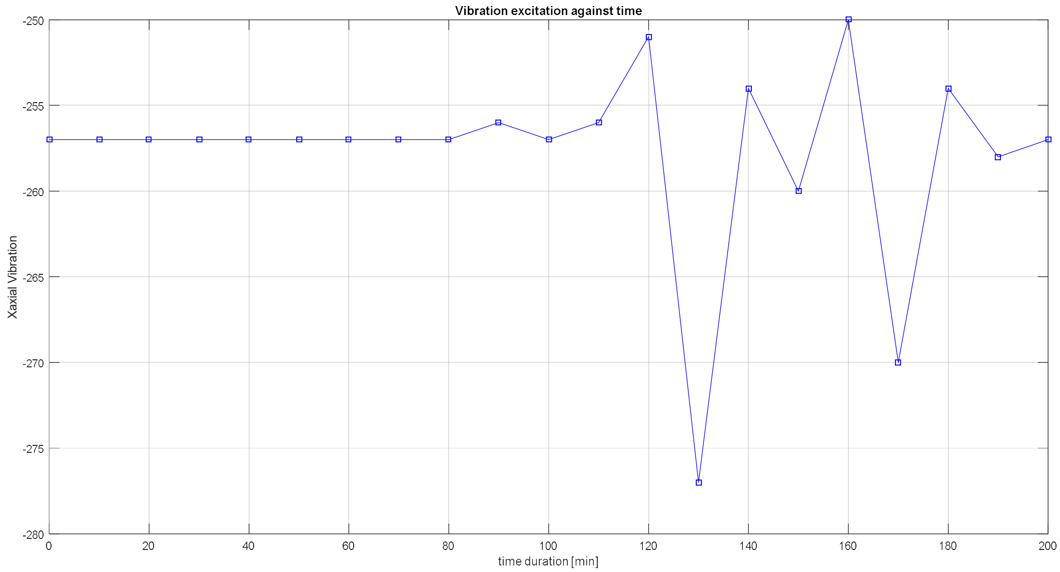

Figure 5.7: X-Axial Vibration Excitation

The range of vibration condition of the system in this axis is -260 mg to -255 mg as earlier analysed from the x-axial graph result, therefore, -277 mg is a severe condition of the elevator system. The data that indicates a severity condition is highlighted on the data shown in Table 5.1. This may, however, not be conclusive until we also consider other axis of vibration of the elevator system to give further clues to the condition of the system.

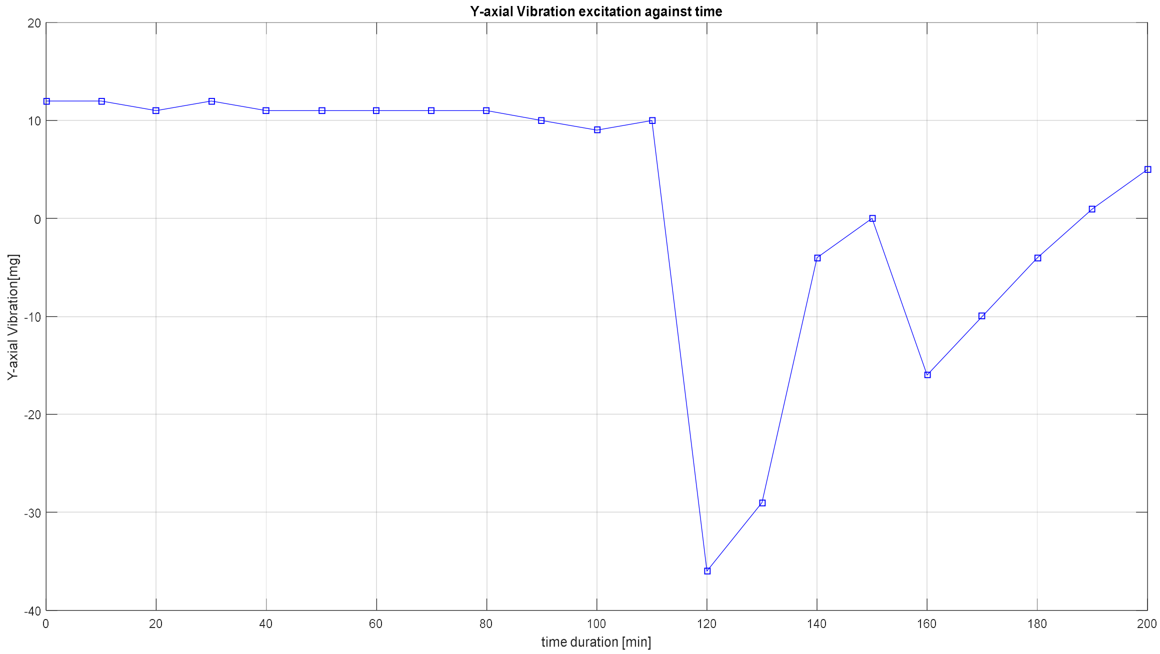

Figure 5.8: Y-Axial Vibration Excitation

The Y-axial vibration excitation graph in Figure 5.8, within the time range considered, also signals that there is malfunctioning in the system as the condition at the same instance became severe. The points -36 mg and -29 mg are great excited points from the limit of vibration parameters of the system as stated earlier. The limit for the normal working conditions of the elevator system considering the y axial vibration is 15 mg to 5 mg. This further supports the previous data that suggests malfunctioning of the system.

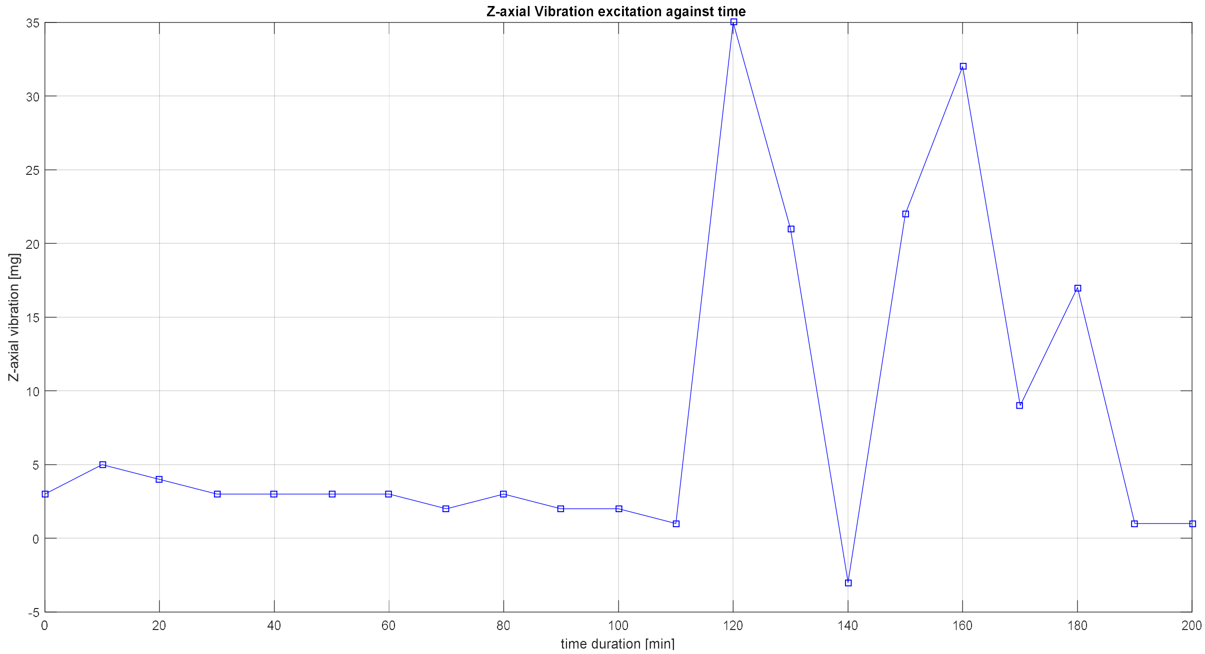

Figure 5.9: Z-Axial Vibration Excitation

Furthermore, the vibration parameter of the z-axis in Figure 5.9 shows that there was excitation at the instance of excitation of other axial vibrations and acoustic parameters. The normal condition limits for the z-axial vibration is -5 mg to 5 mg as discussed earlier from the data graph in Figure 5.4. Therefore, points with 35 mg, 21 mg, 22 mg, 9 mg and 17 mg are an indication of severity in the condition of the elevator system as they fall outside the limit of normal condition. The elevator system at this instance is diagnosed to be faulty from the remotely captured data which further achieves the third objective of the research, which is to detect and notify faults in the system.

To further examine the relative behaviour of the system at the time of damage initiation or malfunctioning of the condition of the system, the four graphs of the acoustic parameters and individual axial vibrations were placed on the same plane. This helps in evaluating the behaviour of the system at the initiation of the damage or malfunctioning of the system. Figure 5.10 shows the combined excitation graph of each individual graph.

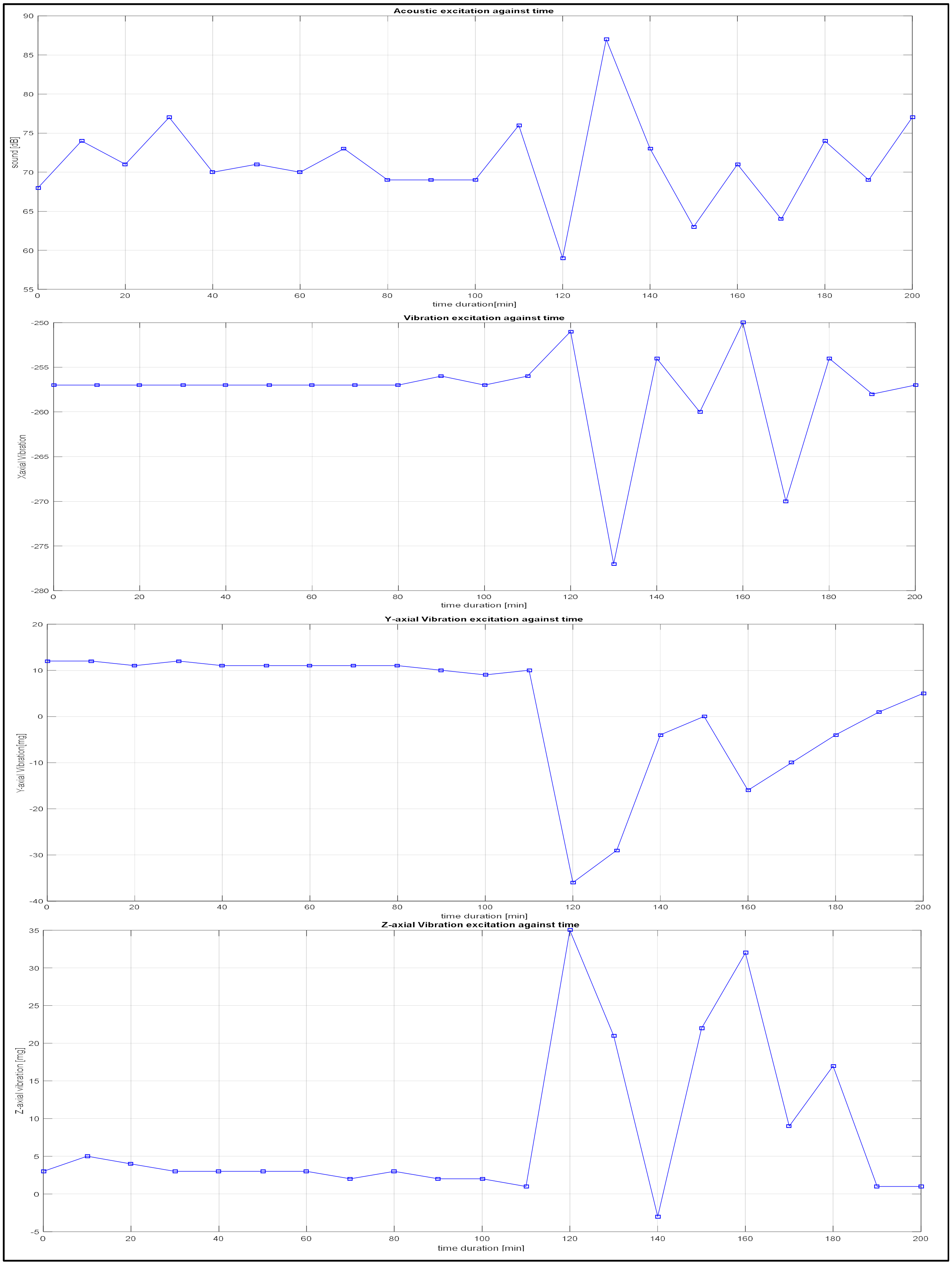

Figure 5.10: Combined Excitation Graph

The combined graph shows that the malfunctioning of the elevator system might have been triggered by an event. The time of the event of the deterioration in condition of the elevator system's acoustic and vibration parameter occurred at almost the same time interval. The elevator system was therefore checked for on-site condition status after 72 minutes of the last notification of fault and it was worth noting that the elevator had stopped working. The historical data of events before the breakdown of the system could help in diagnosing the severity of the breakdown in the elevator system. The maintenance team noticed the elevator car was stopped half way (3^{rd} floor) which indicated a forced stoppage of the elevator car. This further gave a clue on the severity of the condition and the likely nature of the error in the system which helped in troubleshooting. Since there was both severity in vibration and a corresponding severity in the acoustics parameter, faults from the controls in the machine were therefore eliminated during troubleshooting. The elevator was diagnosed to have been disrupted by an obstruction along the braking system on the guide rail, hence the effect of the deterioration in the conditions. The elevator was brought to a forceful stoppage at the closest floor due to the impediment, following the safety procedures embedded on the elevator system. This fault in the elevator system had affected both the vibration and the acoustics parameter of the system simultaneously which gave a diagnostic clue for future occurrence. The data during the breakdown period of the elevator system and the downtime during the repair time were discarded. The downtime during the first breakdown after monitoring was six days, after which the elevator was put back to normal working condition.

There was another fault notification sent to the email around 290 minutes of the remote condition monitoring system. The notification indicates that the system is malfunctioning and therefore requires a proactive maintenance. The data from the remote monitoring system is therefore accessed to have a clue about the condition of the system. The excitation on the x-axis at this instance was -269 mg which was outside the normal vibration range on x-axis. To further check the likely condition of the system at this instance, a check on other axial vibration data showed that there was also a corresponding excitation in the vibration parameter of the y-axis but none on the z-axis. However, there was no excitation in the acoustic parameter of the system at this instance. Subsequent data from the elevator system after 310 minutes of the condition monitoring became normal.

Breakdown in the system had occurred and was noticed after about 150 minutes which was about 460 minutes of commencing the remote condition monitoring. The notification was received immediately when the deterioration was initiated, and the data was analysed remotely but the time of response to the fault notification was 150 minutes. The response time in this context is the time between fault notification and the actual on-site response to the condition of the system. The breakdown in the elevator system had occurred after the sudden excitation in the vibration parameter on both the x-axis and y-axis. The nature of the vibration signal had given up the assumption that the system was still running well after the sudden excitation. The fault experienced by the system was a break in one of the fuses on the controls. The response time for the breakdown as a result of this fault with the system was 150 minutes as indicated in Table 5.2 while the downtime of the system as a result of the repair of the fault was 4 hours as indicated in Table 2. The next notification of malfunctioning occurred due to excitation in the vibration parameter on the x-axis at 650 minutes of the remote condition monitoring system. The vibration on x-axis excites from -258 mg to -279 mg. The vibration of the elevator system on both y-axis and z-axis are still within the normal condition at 650 minutes of remote monitoring. The acoustics parameter at this instance was also within the normal condition. The response time of this malfunction in the elevator's condition was 2 hours as also indicated by Table 5.2. The fault indication in this case had also brought the system to a stop. The system was checked for damage and there was no damaged part found on the system. The system was therefore subjected to routine maintenance of cleaning the door rails and checking the controls.

The next fault notification sent to the email was received at about at 960 minutes of the remote condition monitoring system. The vibration excitation occurred on the x-axis of the system from a magnitude of -258 mg to -269 mg. There was also a little excitation from 10 mg to 7mg on the y-axis of the system but could not independently depict the condition of the system. However, when considered alongside the excitation on the x-axis, it could suggest that the system is malfunctioning. The vibration of the system on z-axis remains within the normal range. The elevator had been brought to a stop due to a faulty assembly of the cabin door drive. This caused the cabin door to jam and system automatically was brought to a stop. This door assembly is represented in Figure 5.11. The response time to this fault notification was 220 minutes and the repair time for the fault was 56 hours. The faulty door mechanism was fixed, and the elevator system was restored into a normal proper working condition.

Figure 5.11: Faulty Door Assembly

Furthermore, another fault notification was sent to the email at about 1500 minutes of starting the remote condition monitoring approach. The evaluation of the 3 parameters at this instance indicate that only the x-axial vibration parameter was a little into the severity range. The other axial vibrations as well as the acoustics parameter at the same instance are within the normal range. The x-axial vibration excitation at the instance of the notification is -249 mg which was just a step below the normal condition range -250 mg to -260 mg. The response time to this fault notification was 32 hours and the condition of the system was okay and the elevator system was in a running condition. The last fault notification sent to the email was based on deterioration of the acoustic parameter. The acoustic graph from Figure 5.2 shows that there was another excitation at around 1700 to 1900 minutes. The excitation was more severe than the previous which is an indication of a faulty condition of the elevator system.

There was excitation in the acoustics parameter from 74 dB to 101 dB at 1710 minutes of the remote monitoring system. At 1800 minutes, the acoustic excitation was 107 dB and 95 dB at 1830 minutes. The excitation in the acoustics parameters shows that the system is malfunctioning. To diagnose the likely damage initiation on the system, it would be necessary to consider the vibration parameter at this instance. Figure 5.3 and Figure 5.4, are the vibration graphs on the y axis and z axis respectively which shows that there was no excitation at the instance when the severity in the acoustic parameter occurred. The response time to the fault notification was 240 minutes. Figure

5.5 also shows that there were some excitations beyond the limit at some time in the vibration parameter on the x axis, but at the instance of the excitation in the acoustic parameter between 1700 to 1900 minutes, there were no excitations beyond the normal condition limits. The excitation in the acoustic parameter therefore called for another on-site maintenance to troubleshoot the problem in the system. A visit to the elevator system revealed that the elevator had stopped working. The acoustic excitation beyond the normal limit confirmed that an event had occurred which had caused a malfunctioning in the elevator system. An excitation from the elevator drive system may have caused the elevator car to vibrate along the three-axis. However, since the deterioration in the condition of the elevator was only indicated by the acoustic parameter, it further required the service of the maintenance team to troubleshoot what may be the likely error in the system. The elevator system was discovered to have had a broken door chain drive and was therefore forced to a stop as the drive for the door stopped working. The chain drive connects the motor which drives the pulley for opening the landing door and the cabin door. Without the proper functioning of the door drives for timely opening and closing, the elevator system was designed to shutdown.

Figure 5.12: Drive Chain for the Doors

Figure 5.12 shows the elevator system with the chain drive for the landing door and the cabin door in good working condition during the installation of the monitoring device. Attached to the driven pulley is the cam and follower link mechanism which opens and closes the elevator doors. Figure 5.13 shows the broken chain of the door drives that caused the excitation in the acoustic parameter. Since the chain drives the door only, this explains the reason for excitation in the sound parameter of the system. The vibration parameter due to this faulty condition, the break in the chain, may remain the same as the elevator system is rendered inactive whenever any critical component is faulty. The repair time for this breakdown was 72 hours as indicated on Table 5.2.

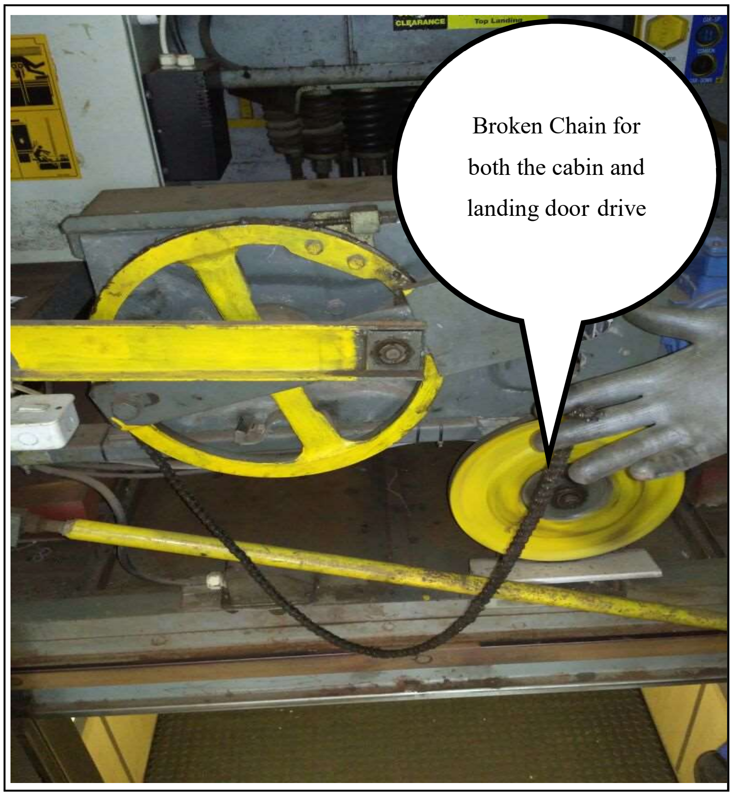

Figure 5.13: Broken/Damaged Door Chain

Therefore, it was very helpful in diagnosing the current state of the elevator system when the acoustic parameter is monitored side by side with the vibration parameter. This would help in filtering out the likely problems and challenges for diagnostic maintenance decision making

Table 5.2 shows the downtime of the elevator system after optimising the maintenance routine from breakdown and scheduled maintenance to remote condition monitoring. The chart in Figure 5.14 presents the data in Table 5.2 which shows the downtime due to the response time and the downtime during the repair of the system. This chart represents the breakdown experienced during the adoption of remote condition monitoring of the system.

Table 5.2: Table of Downtime of the Elevator after Modernisation

	Response Time (Hours)	Repair Time (Hours)
1st Breakdown	1.2	96
2nd Breakdown	2.5	4.0
3rd Breakdown	2.0	24
4th Breakdown	3.7	56
5th Breakdown	32	0
6th Breakdown	4.0	72

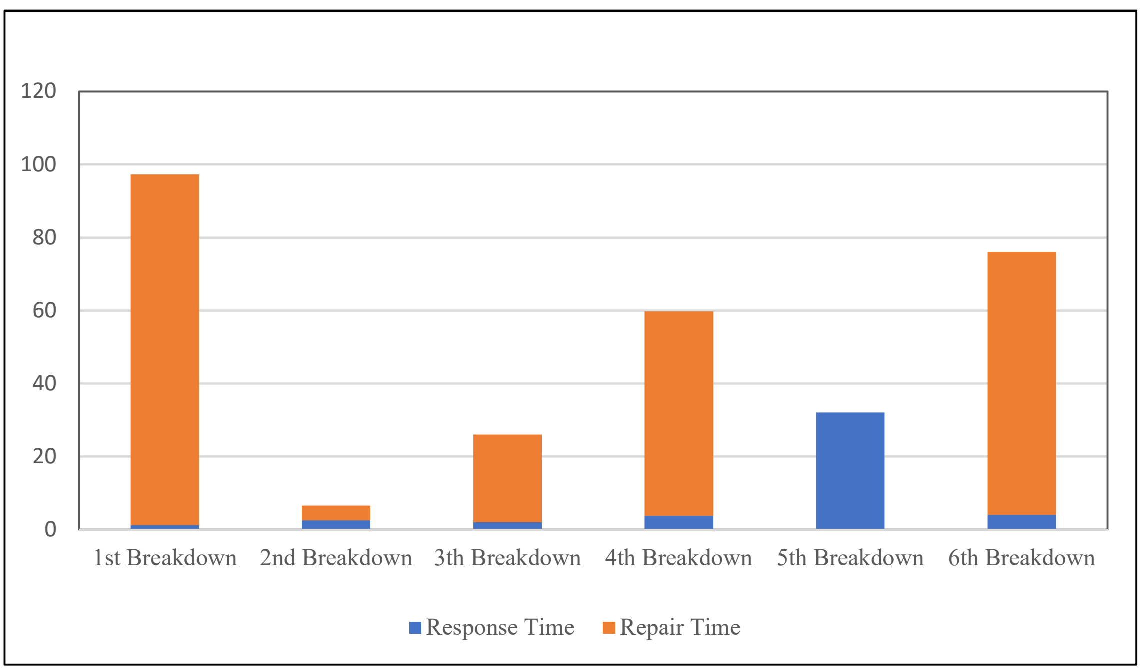

Figure 5.14: Chart of the Elevator after Modernisation

The chart shown in Figure 5.14 shows that there is a considerable reduction in the downtime due to ‘response time’ as compared to the system before modernisation as shown in Figure 5.15. This further supports the achievement of the third objective of the research, of diagnosing the condition of the elevator system for early detection of deterioration in condition. The downtime due to the repair time is also less when compared with the condition before modernisation, however, there was still a pronounced downtime as a result of repair based on the nature of damage on the system. The remotely monitored data could therefore be developed into a process data history, using cause and effect analysis, for diagnosing future events in the system as each fault is initiated in the system and maintenance carried out. The cause and effect analysis of the historical remotely captured data can give a lead to subsequent fault diagnosis and indication in the system. Table 5.4 represents the cause and effect analysis of the system’s fault.

Table 5.3: Downtime of the Elevator Before Modernisation

	Response Time (hours)	Repair Time (hours)
1st Breakdown (27/02/18)	24	8
2nd Breakdown (16/03/18)	72	54
3rd Breakdown (24/03/18)	48	24
4th Breakdown (05/04/18)	96	96

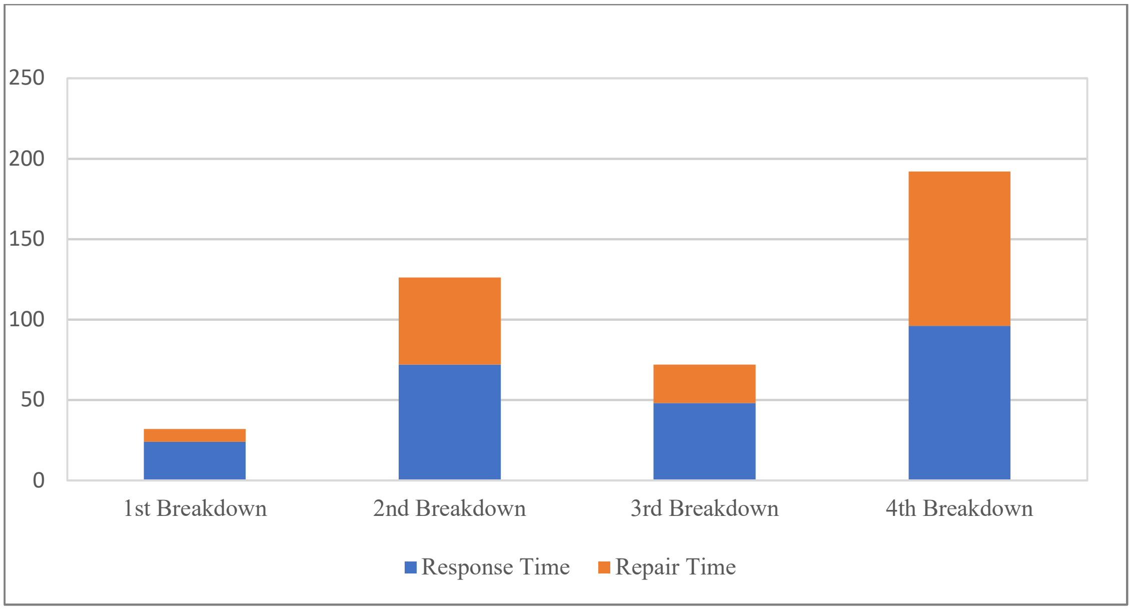

Figure 5.15: Downtime Chart of Elevator Before Modernisation

Table 5.4: Cause and Effect Analysis of Faults

CAUSE	EFFECT
Broken Chain for landing and Cabin door drives	Remarkable Acoustics excitation (up to 30 dB) Breakdown in the system.
Obstruction on the guide rails, worn out rollers or uneven guide rails	Remarkable excitation on all axis x-axis (± 26mg); y-axis (± 46mg); z-axis (± 34mg) Remarkable Acoustic excitation (87dB) Breakdown in the system
Faulty Door Assembly/Blocked door rail	Excitation on majorly x-axis (± 11mg) and a little corresponding excitation on y-axis (± 3mg) Breakdown in the system
Faulty Electronic Component, Power surge	Excitation on x-axis (± 9mg) and a corresponding excitation on y-axis (± 5mg) Little Acoustics excitation (3dB) Breakdown in the system
Maintenance Service Over-due	Excitation on only x-axis (± 19mg) Breakdown in the system

The effect of each fault in the system is indicated in Table 5.4 as the excitation beyond the current parameter value of the elevator condition. This would assist in analysing the condition and diagnosing faults in other elevators as excitations occur which are the increase in the parameters value from its nominal value. The first breakdown was as a result of an obstruction on the guide rail along the hoist way which also affected the rollers. The second breakdown was indicated by the excitation on the x axial parameter and a little on y axis beyond the normal limit. This was as a result of a damaged fuse on the control board, which was troubleshot and replaced. The maintenance was done in a few hours and the system was restored in a good condition.

The third maintenance was a proactive maintenance based on the excitation of the vibration parameter. The system's landing door rail was cleaned up for smooth motion of the door along the rail amongst other maintenance checks. The fourth breakdown was as a result of a disengaged screw rod connecting the landing door mechanism. The system was restored by repairing the faulty part. The fifth fault notification was as a result of a slight deviation in the vibration parameter of the x axis. Even though the excitation is really small, however, it cannot be disregarded. In response to this fault notification, the elevator system was checked on-site and found to be in a running condition. This, however, does not mean such small excitation should be ignored. The last breakdown was the damage door drive chain which also caused a few days' downtime due to an inability to get a replacement part for the system.

Therefore, considering the breakdowns experienced by the system after being optimised, it is still worthy to note that the downtime of the system after the optimisation of the maintenance routine is considerably lower than the condition before optimisation due to the just-in-time fault notification via internet of things devices.

5.5. Optimising the Monitoring System by Adopting Control Chart for Variables

The limits of the parameters can be determined from the current data received from the monitoring system. Control chart for variables help to understand and determine the central line of each parameter in the system and the limits of permissible variation in the parameter value and also to recognise deviation of the system from the normal state.

$$\text{Trial line} = \overline{X} = \frac{\sum_{i=0}^{n} X_i}{n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

Therefore, the central lines of x-axial, y-axial, z-axial vibrations, and Sound is given as;

x-axial = $\frac{-62808}{244}$ = -257.41 mg

y-axial = $\frac{2285}{244}$ = 9.37 mg

z-axial = $\frac{834}{244}$ = 3.42 mg

Sound = $\frac{16819}{244}$ = 68.9 dB

To determine the Upper Control Limits, UCL, and Lower Control Limits, LCL; the following formular is used;

$$UCL_x = \overline{X} + 3\,\sigma_x \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$LCL_x = \overline{X} - 3\,\sigma_x \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where σ is standard deviation of the parameter;

Standard deviation of x-axial vibration, σ_x = 2.55

σ_y = 4.71; σ_z = 3.46; $\sigma_{sound} = 6.59$

UCL_x = - 257.41 + (3 × 2.55) = -257.41+ 7.65 = -249.76 mg

LCL_x = -257.41 - (3 × 2.55) = -257.41-7.65 = -265.06 mg

UCL_y = 9.37 + (3 × 4.71) = 9.37 + 14.13 = 23.5 mg

LCL_y = 9.37 - (3 × 4.71) = 9.37 – 14.13 = - 4.76 mg

UCL_z = 3.42 + (3 × 3.46) = 3.42 + 10.38 = 13.8 mg

LCL_z = 3.42 - (3 × 3.46) = 3.42 -10.38 = - 6.96 mg

UCL_{Sound} = 68.9 + (3 × 6.59) = 68.9 + 19.77 = 88.67 dB

LCL_{Sound} = 68.9 - (3 × 6.59) = 68.9 – 19.77 = 49.13 dB

In order to find the revised trial centre lines and control limits, it is important to consider those points outside the recommended limits by Schindler elevators which stated that the maximum sound pressure on the hoistway is 75 dB.

Revised trial central line, $\overline{X_r}$, is given by;

$$\overline{X_r} = \frac{\sum_{i=0}^{n}(X - X_d)}{n - n_d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$\overline{Sound_r} = \frac{16819-138}{244-17}$ = 67.97;

The revised trial central lines and control limits for vibration parameters is calculated by considering the points outside the limits as stated by Schindler elevator, which was ± 5 mg to the mean vibration which is the trial central line above;

$\overline{X_r} = \frac{-62808+186}{244-7}$ = -257.15 mg

$\overline{Y_r} = \frac{228 \quad (-83)}{244-9}$ = 10.08 mg

$\overline{Z_r} = \frac{834-1}{244}$ = 2.96 mg

The revised standard deviation σ_{x_r}, is calculated by considering the points outside the limit;

σ_{x_r} = 0.840025

σ_{y_r} = 0.858893

σ_{z_r} = 0.769046

σ_{S_r} = 5.171331

From equation 3 and 4, the revised UCL and LCL can now be calculated;

$$UCL_{x_r} = \overline{X_r} + 3\sigma_{x_r} \quad \ldots\ldots (6)$$

$$LCL_{x_r} = \overline{X_r} - 3\sigma_{x_r} \quad \ldots\ldots (7)$$

UCL_{x_r} = -254.63 mg; LCL_{x_r} = -259.67 mg

UCL_{y_r} = 12.66 mg; LCL_{y_r} = 7.50 mg

UCL_{z_r} = 5.27 mg; LCL_{z_r} = -0.65 mg

UCL_{S_r} = 83.48 dB; LCL_{S_r} = 52.45 dB

The severity limits of the elevator system is therefore set to the new revised limits for notifying severity in the condition of the system.

5.6. Conclusion

Remote condition monitoring for maintenance of the elevator system in this research opened the opportunity for monitoring the real-time condition of the elevator system without being on site. This helped in the early detection of deterioration in the condition of the elevator system. Early detection of deterioration in the elevator condition brought about reduced downtime of the machine as faults in the system were detected earlier and fixed, unlike previously when fixed time routine maintenance was done, which achieved the last objective of the research. Remote notification of faults in the system created early awareness of deterioration in the condition and the trend of events were analysed remotely from the data received before on-site proactive maintenance check. The data from the elevator system was also used in diagnosing the state of the machine and suggesting probable faults in the system by adopting a cause and an effect principle.

CHAPTER 6 : CONCLUSIONS AND RECOMMENDATIONS

6.1. Introduction

This chapter focusses on the conclusions of the research stating the objectives of the research work and how each of the objectives was addressed. It also discusses the conclusions based on the optimised maintenance policy as compared to the initial state of the elevator system before applying the new approach. This chapter also discusses some recommendations that are considered based on the previous maintenance policy, which is breakdown and scheduled maintenance as well as the optimised maintenance solution of remote condition monitoring for just-in-time proactive maintenance policy. Future research work on this area is also discussed in this chapter and further suggestions are as well mentioned.

6.2. Research Conclusions

Fault detection and diagnosis play a vital role in the maintenance of machines and facilities. The maintenance policy adopted on the elevator system used as a case study in this research is a scheduled and breakdown maintenance policy. This policy carried out a scheduled maintenance at designated time intervals of operation, while unscheduled maintenance is also done whenever there is breakdown of the elevator system. This is usually the case with maintenance of the elevator system as no indication is given at each breakdown of the elevator system. Hence, whenever there is breakdown of the elevator machine, it usually took a long time to detect, except in cases of an emergency when the user had to call on the maintenance team for immediate action. The downtime of the elevator system is usually high due to the delay in notification of the breakdown in the system, the response time, and the time taken in troubleshooting the fault that may have occurred leading to the breakdown.

The first objective of the research, which was to identify the distributed parameters which were the underlying factors for fault indications on elevator systems, was achieved in section 3.4 and 3.5 of Chapter 3. Temperature, vibration and acoustic parameters were identified as the distributed parameters which could indicate malfunctioning in the operation of the elevator system. The temperature parameter affects the electronic components which are basically the controls in the elevator system, while the vibration and acoustic parameters indicate a faulty drive, motion along the guiderail and braking systems in the elevator. The drive system comprises of both the elevator car drive and the cabin and landing door drives.

The second objective of the research which was to modernise the current maintenance routine to remote condition monitoring for fault detection was also achieved in section 3.5 of chapter three which developed the hardware design for remote condition monitoring of the elevator system. Optimisation of the current maintenance policy to remote condition monitoring of the elevator system has therefore brought about an instant notification of the state and condition of the system through instant remote data capturing and fault notification.

The response time of the maintenance team was also reduced as the team got to know the state of the elevator system and respond proactively whenever there was any deterioration in the condition. The historical data from the elevator system was also developed for diagnosing and troubleshooting the fault in the system using the cause and effect analysis. This has therefore addressed the third objective of diagnosing the condition of the elevator system for early detection of faults and deterioration.

Furthermore, the parameters being monitored, which were the room temperature, the acoustic parameter and three-axial vibrations, were indicative of fault diagnosis on the elevator system. Obstruction in the guide rail, blockage on the door rail path, faulty drive chain or system, and malfunctioning controls due to heat, were common faults diagnosed from the data from the monitoring device. The room temperature, when high could adversely affect the controls, while the acoustic parameter alongside the three-axial vibration gave a more detailed diagnosis of the current condition of the elevator system.

Since most of the faults encountered by the elevator system considered the degraded condition of the system through excitation in the acoustic parameter and the three-axial vibration, it is therefore important to consider both parameters as very important in condition monitoring for maintenance purpose of the system. Excitation in the acoustic parameter of a part or component in motion along a path, just like the guide rail in the elevator system, is often accompanied by a considerable excitation in the axial vibration of the machine as was the case in the elevator system. It is therefore more informative and resourceful to consider both the acoustic parameter of a component in motion together with the three-axial vibrations in order to have a better indication at the initiation of the malfunctioning of the elevator system.

Excessive vibration of the elevator car was an indication that proactive/preventive maintenance should be carried out before critical breakdown of the elevator system. Hence, a routine proactive/preventive maintenance was conducted to prevent critical breakdown of the system. In most cases, the elevator system was not in a running condition when the maintenance team responded on-site to fault notification, however, the historical data received remotely was used in analysing the condition before shutdown and troubleshooting the likely fault which achieved the last objective of the research. This was possible through condition monitoring of the system, and remote condition monitoring has made it more accessible to the maintenance team.

Modernising the current maintenance routine, on the elevator system from scheduled maintenance and breakdown maintenance to remote condition monitoring for reactive and proactive maintenance, reduced the machine downtime due to unnoticed machine breakdown and also avoided catastrophic breakdown of the machine. With the reduced downtime of the elevator system, the cost of running the machine is reduced. Similarly, in the industry where the breakdown of a machine results in loss of production time, condition monitoring for maintenance would help increase the productivity by reducing the machine downtime.

Remote condition monitoring also provided the opportunity of access to remote locations on the elevator systems and machines during working conditions which ordinarily may be impossible or hazardous. The trend in machine conditions being monitored through remote devices on site was also employed for machine condition learning for elevator maintenance and fault diagnosis.

6.3. Recommendations

Remote condition monitoring of a machine using IoT devices provided the possibility of monitoring the condition of a machine at several locations at the same time by the maintenance team. Unlike a scheduled maintenance routine being practised on the elevator system where maintenance is carried out either monthly or at the instance of a breakdown, condition monitoring checks the machine on-condition parameters, diagnosing the conditions used and taking maintenance decisions based on the trend of machine conditions.

In the elevator case study considered in this research, on site condition monitoring of the system requires an operator being stationed on the site. This may however be difficult to achieve because of the several elevator systems installed by the elevator vendor and the overhead cost implications.

Hence, it would therefore be a good practise if remote condition monitoring of the machine is adopted for maintenance of the machine as it would reduce the downtime of the elevator system. In addition, several sensors can be installed on the machine and monitored remotely to capture the condition of each critical component during operations to give more information about the conditions of the machine and diagnosing the most likely affected part.

The challenge of powering the remote monitoring device for a very long period by a DC power source brought about using a 12V (stepped down to 5V) source weighing about 2kg. This may not be absolutely reliable because the battery will at some point be totally discharged and the power source cut off from the monitoring device. Furthermore, the power source for the monitoring device will in a way add to the overall weight of the elevator car. It would therefore be recommended to connect an AC power source close to the location of the remote monitoring device and converted to DC power for the board using the AC to DC power converter. A light solar panel could also be a good source of power supply to the system. This would make the system efficient and the monitoring device could operate as long as the AC power source which powers the elevator system is on.

6.4. Future Research

Remote condition monitoring of machines and systems is gradually being applied for process monitoring for increased production efficiency and machine condition monitoring for maintenance. This research optimized fault detection and maintenance routines in an elevator system by applying remote condition monitoring using an IoT approach. This research therefore applied the use of IoT technology which has over 100 internet applications that could be used for accessing the machine conditions remotely, however the email web application was used. Also, the parameters measured were being captured by a sensor for each of the conditions. The sensors captured the vibration, acoustics and temperature of the elevator car based on the one-point installation on the elevator car roof.

In the light of this, further work can be done by integrating more sensor networks on the elevator components, such as the roller arm supporting the car on the guide rail to monitor both the acoustic and vibration parameter from the roller, the car doors, the door drive as well as the brake cage of the elevator. This would help in detecting the exact part that is malfunctioning and would help to diagnose the likely source of the problem.

Furthermore, the data can be configured to be sent to multi-internet applications, such as email, tweeter, SMS, and also web applications to display the real-time data in form of the human machine interface (HMI). This would enhance the assessment of the condition of the system by many individuals of the maintenance team. There can also be multiple feedback mechanisms from the machine by the monitoring device. This would greatly improve the maintenance diagnosis of the system.

6.5. Conclusion

This research modernised the maintenance approach from scheduled and breakdown maintenance to remote condition monitoring in an elevator system which reduced the system's downtime. Modernisation of maintenance routines for machines and systems to remote condition monitoring using IoT technology could be adopted for early fault detection with notification, reducing the downtime due to the breakdown of the system, and enhancing productivity by reducing the downtime of the machine or system as a result of malfunctioning.

REFERENCE

Abu-Ali, N. and Abu-Elkhu, M. 2015. Internet of Nano-Things Healthcare Applications: Requirements opportunities, and challenges. *Wireless and Mobile Computing, Network, and Communication (WiMob), IEEE 11th International Conference*, pp.9-14. DOI: 10:1109/WiMOB.2015.7347934.

Abuhmida, M., Radhakrishnan, K. and Wells, I. 2015. Performance Evaluation of Mobile Ad Hoc Routing Protocols on Wireless Sensor Networks for Environmental Monitoring. In: Proceedings of *Modelling and Simulation (UKSim), 2015 17th UKSim-AMSS International Conference on*. IEEE, pp. 544-548.

Agrawal, D.P. 2017. Different Types of Transducers. In: *Embedded Sensor Systems*. Springer, pp. 65-104.

Ahamed-Mohideen, P.B. and Ramachandran, M. 2014. Strategic approach to breakdown maintenance on construction plant- UAE perspective. *Benchmarking: An International Journal,* 21(2), pp. 226-252.

Ahuja, I.P.S. and Khamba, J.S. 2008. Total productive maintenance: literature review and directions. *International Journal of Quality and Reliability Management*, 25(7), pp. 709-756.

Alayón, C., Säfsten, K. and Johansson, G. 2017. Conceptual sustainable production principles in practice: Do they reflect what companies do? *Journal of Cleaner Production*, 141, pp. 693-701.

Al-Kodmany, K. 2015. Tall Buildings and Elevators: A Review of Recent Technological Advances. *Buildings*, 5(3), pp. 1070-1104.

Alsyouf, I. 2009. Maintenance practices in Swedish Industries: Survey results. *International Journal of production Economics*, pp. 212-223.

Andrewus, J.A., Watson, J. and Kishk, M. 2007. Wind turbine maintenance optimisation of quantitative maintenance optimisation. *Wind Engineering,* 31(2), pp. 101-110.

Annamdas, V. G. M., Bhalla, S. and Soh, C. K. 2017. Applications of structural health monitoring technology in Asia. *Structural Health Monitoring*, 16 (3): 324-346.

Apodaca, C. 2017. *State Repression in Post-disaster Societies*. Taylor & Francis.

Arduino Yun (Image). 2015. Available: http://www.arduino.com (Accessed: 2nd February 2017).

Atzori, L., Lera, A., and Morabito, G. 2010. The Internet of Things: A Survey. *Computer Networks*, 54, pp. 2787-2805.

Bahr, N. J. 2014. *System safety engineering and risk assessment: a practical approach*. CRC Press.

Balageas, D., Maldague, X., Burleigh, D., Vavilov, V., Oswald-Tranta, B., Roche, J-M., Pradere, C. and Carlomagno, G. 2016. Thermal (IR) and other NDT techniques for improved material inspection. *Journal of Nondestructive Evaluation*, 35(1), pp. 1-17.

Bandyopadhyay, D. and Sen, J. 2011. Internet of Things: Applications and Challenges in Technology and Standardisation. *Spring Science and Business media, LLC, Wireless Personal communication*, 58, pp. 49-69. [online] Available at: DOI: 10.1007/s11277-011-0288-5 (Accessed on 16th February 2016).

Barney, G. and Al-Sharif, L. 2015. *Elevator traffic handbook: theory and practice*. Routledge. (Accessed on: 23rd August 2017)

Bayoumi, A. and McCaslin, R. 2016. Internet of Things- A Predictive Maintenance Tool for General Machinery, Petrochemicals and Water Treatment. Paper presented at the *Sustainable Vital Technologies in Engineering and Informatics*. Columbia, USA, 8-10 November 2016. Elsevier.

Ben-Daya, M., Kumar, U. and Murthy, D. P. 2016. *Introduction to maintenance engineering: modelling, optimization and management*. John Wiley & Sons.

Bernard, A. 2014. *Lifted: a cultural history of the elevator*. NYU Press.

Bevilacqua, M., Ciarapica, F., Giacchetta, G., Paciarotti, C. and Marchetti, B. 2016. Innovative Maintenance Management Methods in Oil Refineries. In: *Quality and Reliability Management and Its Applications*. Springer London, pp. 197-226.

Bousdekis, A., Magoutas, B., Apostolou, D. and Mentzas, G.A. 2015. Proactive decision-making framework for condition-based maintenance, Greece. *Industrial Management and Data Systems*, 115(7), pp. 1225-1250.

Bousdekis, A., Papageorgiou, N., Magoutas, B., Apostolou, D. and Mentzas, G. 2016. A probabilistic model for context-aware proactive decision making. In: Proceedings of *Information, Intelligence, Systems and Applications (IISA), 2016 7th International Conference on*. IEEE, pp. 1-6.

Brittain, D. A. 2004. *System and methods for easy-to-use periodic network data capture engine with automatic target data location, extraction and storage*: Google Patents.

Buehl, R.C. 2010. *Panel mounted appliance elevator apparatus*: Google Patents. [Online] Available at: https://www.google.com/patents/US7806490 (Accessed on 7th November 2016).

Campbell, J.D. and Reyes-Picknell, J.V. 2015. *Uptime: Strategies for excellence in maintenance management*. CRC Press.

Castro, M., Jara, A.J., Skarmeta, A.F. 2012. An Analysis of M2M platforms: Challenges and Opportunities for the Internet of Things. *Sixth International conference on Innovative Mobile and Internet Services in Ubiquitous computing*, pp. 757-762.

CBCnews Montreal. 2012. [online] Available at: http://www.cbc.ca/news/canada/montreal/2-killed-19-injured-in-sherbrooke-factory-explosion-1.1241114 (Accessed on 13th November 2015).

Chandrashekhar, M. and Ganguli, R. 2016. Damage assessment of composite plate structures with material and measurement uncertainty. *Mechanical systems and signal processing*, 75, pp. 75-93.

Chee, K.P., Jun-Hong, Z., Heng-Chao, Y. 2014. PDF and Breakdown Time Prediction for Unobservable wear using enhanced particle filters in precognitive maintenance. *Instrumentation and measurement; IEEE Transactions*, 64(3).

Chen, M., Wan, J., and Li, F. 2012. Machine-to-Machine Communications: Architectures Standards and Applications. *KSII Transactions on Interne and Information Systems*. 6(2) [online] Available at: https://www.researchgate.net/profile/Jiafu_Wan2/publication/264846553_Machine-to-Machine_Communications_Architectures_Standards_and_Applications/links/550b9af60cf265693cef8967.pdf (Accessed on 17th February 2016).

Chen, S., Xu, H., Liu, D., Hu, B. and Wang, H., 2014. A vision of IoT: Applications, challenges, and opportunities with china perspective. *IEEE Internet of Things journal*, *1*(4), pp. 349-359. **DOI:** 10.1109/JIOT.2014.2337336 (Accessed on: 17th February 2016)

Cibulka, J., Ebbesen, M.K., Hovland, G., Robbersmyr, K.G., and Hansen, M.R. 2012. A review on approaches for condition-based maintenance in applications with Induction Machines Located offshore. *Modelling Identification and Control*, 33(2), pp. 69-86.

Clark, E.T., Sarma, M. and Mitchell, J.R., Emerson Climate Technologies Retail Solutions, Inc., 2013. *System and method for monitoring and evaluating equipment operating parameter modifications*. U.S. Patent 8,473,106.

Coss, E., Hickey, S. and Conboy, M.R. 2007. *Fault notification based on a severity level*: Google Patents. [online] Available at: http://www.google.com/patents/US7200779 (Accessed on 10th January 2017)

Costa, B.S.J. 2016. Fuzzy Fault Detection and Diagnosis. In: *Handbook On Computational Intelligence. Vol. 1: Fuzzy Logic Systems, Artificial Neural Networks, and Learning Systems*, pp. 241-278.

Couch, J., 2016. Performance Robust Project Scheduling Polices for Naval Ship Maintenance.

Crespo Márquez, B., Iung, M.M., Khairy Kobbacy, A., Maletič, D., Maletič, M., Al-Najjar, B. and Gomišček, B. 2014. The role of maintenance in improving company's competitiveness and profitability: a case study in a textile company. *Journal of Manufacturing Technology Management*, 25(4), pp. 441-456.

Davies, A. ed., 2012. *Handbook of Condition Monitoring : techniques and methodology.* Springer Science & Business media. (Accessed on 29th August 2017).

Debasis, B.O., and Jaydip, S. 2011. Internet of Things: Application and challenges in technology and standardisation. *Springer science and Business Media, LLC*, 55, pp. 49-69.

Dennis, H.S. 2003. Integrated Condition Monitoring Techniques, *IRD Balancing LLC*, p.7 (Available online) (Accessed on 11th November 2015).

Department of Labour. 2015. *Lift, Escalator and Passenger Conveyor Regulations.* Available: http://www.labour.gov.za/DOL/legislation/regulations/occupational-health-and-safety/regulation-ohs-lift-escalator-and-passenger-conveyor-regulations (Accessed on: 9th February 2016)

Dienst, S., Ansari, F. and Fathi, M. 2015. Integrated system for analysing maintenance records in product improvement. *The International Journal of Advanced Manufacturing Technology*, 76(1-4), pp. 545-564.

Djibring, H. 2016. *Team 1Vertical Circulation*. Available: slideplayer.com/slide/3620662/ (Accessed on: 9th November 2016).

Dmitry, G.A., Boris, E.L., and Viacheslay, P.S. 2009. Intelligent fault detection and diagnostics system on rule-based neural network approach. *IEEE Conference on control Application,* pp. 1815-1819.

Duan, L., Yao, M., Wang, J., Bai, T. and Zhang, L. 2016. Segmented infrared image analysis for rotating machinery fault diagnosis. *Infrared Physics and Technology*, 77, pp. 267-276.

Ehram, S. and Seyed, J.S. 2011. A hybrid method for flowshops scheduling with condition-based maintenance constraint and machines breakdown. *Expert Systems with Applications*, 38, pp. 2020-2029.

Engel, Y. and Etzion, O. 2011. Towards proactive event driven computing. *Proceedings of the 5Th ACM International Conference on Distributed Event-Based Systems ACM*, New York, NY, USA 2011, pp. 125-136.

Engineering, B.H. 2009. *Weer Clamps-Hose Fittings*. [online] Available at: http://www.brighthubengineering.com/hydraulics-civil-engineering/43922-learn-about-hydraulic-lifts-and-elevators/ (Accessed on: 14th March 2017).

Esteban, E., Salgado, O., Iturrospe, A. and Isasa, I. 2016. Model-based approach for elevator performance estimation. *Mechanical systems and signal processing*, 68, pp. 125-137.

Europump guide. 2012. *Improvement of Reliability of Pumps by condition Monitoring: Consequences for MTBR/MTBF.*

Faccio, M., Persona, A., Sgarbossa, F. and Zanin, G. 2014. Industrial maintenance policy development: A quantitative framework. *International Journal of Production Economics*, 147, pp. 85-93.

Fan, H.D., Hu, C.H, and Chen, M.Y. 2011. Cooperation predictive maintenance of repairable systems with dependent failure modes and resources constraint. *IEEE Trans Reliability* 60(1), pp. 144-157

Feng, X., Laurence T.Y., Lizhe, W. and Alexey, V. 2012. Internet of Things. *International Journal of Communication Systems*. 25, pp. 1101-1102.

Friedrich, C., Lechler, A. and Verl, A. 2016. A planning system for generating manipulation sequences for the automation of maintenance tasks. In: Proceedings of *Automation Science and Engineering (CASE), 2016 IEEE International Conference on* IEEE, pp. 843-848.

FUJIHD News. 2016. *Sino –Japan Joint Venture News, 2016. Japan.* [online] Available at: www.fujihd.net/news/hyxw/2016-03-16/Hydraulic-Drive-System-for-The-Elevator.html (Accessed on: 19th June 2016).

Gaw, D. C. 2016. *Remote sensing device, system, and method utilizing smartphone hardware components*: Google Patents.

Genta, G., 2012. *Vibration of structures and machines: practical aspects*. Springer Science & Business Media.

Giusto, D., Iera, A., Morabito, G., Atzori L. 2010. The Internet of Things, Springer. *20th Tyrrhenian workshop on Digital Communications*. ISBN: 978-1-4419-1673-0.

Goyal, D. and Pabla, B. 2016. The vibration monitoring methods and signal processing techniques for structural health monitoring: A review. *Archives of Computational Methods in Engineering*, 23 (4): 585-594.

Grieco, L.A., Rizzo, A., Colucci, S., Sicari, S., Piro, G., Paola, D. D., Boggla, G. 2014. IoT-aided robotics applications: Technological Implications, target domains and open issues. *Computer Communication,* 54, pp. 32-47.

Grondzik, W. T. and Kwok, A. G. 2014. *Mechanical and electrical equipment for buildings*. John Wiley & Sons.

Gulati, R. 2012. *Maintenance and reliability best practices*. Industrial Press. Available: http://www.new.industrialpress.com/9780831133115 (Accessed on: 21th April 2016)

Gulledge, T., Hiroshige, S., Iyer, R. 2010. Condition-based Maintenance and the product improvement process. *Elsevier B.V Computers in Industry,* 61, pp. 813-832.

Hackstein, H., Neubauer, C. and Yuan, C., Siemens AG, 2010. *Supervised fault learning using rule-generated samples for machine condition monitoring*. U.S. Patent 20120304008A1.

Hamilton, C., 2005. Automation Direct, *Automation and Industrial control products* [online] Available at: http://www.reliableplant.com/Read/375/sensors-systems-cbm (Accessed: 25th January 2016).

Hammed, Z., Hong, Y.M., Cho, Y.M., Ahn, S.H., and Song, C.K. 2009. Condition monitoring and fault detection of wind turbines and related algorithms: A Review. *Renewable and Sustainable Energy Reviews*, 13(1).

Hiroyuki Tsutada, T.H., Yutaka Itoh and Satoshi Shiga. 2007. Chain Fault Detection of Escalator Using Handrail Vibration Paper presented at the *14th Iternational Congress on Sound and Vibration*. Australia.

Http://arduino.local (Accessed on: 13th May 2016)

Http://www.electrical-knowhow.com/2012/04/basic-elevator-components-part-one.html (Accessed 22nd June 2016).

Https://www.mitsubishielevator.com/products/elevators/hydraulic (Accessed on: 21th March 2016).

Ibrahim, R., Xiange, T., Fengshon, G. and Andrew, B. 2014. U.K Fault detection, and severity diagnosis of rolling elements bearings using modulation signal bispectrum. University Huddersfield [online] Available at: http://eprints.hud.ac.uk/21053/ (Accessed on 18th May 2015).

Information on Noise and Vibration (online). 2008. Available: https://www.schindler.com/content/in/internet/en/mobility-solutions/products/elevators/schindler-5300/_jcr_content/iTopPar/downloadlist/downloadList/3_1340031711862.download.asset.3_1340031711862/05SML9039_Inform_Sheet_EN.pdf (Accessed on: 23rd May 2017).

Ingold, D. 2009. *Mitigating Elevator Noise in Multifamily Residential Building*. [online] Available at: http://buildipedia.com/aec-pros/construction-materials-and-methods/mitigating-elevator-noise-in-multifamily-residential-buildings (Accessed on 18th December 2016).

International Standard Organisation (ISO)_18738-1:2012. 2012. *Measurement of Life Ride Quality-Part 1: Lifts* (Elevators).

Janipha, N. A. I., Alwee, S. N. A. S., Ariff, R. M. and Ismail, F. 2018. Maintenance and Safety Practices of Escalator in Commercial Buildings. In: Proceedings of *IOP Conference Series: Earth and Environmental Science*. IOP Publishing, 012042.

Jantunen, E., Karaila, M., Hästbacka, D., Koistinen, A., Barna, L., Juuso, E., Pereira, P. P., Besseau, S. and Hoepffner, J. 2017. 8 Application system design-maintenance. In: *IoT Automation: Arrowhead Framework*. CRC Press, pp. 247-280.

Jiang, X. and Rui, Y., 2015. Research on vibration Control of traction elevator. In *International industrial informatics and computer engineering conference (IIICEC 2015), Xian* pp. 2144-2147.

Jin, X., Weiss, B.A., Siegel, D. and Lee, J. 2016. Present Status and Future Growth of Advanced Maintenance Technology and Strategy in US Manufacturing. *International journal of prognostics and health management*, 7 (Spec Iss on Smart Manufacturing PHM)

Kaibiao, S., and Hongxing L. 2010. Scheduling problems with multiple maintenance activities and non-preemptive jobs on two identical parallel machines. *International Journal of production economics*, pp. 151-158.

Kaiser, K. A., Gebraeel, N.Z., 2009. Predictive maintenance management using sensor-based degradation models. IEEE Transactions on Systems, Man and Cybernetics A: Systems and Humans, 39(4), pp. 840-849.

Kalligeros, S. 2012. The necessity of lift inspections in Greece. *Emerging Technologies in Non-Destructive Testing V*, p. 467.

Kar, C. and Mohanty, A. 2008. Vibration and current transient monitoring for gearbox fault detection using multiresolution fourier transform. *Journal of sound and vibration*, 311(1-2), pp. 109-132, [online] Available at: doi:10.1016/j.jsv.2007.08.023. (Accessed on: 13 April 2016).

Kariya, P.M. 2012. Study of after sales services of capital goods industry with special reference to elevator industry of Pune city from year 2000 to 2004.

Kenany, S.A., Anil, M., Backes, K., Brubaker, B., Cahn, S., Carosi, G., Gurevich, Y., Kindel, W., Lamoreaux, S. and Lehnert, K. 2016. Design and Operational Experience of a Microwave Cavity Axion Detector for the 20-100 micro-eV Range. *arXiv preprint arXiv:1611.07123.*

Kenneth, H., Aino, H., and Jari, H. 2005. Prognostics for industrial machinery availability. Maintenance condition monitoring and diagnostics, *POHTO International seminar*, Finland, 12th December 2006.

Khanna, G., Cheng, M.Y., Varadharajan, P., Bagchi, S., Correia, M.P., and Verissimo, P.J. 2015. *Automated Monitor Based Diagnosis in Distributed System*. Purdue e-Pubs Electrical and Computer Engineering Technical Report, Purdue University, Portugal, 2015.

Khazraei, K. 2011. *Design, organisation and implementation of a methods pool and an application systematics for condition based maintenance*. Middle East Technical University.

Kim, S. 2017. *Game Theory Solutions for the Internet of Things: Emerging Research and Opportunities: Emerging Research and Opportunities*. IGI Global.

Kluczek, A. 2017. Quick Green Scan: A Methodology for Improving Green Performance in Terms of Manufacturing Processes. *Sustainability*, 9(1), pp. 88.

Konrad, Z., Phong, B.D., Wieslaw, J.S and Tomasz, B. 2015. Non-linear cointegration Approach for condition monitoring of wind Turbines. *Mathematical Problems in Engineering*, 2015. [online] Available at: doi: 10.1155/2015/978156 (Accessed on 7th February 2016).

Krarti, M. 2017. *Energy-Efficient Electrical Systems for Buildings*. CRC Pess.

Kwangyoun Kim, H.K. 2011. Hierarchical Approach for Abnormal Acoustic Event Classification in an Elevator. Paper presented at the *8Th IEEE International Conference on Advanced Video and Signal-Based Surveillance (AVSS), 2011* 26/09/2011. IEEE.

Lee, C., Cao, Y. and Ng, K.H. 2016. Big Data Analytics for Predictive Maintenance Strategies. *Supply Chain Management in the Big Data Era*, p. 50.

Lee, J., Bagheri, B. and Kao, H.-A. 2015. A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manufacturing Letters*, 3: 18-23.

Lee, J., Kao, H.-A. and Yang, S. 2014. Service innovation and smart analytics for industry 4.0 and big data environment. *Procedia Cirp*, 16: 3-8.

Levitt, J. 2011. *Complete Guide to Predictive and Preventive Maintenance*. Industrial Press, ISBN 0831190396

Liao, W., Wang, Y., and Pan, E. 2012. Single-machine-based predictive maintenance model considering intelligent machinery prognostics. *International Journal of Advanced Manufacturing Technology. Springer-verlag London Limited*. [online] Available at: DOI: 10.1007/s00170-011-3884-3 (Accessed on 27th February 2016).

Li, D.X., Wu, H., and Shancang, L. 2014. Internet of Things in Industries: A Survey

IEEE transactions on industrial informatics, 10(4).

Lingmei, W., Enlong, M., Jianlin, S., Dongjie, G., Shaoping, Y., Jinxiu, J., Ruize, L. and Yuehan, Y. 2017. State Monitoring and Fault Diagnosis of Wind Turbines. In: *Advances in Energy Systems Engineering*. Springer, pp. 803-822.

Longman Dictionary. 2012. Pearson Longman, Maskew Miller Longman, ISBN 978-1-4058-5195-4

Machine condition monitoring market by monitoring type, components, monitoring process, applications, and geography - global trend & forecast to 2020. (2015, Nov 16). *PR Newswire,* 2015, Nov 16. [online] Available at: http://www.reportlinker.com/p03377277-summary/view-report.html

Matthews, J.E., Brown, D.J., Bowers, G.D., Kelley, B.E., Ward, R.A. and Siddall, K.W. 2016. *Multi-link automotive alignment lift*: Google Patents.

Marchitto, N., Fire, E. 2016. *High Temperature Operation of Elevators* (Available: https://www.nist.gov/sites/default/files/documents/2017/04/28/3Marchitto_R9100725_High_Temperature_Ope.pdf) (Accessed on: 12th April 2017)

Maria de Fátima, F.D. and Radwan, A. 2017. *Optical Fiber Sensors for loT and Smart Devices*.

Márquez, A.C. 2007. *The maintenance management framework: models and methods for complex systems maintenance*. Springer Science and Business Media.

Mata-Contreras, J., Herrojo, C. and Martín, F. 2017. Application of split ring resonator (SRR) loaded transmission lines to the design of angular displacement and velocity sensors for space applications. *IEEE Trans. Microw. Theory Techn*, 65 (11): 4450-4460.

Mehta, P., Werner, A. and Mears, L. 2015. Condition based maintenance-systems integration and intelligence using Bayesian classification and sensor fusion. *Journal of Intelligent Manufacturing*, 26 (2): 331-346.

Mingfeng, H. 2012. *Characteristic-signal-ba sed elevator safety checking device and elevator safety checking method*. [online] Available at: https://www.google.com/patents/CN102491140A?cl=en (Accessed on 19th December 2016).

Miorandi, D., Sicari, S., Pellegrini, F. D., Chlamtac, I. 2012. Internet of Things: Visions, applications and Research Challenges. *Ad Hoc Network*, 10(7), pp.1497-1516 [online] Available at: doi:10.1016/j.adhoc.2012.02.016 (Accessed on 16th February 2016).

Moeen, H., Alex, P., Tolga, S., Guarav, S., Mehmet, A., and Gonzalo, M. 2015. Health monitoring and Management using Internet-of-Thing (IoT) Sensing with cloud – based Processing: Opportunities and challenges. *2015 IEEE International Conference on Services Computing*, 15, pp.281-287. [online] Available at: DOI: 10:1109/SCC.2015.47 (Accessed on 13th February 2016).

Molano, J.I.R., Lovelle, J.M.C., Montenegro, C.E., Granados, J.J.R. and Crespo, R.G. 2017. Metamodel for integration of Internet of Things, Social Networks, the Cloud and Industry 4.0. *Journal of Ambient Intelligence and Humanised Computing*, pp. 1-15.

Monir, S., 2016. *A Lightweight Attribute-Based Access Control System for IoT* (Doctoral dissertation, University of Saskatchewan, Canada).

Morshed, A.H.E. and El-Sayed, I.M. 2016. Monitoring of vibrations using multimode optical fiber sensors. In: Proceedings of *2016 33rd National Radio Science Conference (NRSC)*. IEEE, pp. 384-389.

Mortada, M.-A. and Yacout, S. 2011. cbmLAD-using logical analysis of data in condition based maintenance. In: Proceedings of *Computer Research and Development (ICCRD), 2011 3rd International Conference on*. IEEE, 30-34.

Mostafa, S.I. 2004. Implementation of proactive maintenance in the Egyptian Glass company. *Journal of Quality in Maintenance Engineering*, 10(2), pp. 107-122.

Mostafa, A. A. A., Alamin, K. A. H., Ahmed, I. M. M. and Mostafa, A. O. M. 2015. Elevators System Implementation and Security. Sudan University of Science and Technology.

Mourtzis, D., Vlachou, E., Milas, N. and Xanthopoulos, N. 2016. A cloud-based approach for maintenance of machine tools and equipment based on shop-floor monitoring. *Procedia Cirp*, 41: 655-660.

Nadakatti, M., Ramachandra, A. and An, S.K. (2008). Artificial intelligence-based condition monitoring for plant maintenance. *Assembly Automation, 28*(2), pp.143-150. [online] Available at: doi: http://dx.doi.org/10.1108/01445150810863725 Accessed on: 14th December 2016

National Elevator Industry Inc., S., New York. 2013. *Building Conditions Affecting Elevator Performance*. USA patent, [online] Available at: http://www.neii.org/search_content_file.cfm?filename=%2Fneii-1%2Fpage5-26.pdf&apptype=application/pdf&vdata=y (Accessed on 4th December 2016).

Nirosha, R. Scholar, P.G. and Madhan, E. 2014. Condition Monitoring of Arrow Dynamic and Drive Train in wind Turbine using Artificial Intelligence., *IJCSEC- International Journal of Computer Science and Engineering Communications*, 2(3). ISSN: 2347-8586. St Peter's University, TN, India.

Niu, G. 2017. Background of Systems Health Management. In: *Data-Driven Technology for Engineering Systems Health Management*. Springer, pp. 1-14.

Occupational Safety and Health Administration (OSHA). 2015. *Regional News Release*, *U.S.A Department of Labour*, [Online] Available at: www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=NEWS_RELEASES&p_id=28836 (Accessed 10th November 2015).

Ogura, H., Watanabe, H., Sugiyama, G., Karasawa, H., Umeno, Y., Tomikawa, O., Miura, S., Ono, K. and Ochiai, Y. 2006. *Working machine, trouble diagnosis system of working machine, and maintenance system of working machine*: Google Patents. [online] Available at: http://www.google.com/patents/US7079982 (Accessed on 4th January 2017).

O&M Practices Guide, Release 3.0, Chapter 5, *Types of Maintenance Programmes*, [online] Available at: https://energy.gov/sites/prod/files/2013/10/f3/omguide_complete.pdf (Accessed 24th November 2015).

Otis, E.G. About Elevators, p.6. [online] Available at: www.otisworldwide.com/pdf/AboutElevators.pdf (Accessed on 20th June 2016).

Pan, E., Liao, W., and Xi, L. 2012. A joint model of production scheduling and predictive maintenance for minimizing job tardiness. *International Journal of Advanced Manufacturing Technology*, 60, pp. 1049-1061.

Pang, C.K., Zhou J-Hong, Yan, H.C. 2014. PDF and Breakdown Time Prediction for Unobservable Wear Using Enhanced Particle Filters in Precognitive Maintenance. *Instrumentation and Measurement, IEEE Transaction* 64(3) pp. 649-659.

Parida, A., Kumar, U., Galar, D., and Stenstrom, C. 2015. Performance measurement and management for maintenance: a literature review. *Journal of Quality in Maintenance Engineering*, 21, pp. 31-32.

Park, S.T. and Yang, B.S. 2010. An implementation of risk-based inspection for elevator maintenance. *Journal of mechanical science and technology*, 24(12), pp. 2367-2376.

Parra, C., Márquez, A.C., Viveros, P., Llort, G. and Aguilar, A.R. 2016. Case Study on a Maintenance and Reliability Management Model Proposal: A Third Set of Locks Project. *Optimum Decision Making in Asset Management*, pp. 1.

Patents; researchers submit patent application. MAN diesel and turbo SE; method of machine condition monitoring; Patent application approval process. *Politics and Government week,* 1207, 2015.

Pedram, M., Esfandiari, A. and Khedmati, M.R. 2017. Damage detection by a FE model updating method using power spectral density: Numerical and experimental investigation. *Journal of Sound and Vibration*.

Perälä, P., Partanen-Jokela, R., Suur-Askola, S. and Torenius, P. 2005. *Method for monitoring the door mechanism of an elevator*: Google Patents. [online] Available at: http://www.google.com/patents/US6854565 (Accessed on 18th December 2016).

Piety, K.R. and Bethmann, W.F. 1999. *Determining machine operating conditioning based on severity of vibration spectra deviation from an acceptable state*: Google Patents. [online] Available at: http://www.google.com/patents/US5875420 (Accessed on 10th January 2017).

Piper, J. 2006. *Avoiding Elevator Breakdowns* [online] Available at: http://www.facilitiesnet.com/elevators/article/Keeping-Up-To-Avoid-Going-Down-Facilities-Management-Elevators-Feature--4810 (Accessed 31th December 2016).

Pourbabaee, B., Meskin, N. and Khorasani, K. 2016. Sensor fault detection, isolation, and identification using multiple-model-based hybrid Kalman filter for gas turbine engines. *IEEE Transactions on Control Systems Technology*, 24(4), pp. 1184-1200.

Qifeng, F., Guoqing, C. and Zibo, S. 2016. Application of wavelet de-noising method in vibration signal analysis of elevator car. In: Proceedings of *Ubiquitous Robots and Ambient Intelligence (URAI), 2016 13th International Conference on*. IEEE, pp. 610-614.

ReportBuyer 2015. *Global Machine Condition Monitoring Market-Growth, Trends & Forecasts (2015-2020)*. Available: https://www.prnewswire.com/news-releases/global-machine-condition-monitoring-market---growth-trends--forecasts-2015---2020-300147408.html. (Accessed 17 March 2016).

Ridwan, F., Xu, X. and Liu, G. 2012. A framework for machining optimisation based on STEP-NC. *Journal of Intelligent Manufacturing*, 23(3) pp. 423-441.

Roylance, B.J., 2003. Machine failure and its avoidance—what is tribology's contribution to effective maintenance of critical machinery? *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, *217*(5), pp. 349-364.

Ruiz-Cárcel, C., Jaramillo, V., Mba, D., Ottewill, J. and Cao, Y. 2016. Combination of process and vibration data for improved condition monitoring of industrial systems working under variable operating conditions. *Mechanical systems and signal processing*, 66, pp. 699-714.

Sabato, A., Niezrecki, C. and Fortino, G. 2017. Wireless MEMS-based accelerometer sensor boards for structural vibration monitoring: a review. *IEEE Sensors Journal*, 17 (2): 226-235.

Safari, E. and Sadjadi, S.J. 2011. A hybrid method for flowshops scheduling with condition-based maintenance constraint and machines breakdown. *Expert Systems with Applications*, 38(3), pp. 2020–2029, [online] Available at: http://www.sciencedirect.com.dutlib.dut.ac.za/science/article/pii/S0957417410007669 (Accessed 30th January 2016).

Samhouri, M., Al-Ghandoor, A., Alhaj Ali, S., Hinti, I., Massad, W. 2009. An intelligent Machine Condition Monitoring System Using Time Based Analysis: Neuro-fuzzy versus Neural network, *Jordan Journal of Mechanical and Industrial Engineering*, 3(4), pp. 294-305.

Sapena-Bano, A., Pineda-Sanchez, P.M., Puche-Ponadero, R., Roger-Folch, J., Riera-Guasp, M., Martinez-Roman, J. 2014. Condition monitoring of electrical Machines using low computing power devices. *International Conference on Electrical Machine (ICEM).* pp. 1516-1522 [online] Available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6960383&tag=1 (Accessed on 15th February 2016).

Sarangapani, J. and Rangarajan, K. 2002. *Method and apparatus for determining the severity of a trend toward an impending machine failure and responding to the same*: Google Patents.

Saumil, A., Semyon, M.M., and Liang, Z. 2010. Feasibility and optimisation of preventive maintenance in exponential machines and serial lines. *IEEE Transactions*, 42, pp. 766-777.

Schindler. 2017. Schindler 3300 / Schindler 5300 *Information on noise and vibration.* [online] Available at: https://www.schindler.com/content/lv/internet/lv/schindler-latvija/lejupielades/_jcr_content/contentPar/downloadlistcontent_1/downloadList/215_1407223358008.download.asset.215_1407223358008/3300-5300-skana-un-vibracija_EN.pdf (Accessed on 21st August 2017).

Severson, K., Chaiwatanodom, P. and Braatz, R.D. 2016. Perspectives on process monitoring of industrial systems. *Annual Reviews in Control*, 42, pp. 190-200.

Shaomin, W. and Zuo, M.J. 2010. Linear and Non-Linear Preventive Maintenance Models. Reliability, *IEEE Transactions*, 59(1).

Sheng, S. and Veers, P. 2011. Wind turbine drive train condition monitoring- an overview. *Applied systems Health Management conference 2011: Enabling sustainable systems (MFPT'11)*, pp. 1-19.

Shiba, M., Seyedeh, M.B.B. and Ali, M.A. 2013. Role of Maintenance and repairs to reduce production costs in the industries of Mazandaran from managerial view. *World of sciences Journal* 2, [online] Available at: www.engineerspress.com (Accessed 24th November 2015).

Shu, Y., Ming, L., Cheng, F., Zhang, Z. and Zhao, J. 2016. Abnormal situation management: Challenges and opportunities in the big data era. *Computers and Chemical Engineering*, 91, pp. 104-113.

Singh, S. and Singh, N. 2015. Internet of Things (IoT): Security challenges, Business Opportunities & Reference Architecture for E-commerce. *International conference on Green Computing and Internet of Things (ICGCIoT), IEEE conference publications*, 15. [online] Available at: DOI: 10.1109/ICGCIoT.2015.7380718 (Accessed on 13th February 2016).

Siti, N., Asmone, A. and Chew, M. 2018. An assessment of maintainability of elevator system to improve facilities management knowledge-base. In: Proceedings of *IOP Conference Series: Earth and Environmental Science*. IOP Publishing, 012025.

Small Enterprise Development Agency (SEDA). 2012. *Research on the performance of the manufacturing sector,* Um Jwali Market Research. [online] Available at: http://www.seda.org.za/Publications/Publications/Research%2520on%2520the%2520Performance%25 *(Accessed on 30th November 2015).*

Smith, G.T. 2016. Machine Tool Performance: Spindle Analysis; Corrosion and Condition Monitoring; Thermography. In: *Machine Tool Metrology*. Springer, pp. 473-549.

Song, D., Lim, H., Lee, J. and Seo, J. 2014. Application of the mechanical ventilation in elevator shaft space to mitigate stack effect under operation stage in high-rise buildings. *Indoor and Built Environment*, 23(1), pp. 81-91

Sotiriadis, S., Stravoskoufos, K. and Petrakis, E.G. 2017. Future Internet Systems Design and Implementation: Cloud and IoT Services Based on IoT-A and FIWARE. In: *Designing, Developing, and Facilitating Smart Cities*. Springer, pp. 193-207.

South African Department of Labour. 2000/07 Specification for the lift Installation: Government Printer [online] Available at: www.publicworks.gov.za/PDFs/consultants_docs/Dumbwaiter_lift_specification.doc

Srinivas, K. and Michael R.B. 2005. Method of Fault Detection, Diagnosis and prognostics for building system-part 1. *International Journal of HVAC&R Research* 11(1).

Stranieri, P.A. and Mangini, R.J. 2010. *Actively controlled noise cancellation system for an elevator cab*: Google Patents. [online] Available at: https://www.google.com/patents/WO2010033103A1?cl=en (Accessed on 19th December 2016).

Tomlingson, P.D., 2007. *Mine Maintenance Management Reader*. SME. (Accessed on: 28th August 2016)

Torres Pérez, E. 2016. *Study of vibration severity assessment for Machine Tool spindles within Condition Morning.*

Toschi, R. 2009. *Explain that stuff* (online). Available: http://www.explainthatstuff.com/how-elevators-work.html. (Accessed: 13th May 2016).

Ugechi, C.I., Ogbonnaya, E.A., Lilly, M.T., Ogaji, S.O.T., Probert S.D. 2009. *Conditioned-Based Diagnostic Approach for predicting the maintenance requirements of machinery.*

Van-Kranenburg, R., Anzelmo, E., Bassi, A., Caprio, D., Dodson, S. and Ratto, M. 2011. The internet of things, in Proceedings of *1st Berlin Symposium, Internet Soc.,* pp. 25–27.

Venkat, V., Raghunathan R., Kewen, Y. and Surya N.K. 2003. A review of process fault detection and diagnosis Part I: Quantitative model-based methods. *Computers and Chemical Engineering 27* [online] Available at: www.elsevier.com/locate/compehemeng (Accessed on 11th November 2015).

Wan, Z., Yi, S., Li, K., Tao, R., Gou, M., Li, X. and Guo, S. 2015. Diagnosis of Elevator Faults with LS-SVM Based on Optimisation by K-CV. *Journal of Electrical and Computer Engineering*.

Wang, L., Da Xu, L., Bi, Z. and Xu, Y. 2014. Data cleaning for RFID and WSN integration. *IEEE Transactions on Industrial Informatics*, 10(1), pp. 408-418.

Weinberger, K. 2015. *Elevator installation with a sound pick-up*: Google Patents. [online] Available at: https://www.google.com/patents/US9004231 (Accessed on 18th December 2016).

Williams, R., Kim, D., Gleason, K. L. and Hall, N. A. 2017. Toward acoustic particle velocity sensors in air using entrained balloons: Measurements and modeling. *The Journal of the Acoustical Society of America*, 142 (4): 2488-2488.

Wolff, T. 2017. *The Design and Fabrication of a Biomimetic Lifting Aid.* [online] Available at: www.ezinarticles.com/?3-CommonProblems-Fixed-With-Elevator-Maintenance&id=7225764 (Accessed on 29th March, 2016)

www.intorobotics.com (Accessed on 30th August, 2016)

Xia, M., Li, T., Zhang, Y. and de Silva, C. W. 2016. Closed-loop design evolution of engineering system using condition monitoring through internet of things and cloud computing. *Computer Networks*, 101: 5-18.

Xiao, Z., Cao, B., Zhou, G. and Sun, J. 2017. The monitoring and research of unstable locations in eco-industrial networks. *Computers and Industrial Engineering*, 105, pp. 234-246.

Xinhua, Y., Sheng, L. and Fianzhong, F. 2015. Heat exchanger design for a thermoelectric module to drive wireless sensors in spindle monitoring. *Sensor Review*, 35(1), pp. 51-61.

Yang, S., Bagheri, B., Kao, H.-A. and Lee, J. 2015. A unified framework and platform for designing of cloud-based machine health monitoring and manufacturing systems. *Journal of Manufacturing Science and Engineering*, 137 (4): 040914.

Yan, J., Koc, M. and Lee, J. 2007. A Prognostic Algorithm for Machine Performance Assesment and its Application. *Journal of the Chinese Institute of Industrial Engineers*, 22(1), pp. 746-801.

Yen-Kuang, C. 2012. Challenges, and opportunities of Internet of Things. *Design Automation Conference (ASP-DAC), 2012 17th Asia and South Pacific.* IEEE conference publication, pp.383-388. [online] Available at: DOI: 10.1109/ASPDAC.2012.6164978 (Accessed on 12th February 2016).

Ylipää, T., Ylipää, T., Skoogh, A., Skoogh, A., Bokrantz, J., Bokrantz, J., Gopalakrishnan, M. and Gopalakrishnan, M. 2017. Identification of maintenance improvement potential using OEE assessment. *International Journal of Productivity and Performance Management*, 66(1), pp. 126-143.

Zerbst, U., Kliger, C. and Clegg, R. 2015. *Fracture mechanics as a tool in failure analysis-Prospects and Limitations.* BAM Federal Institute for materials Research and Testing, 9.1, D-12205 Berlin, Germany, Bureau Veritas Asset Integrity and Reliability Services Pty Ltd., Murarrie, Queensland, Australia.

Zhang, T., Dwight, R. and El-Akruti, K.O. 2013. Condition based maintenance and operation of wind turbines. *8th World Congress on Engineering Asset Management and 3rd International Conference on utility Management & Safety*. [online] Available at: http://ro.uow.edu.au/eispapers/2271

Zhang, X., Li, H. and Meng, G. 2008. Effect of friction on the slide guide in an elevator system. In: Proceedings of *Journal of Physics: Conference Series*. IOP Publishing, 012074.

Zhang, Y., Kim, C.W., Tee, K.F. and Lam, J.S.L. 2017. Optimal sustainable life cycle maintenance strategies for port infrastructures. *Journal of Cleaner Production*, 142, pp.1693-1709.

Zhang, Y., Sidibé, Y., Maze, G., Leon, F., Druaux, F. and Lefebvre, D. 2016. Detection of damages in underwater metal plate using acoustic inverse scattering and image processing methods. *Applied Acoustics*, 103, pp. 110-121.

Zhao, H.S., Liu, H.Y., Chen, S., Wang, Y.Y. and Zhao, H.Y. 2016. Reliability assessment of distribution network considering preventive maintenance. In: Proceedings of *Power and Energy Society General Meeting (PESGM)*. IEEE, pp. 1-5.

Zipp, K. 2010, Intelligent Vibration monitoring for wind plants. *Wind power Engineering*.

APPENDICES

Appendix 1: Letter of Permission to Install Monitoring Device on Lift System

From: Mendon Dewa
To: Sanjith Dhanny
Subject: RE: REQUEST for PERMISSION TO USE ONE OF THE ELEVATORS FOR RESEARCH
Date: Tuesday, 13 June 2017 2:19:00 PM

Noted, thank you. I do guarantee that there will be no disruptions to the functionality of the lift system

Regards

Mr Mendon Dewa, Pr Eng
Department of Industrial Engineering
Steve Biko Campus, S4 Level 0
Email: mendond@dut.ac.za
Phone: 0313732964

From: Sanjith Dhanny
Sent: Tuesday, 13 June 2017 2:18 PM
To: Mendon Dewa <mendond@dut.ac.za>
Subject: RE: REQUEST for PERMISSION TO USE ONE OF THE ELEVATORS FOR RESEARCH

Dear Mr Dewa
Providing that Otis is doing the installation and you can guarantee that this project will not cause disruptions to the functionality of the lifts, we have no objections!

Regards,
Danny
Facilities Management
DUT

From: Mendon Dewa
Sent: Tuesday, 13 June 2017 12:38 PM
To: Sanjith Dhanny <sanjithd@dut.ac.za>
Subject: FW: REQUEST for PERMISSION TO USE ONE OF THE ELEVATORS FOR RESEARCH

From: Mendon Dewa
Sent: 06 June 2017 11:12 AM
To: Nobukhosi Makhosi Portia Nzama <NobukhosiN@dut.ac.za>
Cc: Andrew Kisten Naicker <naickera@dut.ac.za>; Bakhe Nleya <bakhen@dut.ac.za>; opeyemi olalere <opeflan@gmail.com>
Subject: REQUEST for PERMISSION TO USE ONE OF THE ELEVATORS FOR RESEARCH

Our masters student in the Department of Industrial Engineering, Durban University of Technology, is working on remote machine condition monitoring and is using the elevator as his case study. I do hereby seek official permission for him to install a remote monitoring device for machine maintenance on the elevator car. The installation will be conducted by OTTIS, a company that has been contracted by DUT to service the lift. The device will be installed on the outer elevator car roof without any interference with the operation of the equipment as well as the Safety or Health Hazards to the users. The device is to remotely send machine vibration, sound and temperature data to the internet web application which also has no interference with the DUT IT system. We have also liaised with the maintenance team from OTTIS in charge of the S4 and S3 Elevators which we want to use for the research and they are satisfied the health and safety implications of the device installation. I therefore wish to have an email confirmation for permission from your side, as advised by our Head of Department, Industrial Engineering.

Regards

Mr Mendon Dewa, Pr Eng
Department of Industrial Engineering
Steve Biko Campus, S4 Level 0
Email: mendond@dut.ac.za
Phone: 0313732964

DUT
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28th June, 2017.

The Director,

Security unit.

Steve-Biko Campus

Dear Sir/Madam,

REQUEST FOR PERMISSION TO USE UNIVERSITY FACILITIES DURING THE HOLIDAY (OLALERE, ISAAC -21557828)

I do hereby request the University security to allow Olalere, Isaac O (21557828) who is a Master's degree student in the Department of Industrial Engineering, to access the University during the holiday in order to keep his research work going during the course of the holiday.

If you need any further information, please do not hesitate to contact me at 0313732964, email: mendond@dut.ac.za.

Regards,

Mendon Dewa, Pr Eng (Supervisor)

Appendix 2: Captured Temperature, Acoustics and Vibration Data

	Temp (o_C)	Vibration (g-force, mg)			Sound (dB)	Time (Minutes)
		x	y	z		
	24	-257	12	3	68	00
	24	-257	12	5	74	10
	24	-257	11	4	71	20
	24	-257	12	3	77	30
	24	-257	11	3	70	40
	24	-257	11	3	71	50
	24	-257	11	3	70	60
	25	-257	11	2	73	70
	25	-257	11	3	69	80
	25	-256	10	2	69	90
	24	-257	9	2	69	100
	25	-256	10	1	76	110
	24	-251	-36	35	59	120
	45	-277	-29	21	87	130
	24	-254	-4	-3	73	140
	25	-260	0	22	63	150

	25	-250	-16	32	71	160
	25	-270	-10	9	64	170
	25	-254	-4	17	74	180
	25	-258	1	1	69	190
	27	-257	5	1	77	200
	27	-258	11	3	73	210
	27	-255	11	3	71	220
	26	-257	10	2	71	230
	47	-257	10	3	70	240
	27	-257	10	3	75	250
	26	-258	11	2	70	260
	27	-259	10	3	74	270
	27	-258	10	3	76	280
	27	-269	15	2	77	290
	26	-257	10	3	68	300
	26	-257	10	2	72	310
	26	-257	10	3	79	320
	26	-257	9	3	76	330
	26	-259	9	2	77	340

	26	-257	9	3	61	350
	26	-257	11	3	70	360
	26	-257	9	1	72	370
	Temp (o_C)	Vibration (g-force, mg)			Sound (dB)	Time (minutes)
		x	y	z		
	26	-259	11	2	78	380
	26	-257	10	2	71	380
	26	-258	10	3	73	390
	26	-258	10	2	71	400
	26	-257	10	3	60	410
	26	-257	10	3	71	420
	26	-257	10	3	74	430
	26	-259	12	2	75	440
	26	-257	10	3	70	450
	26	-258	11	4	69	460
	26	-257	10	3	73	470
	26	-257	10	3	75	480
	26	-257	10	3	74	490
	25	-257	10	2	66	500

	26	-258	11	3	69	510
	26	-258	11	3	68	520
	26	-257	10	3	70	530
	26	-258	11	5	64	540
	26	-257	11	4	78	550
	26	-257	9	3	74	560
	26	-257	10	3	68	570
	26	-257	11	4	68	580
	25	-257	10	2	68	590
	26	-257	10	3	70	600
	26	-257	10	4	72	610
	26	-257	10	4	70	620
	26	-258	12	1	68	630
	25	-258	10	2	57	640
	26	-279	11	2	67	650
	26	-258	11	3	69	660
	26	-258	10	3	73	670
	25	-258	11	2	74	680
	25	-258	11	2	70	690

	25	-259	9	3	70	700
	26	-257	11	3	66	710
	25	-257	11	3	70	720
	26	-257	10	2	71	730
	25	-257	9	2	72	740
	Temp (o_C)	Vibration (g-force, mg)			Sound (dB)	Time (Minutes)
		x	y	z		
	25	-257	10	3	59	750
	25	-257	10	4	59	760
	26	-257	10	3	58	770
	26	-258	10	4	73	780
	26	-257	10	3	72	790
	26	-258	10	4	68	800
	26	-257	11	3	63	810
	26	-256	11	2	65	820
	26	-257	10	3	73	830
	25	-257	11	2	59	840
	26	-257	10	3	69	850
	25	-255	11	4	60	860

	26	-258	11	3	76	870
	26	-257	10	3	65	880
	26	-258	9	3	68	890
	26	-258	10	3	69	900
	26	-257	11	4	76	910
	26	-257	10	3	72	920
	26	-257	10	3	68	930
	26	-257	11	3	69	940
	26	-256	10	3	73	950
	24	-269	7	3	72	960
	25	-258	10	4	72	970
	25	-257	10	3	72	980
	25	-258	10	3	66	990
	25	-258	10	3	70	1000
	25	-257	10	4	66	1010
	25	-257	10	3	72	1020
	25	-257	11	3	70	1030
	24	-257	10	4	69	1040
	45	-257	11	4	66	1050

	25	-257	10	3	67	1060
	25	-257	9	3	73	1070
	23	-257	9	3	64	1080
	24	-257	9	4	68	1090
	24	-256	10	2	64	1100
	24	-256	10	3	72	1110
	24	-257	9	3	53	1120
	24	-257	9	3	71	1130
	24	-257	9	4	53	1140
	24	-257	9	3	69	1150
	23	-257	10	2	64	1160
	24	-257	9	3	69	1170
	24	-257	10	3	65	1180
	23	-257	10	4	62	1190
	23	-257	10	4	52	1200
	23	-258	11	3	68	1210
	23	-257	10	4	56	1220
	23	-257	10	2	61	1230
	23	-257	11	2	68	1240

	23	-257	11	2	53	1250
	24	-254	10	2	72	1260
	24	-258	9	2	66	1270
	24	-257	10	3	69	1280
	23	-257	11	2	53	1250
	24	-258	11	4	64	1290
	23	-258	10	3	64	1300
	25	-257	10	3	63	1310
	Temp (o_C)	Vibration (g-force, mg)			Sound (dB)	Time (Minutes)
		x	y	z		
	25	-258	10	3	62	1320
	25	-257	9	3	71	1330
	25	-257	10	3	64	1340
	25	-257	10	3	64	1350
	25	-257	10	2	67	1360
	26	-257	10	3	68	1370
	25	-257	11	4	68	1380
	25	-257	10	3	72	1390
	25	-257	10	3	69	1400

	25	-258	9	3	67	1410
	26	-257	10	3	73	1420
	26	-258	11	3	68	1430
	26	-256	10	3	68	1440
	26	-257	10	4	73	1450
	26	-257	10	3	72	1460
	26	-257	11	3	73	1470
	26	-257	9	4	74	1480
	26	-257	10	4	75	1490
	26	-249	10	3	72	1500
	26	-256	9	3	69	1510
	26	-256	9	3	73	1520
	26	-257	11	4	72	1530
	26	-257	10	2	67	1540
	26	-257	10	4	75	1550
	26	-257	10	3	70	1560
	26	-257	9	5	74	1570
	25	-256	9	3	59	1580
	25	-257	9	3	64	1590

	25	-257	10	3	62	1600
	26	-257	9	4	74	1610
	25	-257	11	3	70	1620
	26	-257	9	4	76	1630
	26	-258	9	3	67	1640
	25	-256	7	4	71	1650
	25	-258	10	1	71	1660
	46	-258	9	3	70	1670
	45	-257	9	4	67	1680
	46	-257	10	3	72	1690
	Temp (o_C)	Vibration (g-force, mg)			Sound (dB)	Time (Minutes)
		x	y	z		
	26	-257	12	2	74	1700
	25	-257	10	3	101	1710
	26	-258	9	2	66	1720
	26	-256	10	2	68	1730
	25	-258	10	3	73	1740
	25	-258	10	3	69	1750
	26	-257	11	4	69	1760

	26	-257	11	2	69	1770
	26	-258	11	2	74	1780
	26	-258	10	3	72	1790
	26	-257	10	3	107	1800
	26	-258	10	3	70	1810
	26	-257	11	3	69	1820
	26	-257	10	2	95	1830
	26	-257	10	3	72	1840
	26	-258	10	4	70	1850
	26	-257	10	4	75	1860
	26	-257	10	2	68	1870
	26	-257	11	3	69	1880
	26	-257	10	2	70	1890
	26	-258	10	3	70	1900
	26	-257	8	3	65	1910
	25	-258	12	3	68	1920
	26	-256	10	2	69	1930
	26	-257	11	3	71	1940
	26	-258	10	3	72	1950

	26	-257	11	3	71	1960
	25	-258	10	2	69	1970
	26	-257	9	3	72	1980
	26	-257	11	2	72	1990
	25	-257	10	3	68	2000
	25	-257	8	4	68	2010
	25	-258	9	3	71	2020
	25	-257	10	3	74	2030
	25	-258	10	3	66	2040
	25	-258	10	3	73	2050
	25	-257	10	4	72	2060
	25	-257	10	3	74	2070
	Temp (o_C)	Vibration (g-force, mg)			Sound (dB)	Time (Minutes)
		x	y	z		
	25	-257	11	3	69	2080
	25	-257	10	3	67	2090
	24	-257	11	3	68	2100
	24	-257	11	3	55	2110
	24	-258	10	4	71	2120

	24	-257	10	4	66	2130
	24	-257	9	2	62	2140
	24	-257	9	4	72	2150
	24	-258	10	3	66	2160
	24	-257	10	2	70	2170
	24	-257	11	4	71	2180
	23	-257	10	4	70	2190
	24	-257	10	3	68	2200
	24	-257	10	4	69	2210
	24	-257	10	3	54	2220
	24	-257	9	3	67	2230
	22	-258	10	5	54	2240
	22	-258	10	4	52	2250
	23	-258	10	3	53	2260
	23	-257	10	3	63	2270
	23	-257	10	2	65	2280
	23	-257	10	4	71	2290
	23	-257	11	3	63	2300
	22	-257	11	2	59	2310

	23	-256	10	2	61	2320
	23	-257	10	2	53	2330
	23	-258	11	1	69	2340
	23	-258	9	2	70	2350
	23	-258	10	3	68	2360
	23	-257	10	4	68	2370
	23	-256	10	2	64	2380
	23	-257	11	4	67	2390
	23	-257	10	3	58	2400
	23	-257	10	3	55	2410
	23	-258	10	3	62	2420
	26	-257	10	3	60	2430
	26	-257	10	3	71	2440
	26	-257	10	3	74	2450
	Temp (o_C)	Vibration (g-force, mg)			Sound (dB)	Time (minutes)
		x	y	z		
	26	-259	12	2	75	2460
	25	-257	11	2	73	2470

Appendix 3: Telephone Interview with Otis Maintenance Supervisor

Telephone interview was granted by Otis branch manager on 23rd February 2017. The conversation entails the commissioning of the elevator system cited on campus. The following questions were asked:

I want to find out if you are a proprietary to any elevator on campus

Response: Yes

How many elevators are you manging on campus

Response: The company manages 4 elevators at Steve Biko Campus, S building and 3 other elevators at ML Sultan campus with 4 escalators at ML Sultan.

When was the installation date?

Response: The elevators were installed in the year 1984

What is the maintenance routine carried out on the system?

Response: Troubleshooting the controls, checking the braking system, cleaning the guide rails and lubrication.

How often is the maintenance carried out?

Response: Maintenance is carried out monthly.

What are the challenges that is encountered on the maintenance of the system?

Response: The maintenance of the system is challenged by frequent breakdown of the elevators due to the system being old and also a long downtime due to late fault notification and repair.

I will like to visit for further enquiry if possible.

Response: You are welcome.

Appendix 4: Source Code for Configuring the Arduino Toolkit

```
/*
  SendAnEmail
  Demonstrates sending an email via a Google Gmail account using the Temboo Arduino Yun
SDK.
  This example code is in the public domain.
*/
#include <Bridge.h>
#include <Temboo.h>
#include "TembooAccount.h" // contains Temboo account information
#include <Wire.h>
# define accel_module (0x53)
  byte values [6];
  char output [512];
/*** SUBSTITUTE YOUR VALUES BELOW: ***/
// Note that for additional security and reusability, you could
// use #define statements to specify these values in a .h file.
// your Gmail username, formatted as a complete email address, eg "bob.smith@gmail.com"
const String GMAIL_USER_NAME = "elevatordatamonitoring@gmail.com";
// your Gmail App-Specific Password
const String GMAIL_PASSWORD = "jbohfelyqrpeditp";
// the email address you want to send the email to, eg "jane.doe@temboo.com"
const String TO_EMAIL_ADDRESS = "elevatordatamonitoring@gmail.com";
boolean success = false; // a flag to indicate whether we've sent the email yet or not
```

```
int calls = 1; // Execution count, so this doesn't run forever
int maxCalls = 20000; // Maximum number of times the Choreo should be executed
int tempPin = 0;
int tempC;
int tempIn;
int ledPin = 13;
int incomingByte;
int soundPin = 1;
int soundValue = 0;
int vibration;
void setup() {
  Bridge.begin();
  Console.begin();
  // for debugging, wait until a serial console is connected
  delay(4000);
  while(!Console);
Wire.begin();
pinMode(ledPin, OUTPUT);
Wire.beginTransmission(accel_module);
Wire.write(0x2D);
Wire.write(0);
Wire.endTransmission(accel_module);
Wire.write(0x2D);
Wire.write(16);
```

```
Wire.endTransmission();
Wire.beginTransmission(accel_module);
Wire.write(0x2D);
Wire.write(8);
Wire.endTransmission();
}
void loop()
{
 tempIn = analogRead(tempPin);
 tempC = (500.0*tempIn)/1024.0;
 Console.print("TEMP: ");
 Console.print((byte)tempC);
 Console.println(" C");
 String tempString = String(tempC);
 soundValue = analogRead (soundPin);
 Console.print("Sound = ");
 Console.print(soundValue);
 Console.print("\t");
 String soundValueString = String(soundValue);
 int xyzregister = 0x32;
 int x, y, z;
 Wire.beginTransmission(accel_module);
 Wire.write(xyzregister);
 Wire.endTransmission();
```

```
  Wire.beginTransmission(accel_module);
  Wire.requestFrom(accel_module, 6);
  int i=0;
  while(Wire.available()){
  values [i]=Wire.read();
  i++;
  }
 Wire.endTransmission();
x = (((int)values[1]) << 8 ) | values[0];
y = (((int)values[3]) << 8 ) | values[2];
z = (((int)values[5]) << 8 ) | values[4];
//sprintf (output, "%d %d %d", x, y, z);
  //vibration = output;
  Console.print("Vibration = ");
  //Console.print(x);
  //Console.print(vibration);
// String vibrationString = String(vibration);
  String combinedValueString = "sound = " + soundValueString + "  " + "Temperature = " +
tempString + " C" + " Vibration =  " +  x  + "   "+  y  + "    " +  z;
  // only try to send the email if we haven't already sent it successfully
  if (calls <= maxCalls) {
    Console.println("Running SendEmail - Run #" + String(calls++) + String(calls++));
    Serial.println("Running SendAnEmail...");
    TembooChoreo SendEmailChoreo;
```

```
// invoke the Temboo client
// NOTE that the client must be reinvoked, and repopulated with
// appropriate arguments, each time its run() method is called.
SendEmailChoreo.begin();
// set Temboo account credentials
SendEmailChoreo.setAccountName(TEMBOO_ACCOUNT);
SendEmailChoreo.setAppKeyName(TEMBOO_APP_KEY_NAME);
SendEmailChoreo.setAppKey(TEMBOO_APP_KEY);

// identify the Temboo Library choreo to run (Google > Gmail > SendEmail)
SendEmailChoreo.setChoreo("/Library/Google/Gmail/SendEmail");
// set the required choreo inputs
// see https://www.temboo.com/library/Library/Google/Gmail/SendEmail/
// for complete details about the inputs for this Choreo
// the first input is your Gmail email address
SendEmailChoreo.addInput("Username", "elevatordatamonitoring@gmail.com");
// next is your Gmail App-Specific password.
SendEmailChoreo.addInput("Password", "jbohfelyqrpeditp");
// who to send the email to
SendEmailChoreo.addInput("ToAddress", "elevatordatamonitoring@gmail.com");
// then a subject line
SendEmailChoreo.addInput("Subject", "Remote Machine Condition Monitoring");
 // next comes the message body, the main content of the email
SendEmailChoreo.addInput("MessageBody", combinedValueString);
```

```
//SendEmailChoreo.addInput("MessageBody", soundValueString);
// tell the Choreo to run and wait for the results. The
// return code (returnCode) will tell us whether the Temboo client
// was able to send our request to the Temboo servers
unsigned int returnCode = SendEmailChoreo.run();

// a return code of zero (0) means everything worked
```

$$\text{If } \overline{X} - 5mg \geq X \geq \overline{X} + 5mg \quad \text{OR}$$

$$\overline{Y} - 5mg \geq Y \geq \overline{Y} + 5mg \quad \text{OR}$$

$$\overline{Z} - 5mg \geq Z \geq \overline{Z} + 5mg \quad \text{OR}$$

$$tempString > 35^{o}\text{ C} \quad \text{OR}$$

$$SoundPin\ > 70dB$$

```
if (returnCode == 0) {
   Console.println("Success! Email sent!");
   success = true;
} else {
  // a non-zero return code means there was an error
  // read and print the error message
  while (SendEmailChoreo.available()) {
   char c = SendEmailChoreo.read();
   Console.print(c);
  }
}
SendEmailChoreo.close();
```

```
    // do nothing for the next 2 minutes
    delay(900000);
  }
}
```