INTELLIGENT MANAGEMENT SYSTEM FOR DRIVERLESS VEHICLES

By

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DOCTOR OF PHILOSOPHY

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RESEARCH STUDENT DECLARATION

Type of Award: Doctor of Philosophy

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1. Concurrent registration for two or more academic awards

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2. Material submitted for another award

I declare that no material contained in the thesis has been used in any other submission for any academic award and is solely my own work.

3. Collaboration

This work presented in the thesis was carried out at the Intelligent Systems Lab, EIC, University of Central Lancashire. The work described in the thesis is entirely the candidate's own work.

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No proof-reading service was used in the compilation of this thesis.

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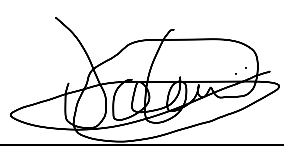

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ABSTRACT

This research addresses concerns related to driverless vehicles by proposing the development of an Intelligent Management System (IMS). Emphasised in 'The Pathway to Driverless Cars Summary report and action plan' by the UK Department of Transport, key areas for improvement lie in vehicle reliability, maintenance, and passenger safety. The study targets compliance with Society of Automotive Engineers (SAE) Level 5 automation, concentrating on fully autonomous vehicles to enhance commuter satisfaction and overall vehicle performance. Despite advancements, challenges such as on-road safety and integration persist.

The research unfolds through a two-stage development process aimed at achieving an Intelligent Management System for Driverless Vehicles (IMSDV). The initial stage, described in chapter 3 involves the creation of a 'Single Seat Driverless Pod' as a test apparatus, simulating various features found in existing driverless vehicles. This includes the development of mechanical steering components and a control system incorporating electronic hardware, sensors, actuators, controllers, wireless remote access, and software. The subsequent phase, described in chapter 4 focuses on autonomous navigation using Google Maps, intelligent motion control, localisation, and tracking algorithms within the driverless pod.

The latter chapters of the thesis present the investigation of possible improvements in steering system components. A novel encapsulated vehicle wheel condition monitoring system, integrating the Internet of Things (IoT), is proposed to enhance maintainability, reliability, and passenger safety for driverless vehicles.

Testing and validation are conducted in two segments. The driverless pod undergoes initial testing to validate its features and generate data for further sub-system development. Separately, the IoT-based monitoring system undergoes individual testing. The final step involves integrating the IoT capabilities into the driverless pod, testing the sub-system, and capturing relevant data.

The thesis outlines the research scope, emphasising significant contributions, with a particular focus on the monitoring system for steering components in driverless vehicles, employing embedded IoT technology. This augmentation, alongside other original contribution, is strategically poised to enhance the maintainability, reliability, and safety of driverless vehicles at SAE Level 5. The concluding chapter succinctly revisits these distinctive contributions and additionally provides recommendations for advancing intelligent management systems for driverless vehicles.

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DEDICATIONS

"This achievement is dedicated to my beloved family & friends who have been there for me and supported me throughout."

LIST OF ABBREVIATIONS

ABS	Anti-lock Braking System
AC	Alternating Current
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
ADC	Analog-to-Digital Converter
AE	Acoustic Emission
AI	Artificial Intelligence
ANN	Artificial Neural Network
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
AV	Autonomous Vehicle
BLE	Bluetooth Low Energy
BOSCH	Robert Bosch GmbH (a German multinational engineering and technology company)
CAD	Computer-Aided Design
CAN	Controller Area Network
CM	Condition Monitoring
CoAP	Constrained Application Protocol
DAQ	Data Acquisition
DARPA	Defence Advanced Research Projects Agency
DC	Direct Current
DOF	Degrees of Freedom
ECU	Electronic Control Unit
EIC	Engine Instrumentation and Control
EPS	Electric Power Steering
ESC	Electronic Stability Control
FFT	Fast Fourier Transform
FPGA	Field-Programmable Gate Array
GA	Genetic Algorithm
GPIO	General Purpose Input/Output
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HMI	Human-Machine Interface
HTTP	Hypertext Transfer Protocol
I2C	Inter-Integrated Circuit
IC	Integrated Circuit
IEEE	Institute of Electrical and Electronics Engineers
IHM	Integrated Health Management
IMS	Intelligent Management System
IMSDV	Intelligent Management System for Driverless Vehicles

IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IoT	Internet of Things
ITS	Intelligent Transportation System
IVHM	Integrated Vehicle Health Management
JSON	JavaScript Object Notation
JTAG	Joint Test Action Group
LABVIEW	Laboratory Virtual Instrument Engineering Workbench
LED	Light Emitting Diode
LIDAR	Light Detection and Ranging
LVDT	Linear Variable Displacement Transformer
M2M	Machine-to-Machine
MCU	Microcontroller Unit
MEMS	Microelectromechanical Systems
MPH	Miles Per Hour
MQTT	Message Queuing Telemetry Transport
NASA	National Aeronautics and Space Administration
NI	National Instruments
NMEA	National Marine Electronics Association
NVH	Noise, Vibration, and Harshness
OBD	On-Board Diagnostics
PCB	Printed Circuit Board
PID	Proportional-Integral-Derivative
PM	Preventive Maintenance
PMP	Personal Mobility Pod
RADAR	Radio Detection and Ranging
REST	Representational State Transfer
RLDA	Road Load Data Acquisition
RMS	Root Mean Square
ROV	Remotely Operated Vehicle
SAE	Society of Automotive Engineers
SCADA	Supervisory Control and Data Acquisition
SDK	Software Development Kit
SMS	Short Message Service
SOM	Self-Organising Map
SPDT	Single Pole Double Throw
TCP	Transmission Control Protocol
TLS	Transport Layer Security
TPMS	Tire Pressure Monitoring System
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
UI	User Interface

USB	Universal Serial Bus
VIPM	VI Package Manager
VMS	Vehicle Management System
XDK	Cross-Domain Kit

CHAPTER 1

INTRODUCTION

1.1. Background

The recent century has seen great new inventions of many classes. No other invention has been more influential than the automobile. Cars are now a primary mode of transport all over the world. In fact, estimations of over 1.2 billion cars are on the roads worldwide (Thrun, 2010). According to UK's national Travel Survey, considerable rise in use of cars as opposed to walking/cycling and public transport is clear (DfT, 2015).

Despite the importance of automobiles, inefficiency of cars is an increasing concern. Anything that compromises basic resources, such as human health, energy and productivity is a huge expenditure (Thrun, 2010). The average driver in England spends 235 hours driving every year. These hours account to the equivalence of six working weeks (DfT, 2015). Current statistics concerning the numbers of accidents on the roads are worrying. Reports issued by the UK Department for Transport state that 90% of UK road accidents are due to human error, including speeding (32% of accidents), alcohol (21%) and distraction (17%). The average driver in England spends 235 hours driving every year, standing for the equivalent of six working weeks. In addition, according to the World Health Organization, road traffic injuries account for approximately 1.3 million deaths a year across the globe. Additionally, commuters experience tremendously lengthy delays due to congestion and road accidents. The prolonged inconveniences of on the road safety risks affect all types of road users, the society, and the environment. Researchers have been trying to address the current issues and increase the efficiency of automobile technology by including intelligent robotic technology in cars to improve efficiency (Fagnant and Kockelman 2015). Autonomous driving could help prevent accidents by ending the role of human error in driving (DfT, 2015).

Since the conception of Intelligent Transportation Systems (ITS) in the 1980s, many researchers have gone on to work on the development of incident-management models and integrated systems for real-time operations (Ozbay and Kachroo, 1999). Several attempts to develop fully autonomous vehicles have been made, and many milestones have been reached. The challenge of DARPA (Defence Advanced Research Projects Agency) in 2004 was perhaps the major spur behind the research for autonomous driving and autonomous vehicles, resulting in some of the most intensively researched and publicly followed technologies in the transportation domain (Beiker, 2012). The challenge was introduced to emphasise the development of fully autonomous ground vehicles. DARPA invited major companies and research organisations to take part, and over 50 robotic and non-robotic vehicles competed, of which only six vehicles successfully completed the race. While the DARPA Challenge is still the largest demonstration of autonomous vehicle technology to date, it excluded many capabilities and requirements critical for actual driving in cities, not progressing beyond completing an off-road course within a time limit (Buehler et al., 2009).

Leading automotive companies (Ford, GM, Nissan, Volvo, etc.) and technology companies (Google, Induct, etc.) started exploration to the field to address the issues for commercial use (Anderson et al., 2014) and have already proved autonomous driving through working prototypes. The automotive industry is aware of the potential market appearing from autonomous driving, and companies are competing to position themselves for future revenue from its increased potential and beneficial factors. Benefits to individual consumers as well as society at large are a leading factor in attracting so much attention to the research.

Several Advanced Driver Assistance Systems (ADAS), such as active lane keep assist, adaptive cruise control and self-parking already available on the market, have been combined as a major aspect pushing the development of driverless vehicles. The replacement of a human with technology requires critical sensory functions to be performed using various technologies simultaneously. Many of these facilities currently exist in the latest technology, helping “Level 3” Society of Automotive Engineers (SAE) J3016 automotive automation standards (Figure 1.1), but requiring an elevated level of training to be practical for consumer use (SAE, 2013). Several areas require mastery – vehicle location, prediction and decision algorithms, real-time accuracy, etc. – as technology must perform better than human eyes, ears, memory, and coordination. This requires a prominent level of advancement. The UK has diagnosed key areas which need consideration: Safety & Integration (Greenwich), Vehicles on roads (Milton Keynes & Coventry), Legal/Insurance (Bristol).

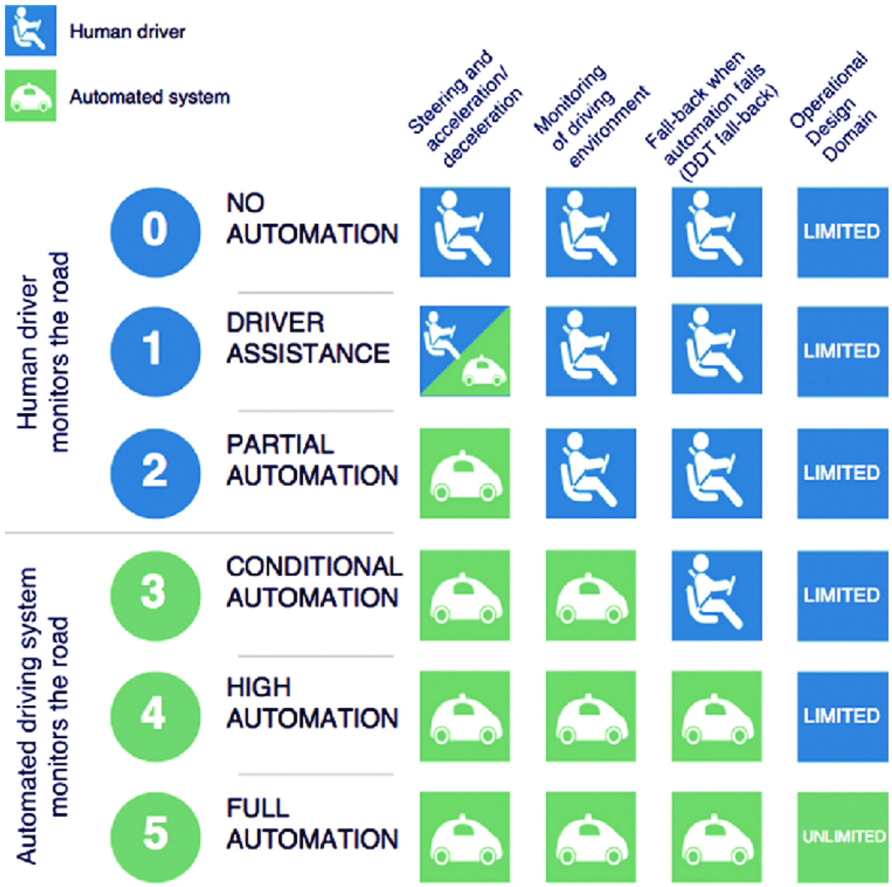

Figure 1.1: SAE J3016 levels of driving automation (Serban, A et al., 2020)

Persistent transformation through the stages of autonomous driving is consistent in the latest technology, although mastery in all areas has not yet been achieved. Contributing to research in health, safety, and the integration on roads of driverless vehicles, monitoring vehicle condition through Intelligent Management System for Driverless Vehicles (IMSDV) is a prerequisite. Through this study, the goal is to find key areas which need substantial attention through developing an intelligent management approach for driverless vehicle systems.

Considering the various sectors in the field of driverless vehicles and earlier discussions, the proposed development was proven, aiming to develop a new single seat designed ‘Driverless Pod.’ It is proposed that adding further sensory fusion systems to the current driverless vehicle management system may address current issues in driverless vehicles. The system will be used to gather real data which can be used for developing an IMSDV.

1.1. Aim

The aim for this PhD research is to develop an Intelligent Management System for Driverless Vehicles (IMSDV).

The research investigates new possibilities to contribute to the heavily researched field of driverless vehicles. Incorporating both design methods and computational systems that would allow to develop an Intelligent Management System for Driverless Vehicles with the aid of a 'Driverless Pod' with regards to current technological developments. The rationale behind the developments of the 'Pod' is not to replicate the advances of a driverless vehicle, but to use as a test apparatus for gathering real data to develop an IMSDV.

1.2. Objectives

1. Investigate and incorporate various sensory and actuation systems used in unmanned systems and active condition monitoring systems
2. Develop a suitable test bench that includes driverless vehicle subsystem or system
3. Addressing current issues in driverless cars steering system, the PhD includes developing new monitoring system for Steering Wheel and Vehicle Tyre alignment using embedded systems. It is expected that this novel system will improve driverless car's health and safety.
4. The research project will incorporate a second sub-system that will monitor wheel balancing, which is monitored in conventional cars by users; level 2 - 3 SAE Standards of Automation.
5. Develop an Intelligent Management system for driverless cars steering system using the developed system in (3) and (4) and including intelligent algorithm.
6. Validation of the developed systems in (3), (4) and (5) in laboratory and field environment using the driverless test bench developed during the MPhil phase.

1.3. Original Contributions

- Designed and developed a functional test bench incorporating driverless vehicle subsystems.
- Addressed steering system issues in driverless cars by creating a new monitoring system using embedded IoT.
- Improved safety and reliability of driverless vehicles with a monitoring system for steering components for SAE Level 5 automation.
- Validated the developed systems in both laboratory and field environments using the developed test apparatus – Personal Mobility Pod.
- Rigorously tested and evaluated systems' performance, reliability, and effectiveness. Provided valuable insights for future developments and real-world implementation.

1.4. Statement of the Hypothesis

The hypothesis is "will it be possible to improve present driverless vehicle developments and address current issues - also considered by the UK Department of Transport - in the areas of safety & integration and feasibility of vehicles on the road" (DfT, 2015). It is proposed that adding further multi-sensors fusion systems to the current driverless vehicle management system may address current issues in driverless vehicles.

The first course of study focuses on the development of a single seat 'Driverless Pod' where the system would include various sensors to monitor its surroundings, testing its running conditions and suitability with the research, thus, validated. The Pod will contribute to developing an IMSDV, as it will be used as a test apparatus to gather real data.

Following the testing and validation of the Pod, multi-sensory fusion will enable gathering of raw data for constructing a management system for the Driverless Pod. This would allow creating an Intelligent Management System capable of addressing current issues in the areas of reliability and safety of driverless vehicles with original contributions (Schaefer, Straub 2016). The study will contribute to the research field by reviewing current research and development covered within driverless vehicles at the national and international level and focus on how to improve existing developments.

This research collaborates on the areas of research covered by UK Department of Transport as part of the Tribotronics and Intelligent Condition Monitoring research plan of the 'Intelligent Machines and Maintenance' EIC group. The work is self-funded for the degree of Doctor of Philosophy (via Master of Philosophy) in the School of Engineering, at the University of Central Lancashire.

1.5. Thesis Structure

An overview of the thesis structure is presented in Figure 1.2. The thesis has been separated into: Background Study, System Development, Results and Conclusion.

Chapter 1: Introduction – Provides the background study regarding the research, thus, gives an insight to the main aim and to achieve this aim, what objectives will be covered.

Chapter 2: Literature Review – deeper understanding revolving the current research for driverless vehicles, management systems, intelligent systems and summarising the current issues to find areas which need further improvement.

Chapter 3: Design and Development of a PMP - The research including theoretical, software as well as hardware applications, the combination of several crafts is to be achieved. A well-suited test apparatus which will feature various aspects covered in driverless systems to aid developments of an IMSDV sub – system.

Chapter 4: Design and Implementation of An IoT Based Remote Monitoring System – Following the UK’s focus area of Driverless Vehicles’ Health & Safety, a remote monitoring system which would contribute towards the health & safety of driverless vehicles is demonstrated through the use of the developed PMP system.

Chapter 5: Testing and Validation – Both the designed and developed systems are tested within the laboratory environment and on-field. This chapter demonstrates the outcomes of these subsystems. Additionally, using the test apparatus discussed in Chapter.3, the system design of the new health development system discussed in Chapter.4 is validated.

Chapter 6: Discussion and Conclusion – Concluding the research, a summary of the work carried out is detailed. Discussion of the original contributions that suffice the PhD purpose. Further recommendations for future work are highlighted.

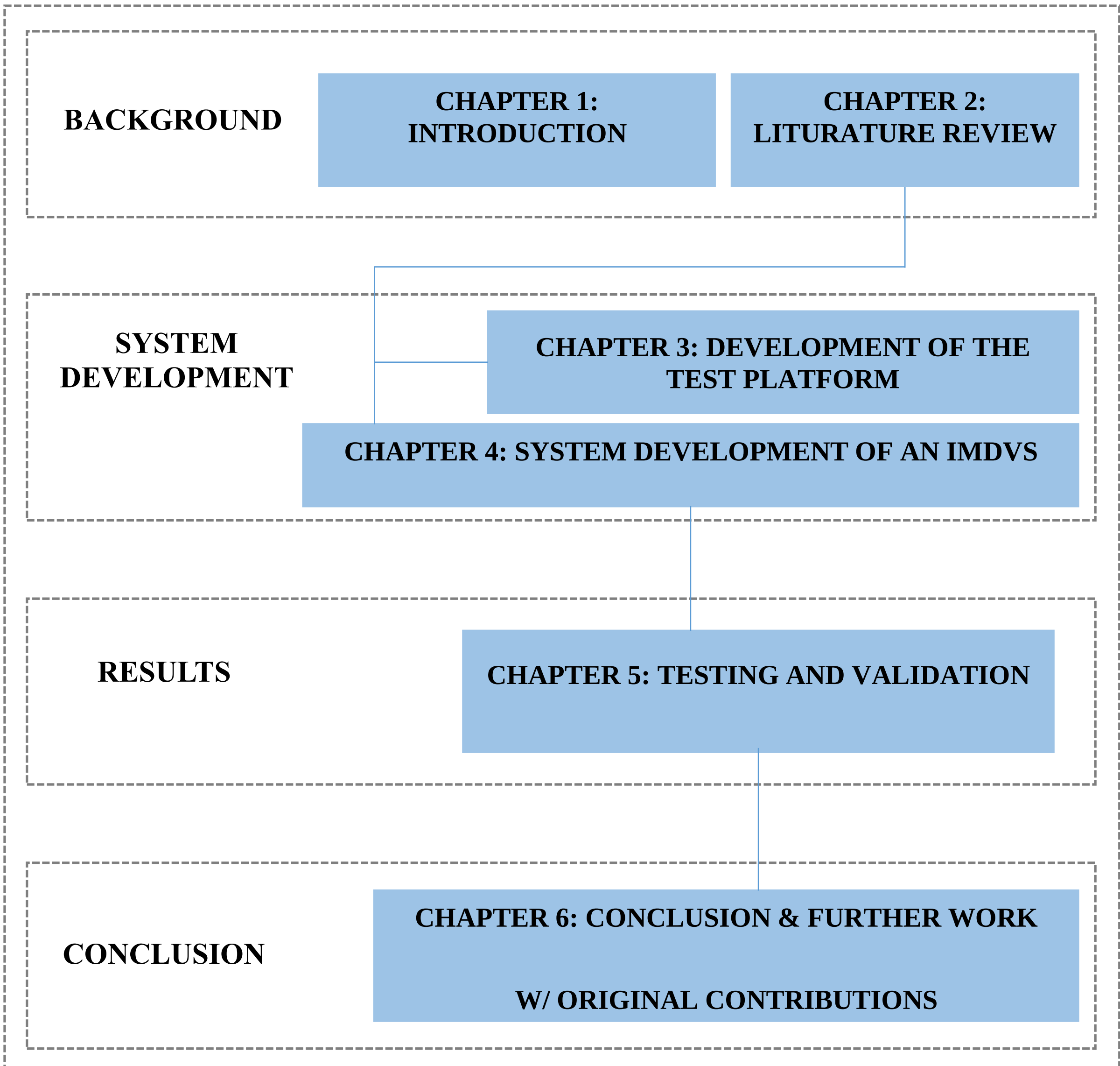

Figure 1.2: Overview of Thesis

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The ongoing research of driverless technology has come a long way; researchers and manufacturers have gathered the benefits of the widespread use of driverless systems. It is being proposed as a near-term solution to many mobility issues we face today: congestion, pollution, road fatalities and changing demands of the young and elderly. Research has revealed the technical capability to build such technology – manufacturers are aiming to fulfil requirements for ideal consumer necessities.

This chapter embodies the literature within the field of research, including evolution of driverless vehicles, current affairs, and some predicaments within the research.

2.2. Overview

The relationship between man and machine has been changing and subjected to significantly continue over the years. Recent ongoing research and innovations of modern technology has created new and different possibilities and opportunities. Autonomous/ Unmanned systems is a division which has opened various prospects for future expansions – investment opportunities, environmental benefits, new employment prospects etc. These are some examples of growth in economy that derive from the advances of driverless vehicle technology. Likewise, technical factors incorporated with the technology introduces increased health & safety, ease of mobility etc., mentioned in (One Box: Driver and Vehicle Data Management System Criteria. 2012).

Driverless / Unmanned / Autonomous; all three of these adjectives summate to a similar definition, within its context to describe the subject technology. “Independent,” “self-governing” “without the physical presence of people in control” – all associating to suggest a system that is self-controlled without user input. Hence a system that can process data and act accordingly to gathered data without the intervention of a human. These unmanned system features apply to a wide range of areas. Transportation of any type: land, airborne, or water, could receive help from autonomous operation.

For instance, underwater expedition – subsea engineering– for oil and gas repairs currently use Remotely Operated Vehicles (ROV). Though, these systems are not yet fully autonomous, the current systems are unmanned. These ROVs are tailored to obtain samples of desired minerals, with drills and cutting tools to be further analysed (Yuh and Choi, 2015). Unmanned Ariel Vehicles are also an area that is extensively researched. Widespread use of such machinery has the possibility of easing the workload for humans, illustrated in Figure 2.1.

Figure 2.1: Subsea Light Work class ROV, Sub Atlantic Comanche (Comanch ROV); UAV, DJI Phantom 3. Adopted from: ROVOP (n.d.). and (DJI, 2017)

Furthermore, focusing on terrestrial active systems as reviewed in this paper - driverless cars offer major potential benefits and could profoundly change our lives for the better. Transportation today is far more advanced than ever before. For a person to get from point A to B is made far simpler and quicker than comparing to 100 years ago.

However, convenience is costing thousands of people's lives every year (Mais, 2015). In hindsight, it is the leading cause of death for people across the world, more dangerous than gun crimes. 1.25 million people are killed every year and mostly due to human error (Peden, Scurfield et al., 2004), (DfT, 2015). Figure 2.2 details statistics of UK road users.

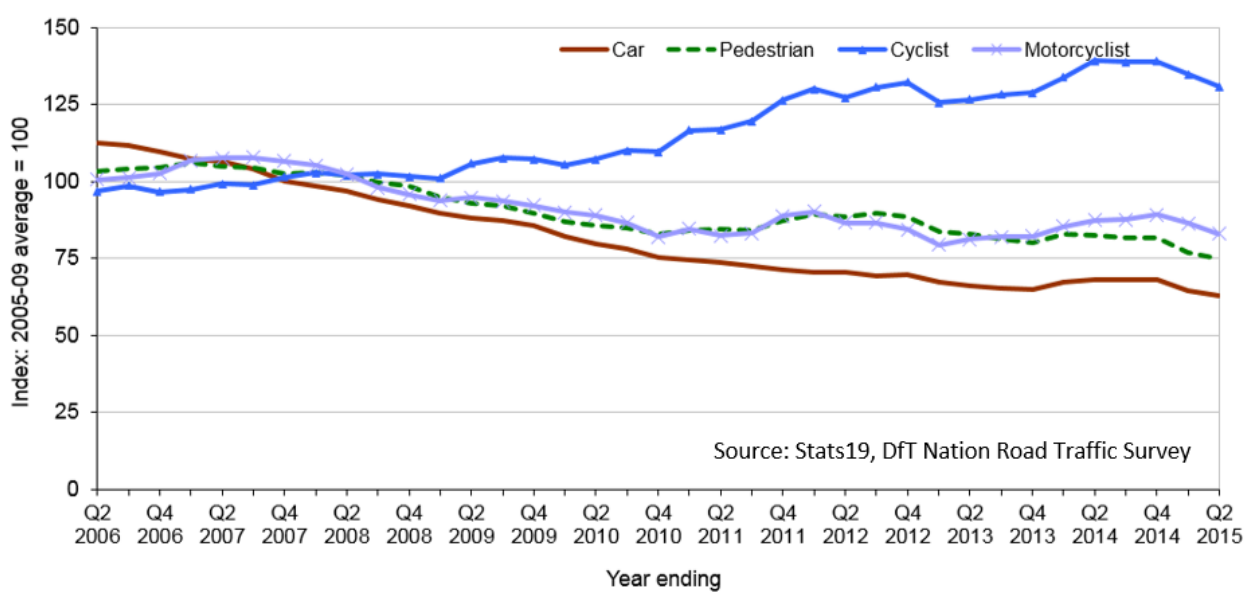

Figure 2.2: Department for Transportation Statistics – Killed or seriously injured road casualties by road users (National Statistics, 2015)

Driverless technology presents an opportunity to develop a system that is constantly alert and aware of its surroundings, potentially leading to significant benefits such as increased road safety, reduced emissions, and improved traffic flow (Figure 2.3). This could make the driving experience more convenient and pleasant, resulting in happier commuters. Additionally, with advancements in technology, a wider range of individuals, including elderly people who are unable to drive, may have access to vehicles. All these factors combined have the potential to create a better world for everyone. (DfT, 2015).

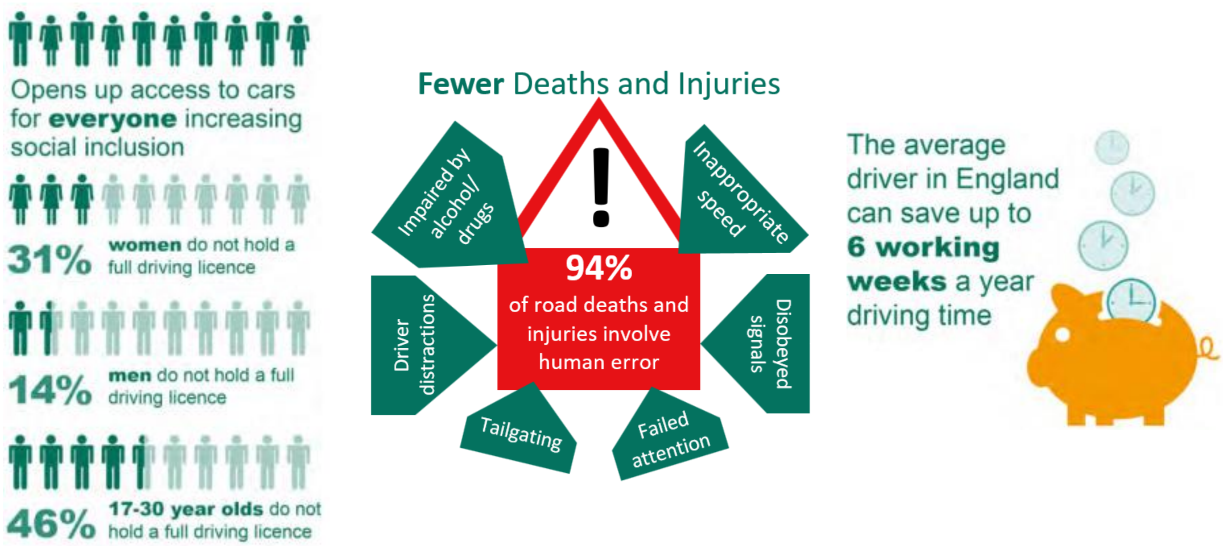

Figure 2.23: Social, economic, and environmental benefits of driverless vehicles. Adopted from (DfT, 2015)

2.3. Driverless Vehicles

Robots have been around for many years. Though not a great deal of technology was developed in the first stages, robots have always been idolised and characterised in movies and novels for years. There have also been instances where concepts started by fictional stories have been developed as part of research.

The concept of autonomous vehicles was not much different. Recognition of these vehicles was admired in movies – Volkswagen Beetle, featured originally in “The Love Bug Rally,” a German series of movies (Zehetgruber, 1971). In literature, the famous science fiction writer Isaac Asimov wrote about autonomous cars having "positronic brains" that can communicate by honking horns and saving their caretakers (Asimov, 1989).

Exploration into autonomous ground vehicles originated in the 1960s when scientists created the "Stanford Cart". The idea of driverless cars has been contemplated ever since the invention of cars. Originally constructed by James L. Adams (mechanical engineering graduate), the Cart (Figure 2.4) was created to support his research on the problem of controlling a remote vehicle using video information for the application of Moon rover (Moravec, 1983).

The mobile robot equipped with a remotely controlled television, was programmed to drive through a cluttered room. The robotic paradigm – a mental model of how the Cart works, can be described by the three primitives: sense – plan – act. The Cart used several methods to locate its position and objects around it in three dimensions. It would plan an obstacle avoidance path with the information it gathers. Though, if a new obstacle interrupt planned route, a new route is diagnosed. The system was reliable for short runs; although, terribly slow. Movements of up to one meter would be travelled every 10-20 mins. Thereafter, new pictures would be taken and then revaluated for extended periods of time. The successful journeys of the Cart involve up to 20-meter courses each taking up to 5 hours (Moravec, 1983)

Figure 2.3: Stanford Artificial Intelligence Laboratory Cart, 1964-71 (Moravec, 1983)

The advancement of automotive technology developed with progression in driver assistance. Advancement in this field increased at spectacular rates - details progression. In 1968 the first, electronic cruise control was invented, in 1995, Mitsubishi Diamante introduced laser based adaptive cruise control. Later, Nissan introduced lane departure warning system - 2001, Toyota Harrier with pre-crash mitigation system – 2003 (Michalke et al., 2018).

With the introduction of the DARPA Grand Challenges in 2004, automotive industry took a turn to its biggest cusp. DARPA (Defence Advanced Research Projects Agency) challenge originated along with the research groups study for driverless vehicles. The challenge was introduced to emphasise the development of a full autonomous ground vehicle which is suitable for completing an off-road course within a time limit. The agency cordially invited major companies and research organisations each year of the challenges – 2004/ 2005/ 2007. New and advanced technology had been presented every year succeeding innovative autonomous systems (Thrun, Montemerlo et al. 2006). The Figure 2.5 below details some of the progressions of the technology for driverless vehicles: (DfT, 2015)

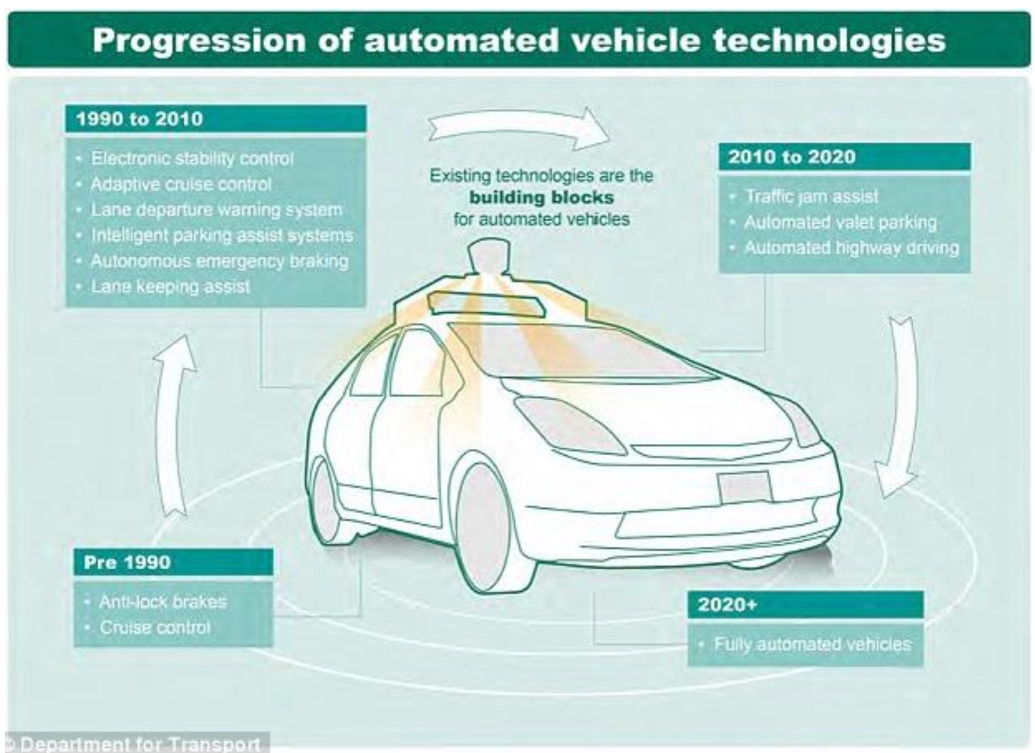

Figure 2.35: Evolution of driverless technology (DfT, 2015)

Ever since the challenges had started, various companies have considered the issues and have evaluated the benefits of overcoming the challenges. Car manufacturing companies are readily evolving to address the matter - to develop the technology to create advanced automated vehicles for commercial road use. Companies like Nissan (IDS autonomous electric) and Tesla (autopilot mode) are newly making high achievements in the field.

In the current industry, the google car (formerly known as the Google Self-Driving Car Project, Waymo LLC is now established under Alphabet as a self-driving technology company) among others feature leading efforts, consisting of various new and improved technologies allowing full automation. In accordance with the Society of Automotive Engineers (SAE), the google car ties in with Level 5 of automation (SAE 2019). It is currently still being tested under road conditions and soon enough, will be out in production. Some of the on-board equipment's in the Google car are illustrated in Figure 2.6.

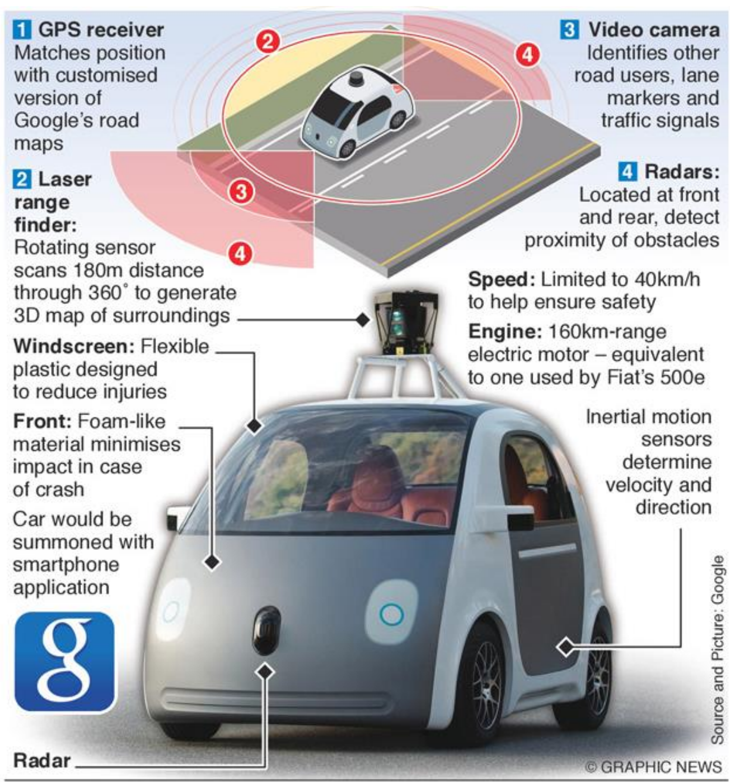

Figure 2.36: Googles self-driving car (Bou, 2014)

Researchers have been focusing on development of sensors, controllers, actuators, vision system, software etc. These parameters will be discussed in the subsequent sections.

While the DARPA Challenge remains the major demonstration of autonomous vehicle technology to date, it excluded many capabilities and requirements critical for actual city driving. It has been suggested, for a true multi-class fleet of autonomous vehicles, where each class of vehicle would be selected depending on the intended environment, would widen the possibility for all types of commuters whether it be young, elderly or a disabled individual.

Wheelchair systems has shown a significant development in the recent years, a few numbers of studies focused on the scooter type vehicle and its autonomous development while the recent high demand of it (Figure 2.7). Started with semi-autonomous scooters that aim to assist disabled people while driving this scooter and provide a Collison-free algorithm (Sato et al., 2011). Then, using Suzuki Motor Corp., a Japanese team developed a fully autonomous scooter to participate in the Tsukuba Real World Robot Challenge (Date and Takubo 2020). This study focused on the improvement of the obstacle avoidance system and used a traditional look-ahead path following strategy. The stability of this system depends on the right selection of the target point (Hirai, 2012).

Amongst the latest technology, the release of the new fleet of self-driving scooters will create solutions to many issues previously seen as the root cause of rejecting mobility on demand scooters. The newly improved fleet of autonomous scooters navigate to designated areas where essential services may be carried out till a new user request it. This ground-breaking innovation paves a new range of possibilities for the mobility on demand sector for scooters. Companies such as ‘Go X’ and ‘Tortoise’ have begun the journey to create publicly viable scooters on demand.

Another study focused on the safety of the scooter which developed a mobility on demand function, where a user can order the vehicle using an online booking service. The scooter would pick-up the user from an agreed location and drop-off at the desired location. This system used high-cost compact Gigabyte BRIX Pro computer and multiple LIDAR sensors to localize the vehicle within the surrounding obstacles. The planning system consist of three layers, mission planner, behavioural planner, and local planner. The system integrated the use of path tracking, pure pursuit algorithm and PID controllers with feed forward compensation (Andersen et al., 2016). Subsequent sections detail some of the essential technology.

Figure 2.37: Mobility on Demand – Autonomous Personal Mobility Scooter by MIT (left), Self-Driving scooter (right) (Andersen et al., 2016)

2.3.1. Hardware Sensors

An autonomous system itself is defined as a device that is “capable of performing missions on its own” (Meyrowitz et al., 1996). Hence, a system which can process data and act accordingly to gathered data without the intervention of a human. For an automated system to function, some certainty for sensing, likewise for planning must be viable for automated systems to act. This can be clarified by the robotic paradigm of how a robot operates. Three primitives of robotics being Sense, Plan, Act, describes how sensory data gets processed and distributed through a system (Arkin, 1998). The devices which brand autonomy include sensors to sense the data, controllers to gather and plan, actuators to make the action happen.

The controller diagram illustrates the process:

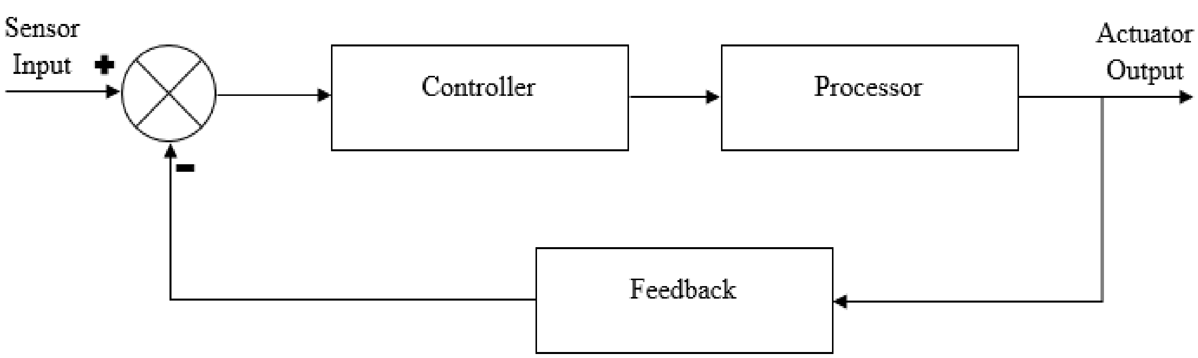

Figure 2.38: Example controller circuit of a sensor actuation system (Aström, 2010)

2.3.1.1. Video Camera

A video camera is an electronic motion picture acquisition method. In driverless cars, it is used to detect traffic lights, read road signs, and keeps track of other road vehicles, while also looking out for pedestrians and other obstacles. The information gathered from the surroundings is used to control the car on the road. Road markings and other parameters are processed in comparison with other collected data (Rayej, 2013).

2.3.1.2. Light Detection and Ranging (LiDAR)

Prior to making any navigation decisions and using sensors to acquire data measurements, the vehicle itself must first build a map of its environment and precisely localize itself within that map. Frequently used sensor devices used for map building are cameras and range finders.

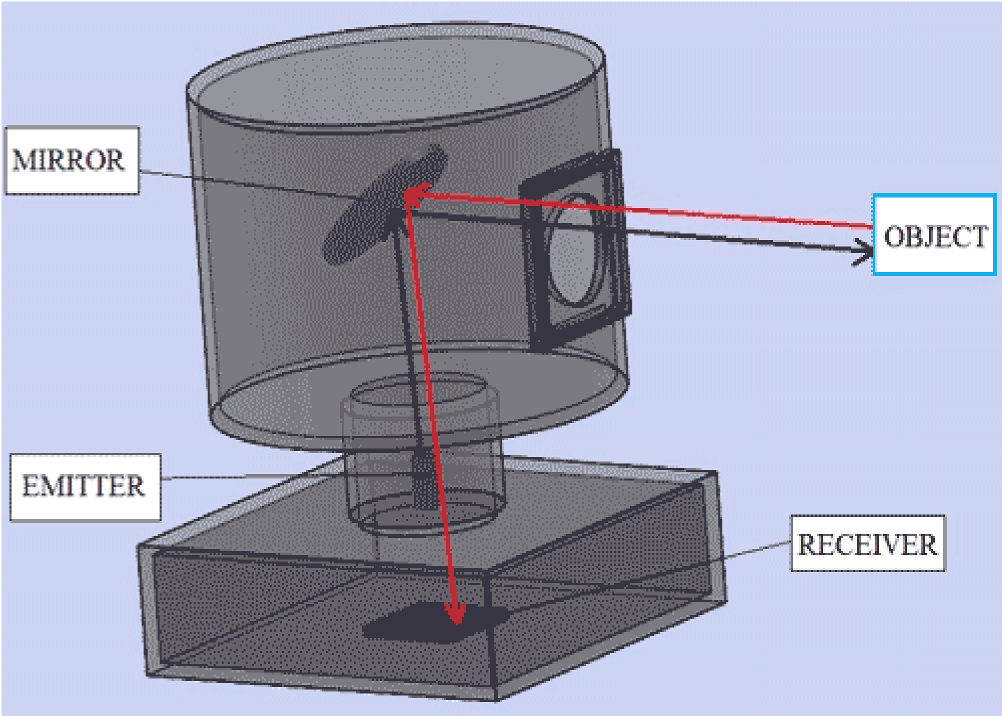

Figure 2.3: Simplified diagram of a LiDAR (Vallabhaneni, 2018)

Light Detection and Ranging (LiDAR) is a remote sensing technology used to measure distances - like RADAR technology which emits radio waves to calculate the distance to an object by the delay in transmission/ receive process. In comparison, LIDAR uses the properties of scattered light for measurement in the form of pulsed laser beams. These pulses of light generate accurate and precise, three-dimensional arrays of information about the shape of the surrounding surface characteristics. NASA has identified LIDAR instruments as key for enabling precise autonomy for safe landings (Amzajerdian et al., 2011).

For accurate readings and view of 360° surrounding; LIDAR sensors are usually mounted on the roof of a driverless vehicle - among the most important pieces of equipment on the vehicle.

The LIDAR consists of an emitter, mirror, and receiver. The emitter sends out a LASER beam that bounce off a mirror that is rotating along with the cylindrical housing at 10 revolutions per minute. Distances to nearby objects are measured using the time it takes for each laser beam to travel to the object and back. The returned laser beam reflects of the mirror and is bounced back towards the receiver, where it can be interpreted into data. Using this information, the vehicle can then generate a map of its surroundings and use the map to avoid objects. The Figures 2.9, 2.10 illustrates detailed functionality of the sensor (Vallabhaneni, 2018).

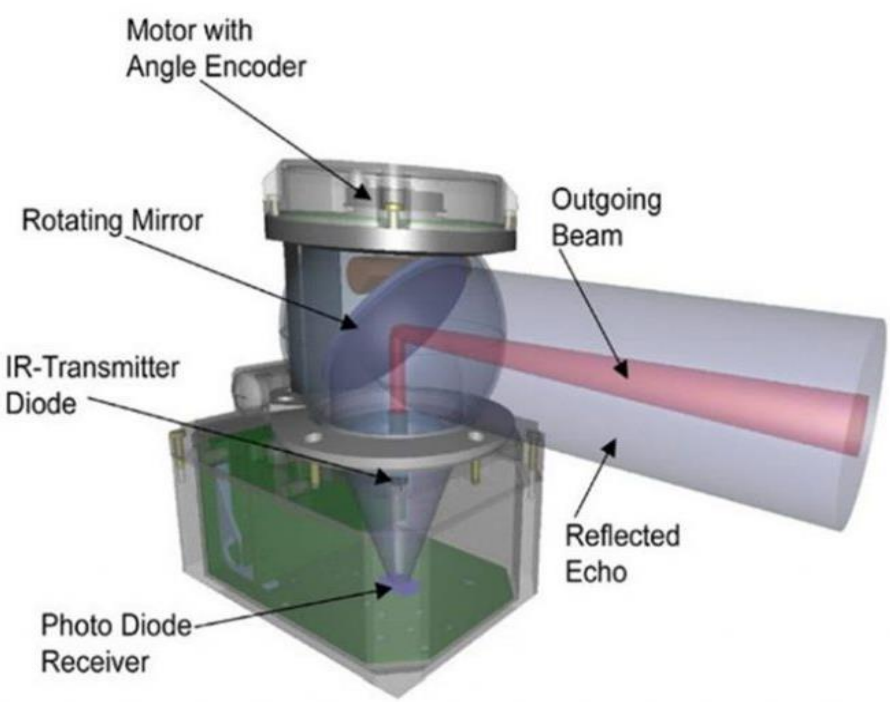

Figure 2.310: How a LiDAR sensor operates: Infrared scanner – The base of the robot cars sensorium, providing signals that help to compute virtual 3D environment image.

An advantage of laser rangefinders is that depth information is readily available to the vehicle for building a three-dimensional map. However, it is difficult to obtain accurate distance readings greater than 100m away using most state-of-the-art laser rangefinders, which limits the amount of reliable data that can be captured in the map. Therefore, the vehicles must filter the information received. Using sensors, aggregates of information create a comprehensive map used for path planning. In addition, a video camera assists in extracting scene colour which is crucial for various computer vision tasks, such as object detection, lane tracking, and obstacle recognition (Rayej, S., 2013).

For the self-driving vehicle to navigate its precise location, combination of three independently operating technologies would be evident. By using GPS, inertial navigation units and sensors, the vehicle estimates where is in relation to other surrounding objects. Though, estimates of the location off by several meters due to signal delays caused by several other factors. This may be caused by atmospheric changes, buildings and surrounding terrain, leading to accumulative error overtime from inertial navigation units. Localization algorithms provide a solution to this issue by integrating maps and sensor data collected from the same location. Through map matching, these algorithms align real-time sensor data with pre-existing maps, correcting errors, and refining the vehicle's estimated position. Sensor fusion techniques combine information from diverse sensors like GPS, lidar, and cameras, utilising filters such as Kalman filters to smooth noise and improve reliability. Loop closure events, where the algorithm recognises previously visited locations, further contribute to error correction and accuracy. Additionally, online map updating accommodates dynamic environments, allowing the algorithm to adapt to changes and maintain precise localisation in evolving conditions. This integration of prior data significantly reduces uncertainty, making autonomous vehicles more adept at navigating complex and changing surroundings (Rayej, S., 2013). An example of a generated map is illustrated in the Figure 2.11 below.

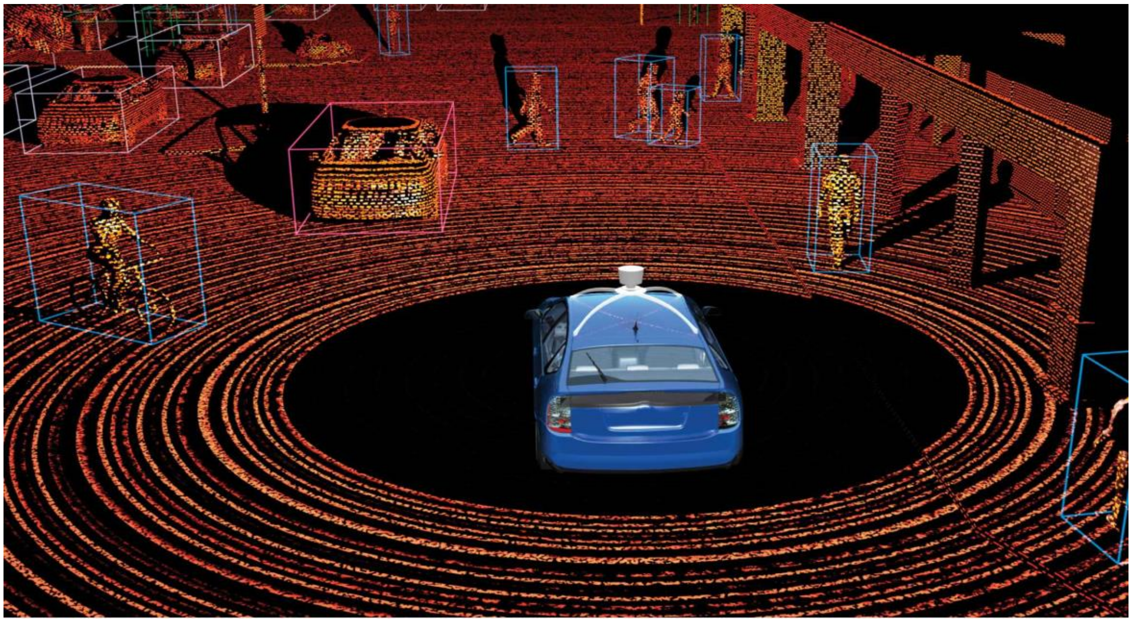

Figure 2.311: How a self-driving car sees the world using LiDAR technology (Fisher, 2018)

2.3.1.3. Distance Sensors

High performance distance sensors are used in driverless cars to detect measurements of distance and speed, at which the object is moving. By transmitting pulses of electromagnetic waves that bounce of bordering objects, the sensors return analogue signals of data. The voltage of the return signal determines proximity. These types of sensors are reliable for long term uses as there are no physical contacts with the sensors, yet exceptionally reliable readings can be obtained; within range (Thrun, 2010).

Varied types of sensors are on offer for the application. Current automotive market includes the technology in luxury cars for assistance in active intelligent cruise control systems.

2.3.1.4. Position Estimator

Position estimators are used to track the movement and determine vehicle location. Ultrasonic sensors mounted on exterior sides of the vehicle assist in monitoring movement of the car as well as updating information instantaneously, allowing up to date position of the vehicle on the map.

2.3.1.5. GPS

To locate and give guidance to a driverless vehicle – a navigation system must be evident. A map used as reference to move without human intervention.

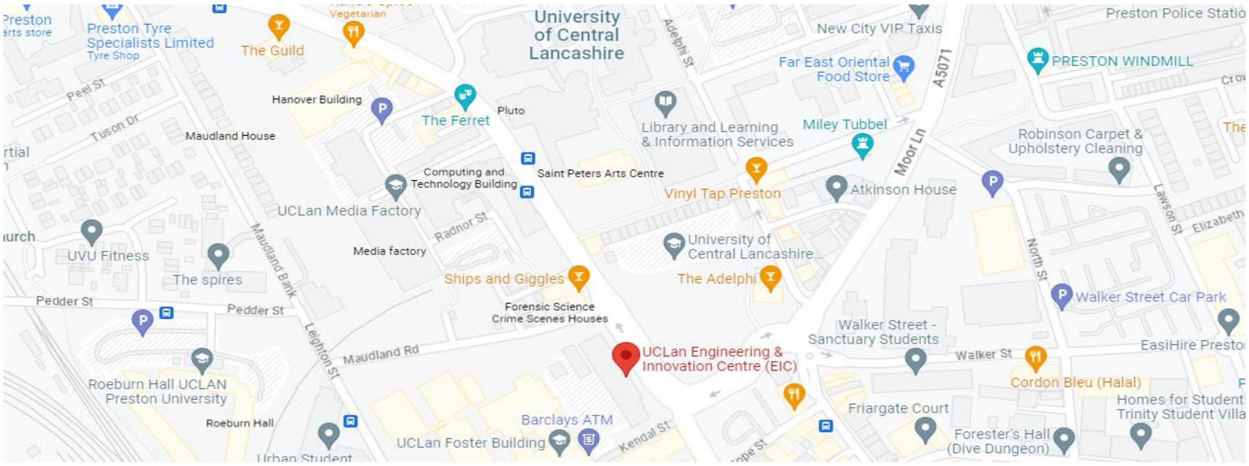

Figure 2.12: Localised Google Maps Image

GPS (Global Position System) is a course-plotting system developed by the U.S military. Initially intended for military use, it was later publicised for commercial use. It works in any weather conditions, 24 hours of the day, all over the word. It has been the greatest advancement in the way of navigating. Using satellite-based information, made up of a network of 24 satellites placed into orbit by the U.S. Department of Defence – GPS provides accurate location (Bajaj et al., 2002).

In Google's driverless car, Google Maps interacts with GPS to provide accurate location (Figure 2.12). It also acts as a database with real-time embedded data. Range of information regarding oncoming traffic, collisions (if any), reroutes etc. are available with the Maps. In addition, speed limits are integrated within the maps which control the speed of the car, depending on the terrain and road conditions. Google cars overall is directed by the Maps without any human intervention. The real-time information gathered is processed and put into action (Thrun, 2010).

2.3.2. Processor

As mentioned in preceding sections, with the gathered information by the sensors, a processing unit plans the action/ direction of travel for a driverless vehicle.

The processor cross-checks all the obtained measurements from the different sensors - this procedure ensures different obstacles or objects are dealt with accurately to make sure collision avoidance driving is accomplished. Collation of various sensor devices deployed to work effectively for the given task gathers the data. Strong software manipulation allows processing the data acquired through the sensors. The processed data hereby enables completion of tasks through actuators. In addition, Artificial Intelligence (AI), is a key component that determines the function of the driverless vehicle; accountable for speed, the acceleration, breaking, steering control etc. The aim of AI is to direct the car through the course of travel from departing to arrival at desired destination safely, legally and on time (Thrun, 2010).

2.3.3. Actuator

From the robotic paradigm to sense, plan, and act; actuators are the last step - to perform an action from the sensed data and processed plan.

A device which is responsible for moving or controlling a mechanism is a type of actuator. Based on the information fed from the sensors, the software-based control unit transfers a signal to the actuators, which in turn control the vehicle. Also, real time information of the surroundings is output to the user interface located inside the vehicle.

Some of the actuators expected to find in driverless cars include Servo Motors, Relays, Steering wheel control, Brake control, Throttle control, user interface etc.

Preceding sectors in this review explains the various technologies used in driverless vehicles. The Figure 2.13 illustrates these devices implemented on a self-driving car.

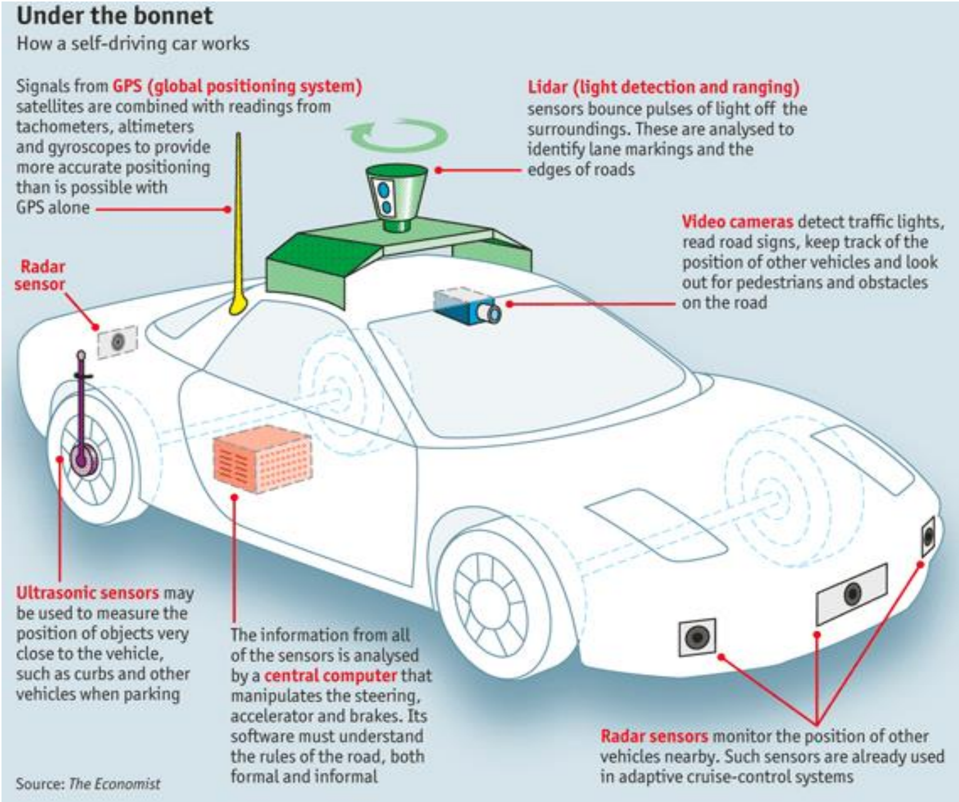

Figure 2.313: How a self-driving car works (Bou, 2014)

In correlation with the health and safety levels set by SAE, the safety of passengers reflects on how safe and reliable any vehicle is in which commuters travel. An area which this thesis focuses on, is the safe operation of the steering systems. Manoeuvrability and deterioration of steering based elements is a field which needs further consideration as it cannot be neglected. Especially as the degree of automation in these mutually exclusive levels increases on a gradient, with Level 0 featuring absolutely no automation, and Level 5 featuring all dynamic driving tasks performed by the vehicle i.e., at level 5 automation, where a user of such vehicle becomes more of a passenger than an owner, certain mechanical aspects could be neglected. Such that a deteriorating wheel bearing, or wheel misalignment could influence the performance of the vehicle. Such elements require continued monitoring as part of an advanced vehicle management system.

2.3.3.1. Wheel Alignment

Wheel alignment is a crucial factor to any vehicle. It is vital for driverless vehicles to ensure precise navigation, accurate sensor data, optimal energy efficiency, enhanced safety, longevity of components, and consistent performance. These factors collectively contribute to the reliable and efficient operation of autonomous vehicles in various driving conditions.

The term alignment refers to an adjustment of a vehicle's suspension. No adjustments are made to the tyre or wheels themselves but to the wheel to vehicle linking system. The angle at which the tyres contact the road surface is fine-tuned to achieve successful alignment. The combination of three major alignment parameters are Camber, Caster and Toe.

Camber

Camber angle as illustrated in Figure 2.14 is the inward or outward slant of the wheel when viewed from the front of the vehicle. Negative and positive camber, respectively, refers to too much inward or outward tilt. It indicates improper alignment and will need to be adjusted. Worn bearings, ball joints, and other wheel-suspension elements may contribute to camber misalignment.

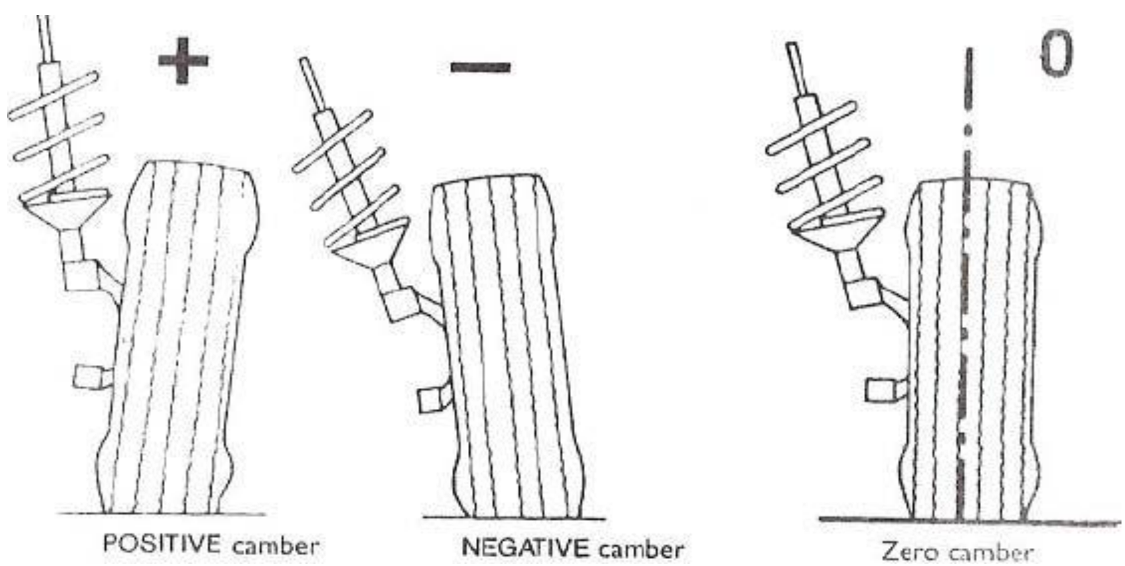

Figure 2.314: Diagram illustrating various camber angles. Positive Camber: the bottoms of the wheels are closer together than the tops. Negative Camber: the tops of the wheels are closer together than the bottom. Zero Camber: the tyres are straight, perpendicular to the road and parallel to each other (Esfahani et al., 2010)

Caster

In the steering mechanism, the wheels rotate around a pivoting point. The caster angle is the angle between the vertical axis of the steering pivot and the centreline of the wheel/tire assembly as shown in Figure 2.15.

Positive caster means the steering axis tilts towards the driver and negative caster tilts forward towards the front end of the vehicle. Correctly positioned caster angles contribute towards well balanced steering, stability, and cornering.

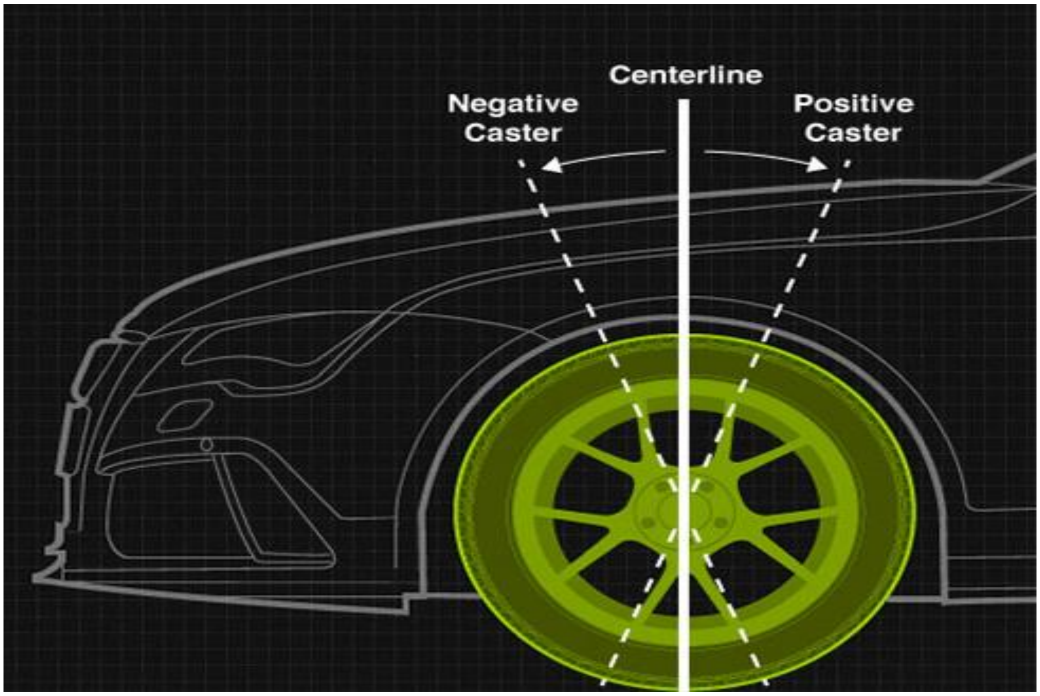

Figure 2.315: Caster Angles (Donkiespeed 2018)

Toe

Toe is the measure of how far inward or outward the leading edge of the tire is facing, when viewed from the top, illustrated in Figure 2.16. Toe is measured in degrees and is generally a fraction of a whole degree. It has a large effect on how the car reacts to steering inputs as well as on tire wear. Ideally, 0˚ toe angle would give minimum wear to the tyre. Aggressive toe angle will cause the tire to develop feathering across its surface.

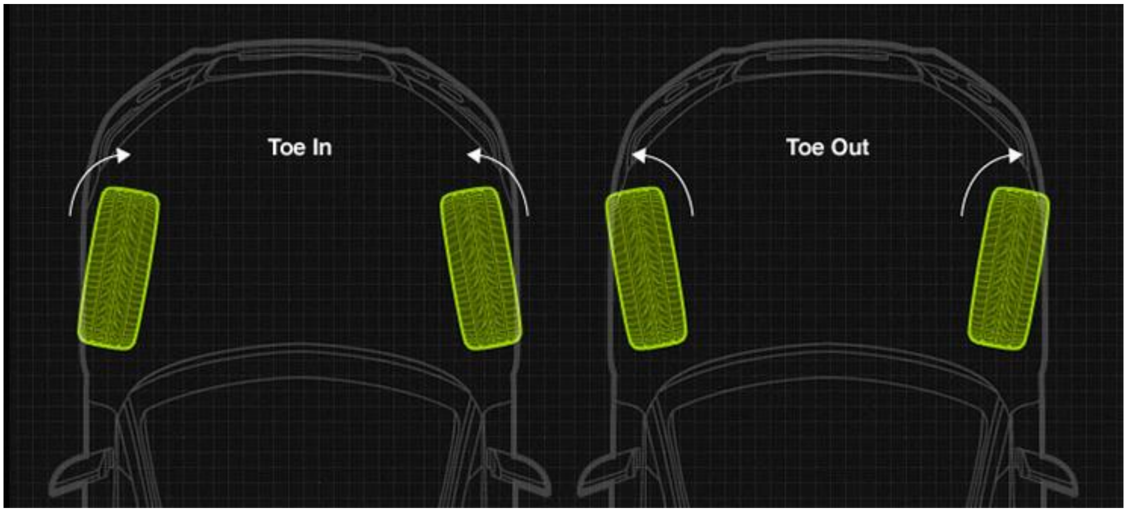

Figure 2.316: Toe In/ Toe Out (Donkiespeed 2018)

To improve vehicle performance, each manufacturer specifies some pre-determined angles to the wheels of their cars. These angles may undergo considerable variations over time, resulting in excessive tyre wear. A routine wheel alignment procedure is imperative. These optimised settings allow better and longer lasting performance from tyres and other consumable parts. Additionally, improve handling of the vehicle, reduce tyre wear, steering wheel returnability and cornering performance. On the other hand, improper alignment can cause tyres to wear prematurely and unevenly. The Figure 2.17 below illustrates some of the drastic results from unmonitored tyre wear along with explanations for its cause.

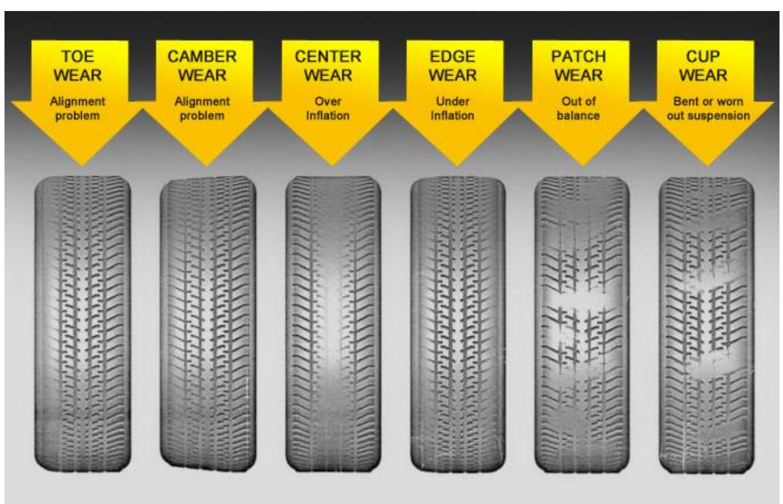

Figure 2.317: Common Types of Tyre Wear and Its Cause (*PitStopArabia (2019)*

Additionally, uneven tire wear, wheel wobble, ABS failure, vehicle pulling to one side, steering wheel vibration, and excessive play in the steering are all possible indication of a defective wheel bearing.

As mentioned earlier, the steering system is a sophisticated mechanism that is intended to work in conjunction with other subsystems of a vehicle. Wheel bearings play a vital role in the vehicle's braking, steering, and suspension system, as they allow the wheels to turn smoothly. The one-piece hub assembly integrates the wheel bearings, ABS wheel speed sensor, and mounting flange and is situated between the drive axle and brakes. A monitoring system that regularly inspects the conditions of the steering system and its associated components are essential to ensure the reliable and safe performance of autonomous vehicles.

The bearings themselves are tightly packed in a grease-filled, waterproof, sealed housing. This housing is a sealed metal ring, often referred to as a race, and located inside the hub of each wheel. Wheel bearings have been engineered to sustain the entire weight of the vehicle. Figure 2.18 illustrates the full assembly.

Figure 2.318: Wheel hub/ bearing cutaway (Source: FAI Auto)

Theoretically, the life of these bearings should surpass the life expectancy of the vehicle. There are no planned maintenance schedules for replacing wheel bearings, nor is there constant source of lubrication. Hence, they are prone to damages. They are especially vulnerable if driving conditions are poor. i.e., potholes, tall curbs, speed bumps etc. may reduce the likelihood of wheel bearing life expectancy. Additionally, if water, mud, road salt or sand get past the seal and contact the bearings, it will contaminate the grease, causing the bearings to prematurely wear down, eventually leading to failure. If worn/ damaged wheel bearings are ignored, it may lead to further complications in vehicles. Replacing damaged wheel bearings can be expensive due to components cost and labour.

If signs of failures are ignored/ unmonitored, one scenario could be such that, whilst travelling along a motorway, suddenly, the tire and wheel could break off, sending the vehicle out of control and risking lives. Especially in driverless vehicles, as levels of automation increases, whereby all dynamic driving tasks are carried out by the vehicle itself, passengers would be oblivious to such indicators, leading to putting lives at risk.

2.4. Vehicle Management System

Driverless vehicles have advanced technological features that enable them to operate without human intervention. These additional capabilities necessitate an advanced control system that can manage them effectively. As the number of devices used in a driverless vehicle increase, the complexity of the management system required also increases. The idea of a vehicle management system was initially developed in the aerospace industry, where system and component failures can have significant financial and safety implications. The key feature of a vehicle management system is the ability to monitor the health of its own systems and take proactive measures to schedule maintenance as needed. This type of system can improve the reliability and lifespan of a vehicle while reducing the likelihood of unexpected failures. (Jennions, 2013).

In the recent years, assistive electronic systems have made a tremendous effort in automotive safety. Cars today rely a great deal on electronic systems to compensate for driver error and on the road abnormalities. Some of these intelligent systems include Electronic Stability Control (ESC), adaptive cruise control, collision avoidance mitigation, lane change assist and blind spot detection.

As automotive industry relies more on these intelligent systems for passenger safety, increased efforts to ensure the reliability of these systems is vital – as the intended use of the safety features must readily be available 100% of the time. Redundancy systems in automotive vehicles are lower than other systems. In comparison, aerospace systems have multiple redundancy checks, which cover every aspect of the system. An automotive system relies heavily on singular components to work effectively. Thus, in the occurrence of a failure, fail in a safe manner. This creates a huge risk in an automotive system, as a failure is much more likely to disable the whole vehicle. This elaborates based on a vehicle management system (Jennions, 2011).

Integrated Vehicle Health Management often abbreviated as IVHM is the unified capability of a system assessing the current or future state of each individual system to monitor its operational demand (Jennions, 2011). A vehicle management system acts as a primary controller with links to other sub-system controllers. All Electronic Control Units (ECU) communicating through complex buses such as the Controller Area Network (CAN) and gateways. The aims of IVHM are improved management of a vehicle and expand its safety through better maintenance scheduling, use of diagnostics and prognostics software to fix faults before they occur. Both hardware and software elements would be embedded in the vehicle's sub-systems for maintenance operations, providing real time feedback of life cycle and health information. Subsequently, up to date knowledge of the state of the vehicle will be continuously databased aimed at critical failures for condition monitoring (Gorinevsky et al. 2010).

Condition monitoring (CM) is the process of monitoring the state of a system to detect negative distortion. The parameters of CM vary depending on the application; to measure vibration, temperature, noise etc. The main function of condition monitoring is to provide the knowledge of the condition of a system and its rate of change with respect to time. The graph below (Figure 2.19) elaborates (Rao 1996).

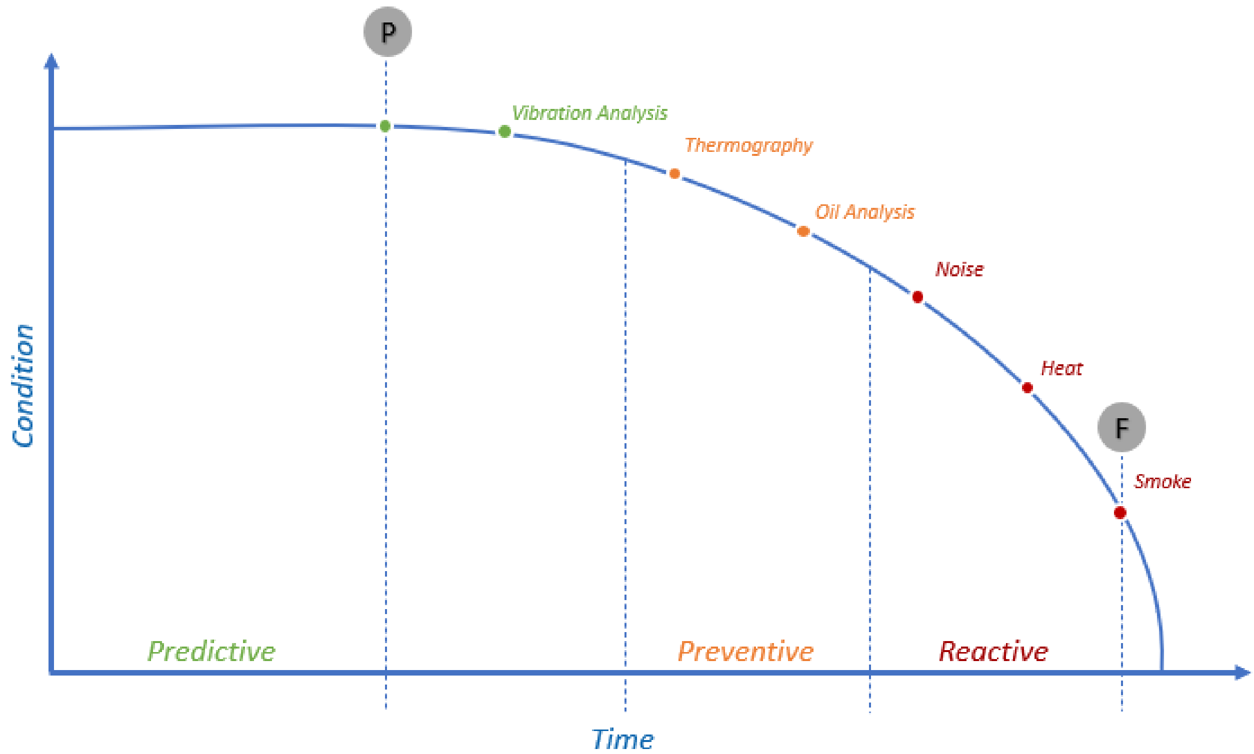

Figure 2.419: The warning signs of machine failure - using a machine condition monitoring system

P = Point at which you recognise a potential failure

F = Point at which the failure occurs

Noticeable failure in mechanical devices initiate through vibration. This is an indication to the condition change of a system, notifying a failure may occur if not addressed or lack of scheduled maintenance is in place. Furthermore, Acoustic Emission (AE) is the advancement of failure from vibration. Overheating of a device the cause of friction, part misalignment and/or improper lubrication applied to a mechanical surface. If maintenance is not carried out immediately, this can lead to detection of smoke. Presence of smoke is one of the last indications to part failure, therefore, the system must be shut off instantly. Otherwise, severe damage would be evident. If all parts were to fail in such a manner without any condition monitoring or adequate maintenance procedures in place, loss of money, downtime, efficiency in production would all be affected (Bodensohn, et al. 2005).

For a self-driving vehicle's maintenance strategy, predictive maintenance is necessary. Unlike reactive or preventive maintenance, Predictive Maintenance (PM) techniques calculate the state of in-service systems in advance, to predict when maintenance must be performed. This approach leaves maintenance strategies to be performed only when it is essential. This type of maintenance is suitable for applications that have a critical operational function (Mobley 2002).

In addition, predictive maintenance and enough intelligence incorporated within IVHM for driverless vehicles leads to rapid recognition and corrective conditioning. As a result, a coherent system would be in place with minimised failures and reduced costs in maintenance through avoidance of unscheduled or excessive maintenance (Gorinevsky et al. 2010).

Typically, IVHM systems are more so used in airborne system. Figure 2.20 below illustrates the technique used in the system; denoted by the sequence: sense – acquire – transfer – analyse – act. The gathered information via the sense elements gets processed. Hereby, data is fed into the operational controller where decisions are made. Decisions are analysed by utilization of knowledge provided from condition monitoring techniques (Jennions, 2013).

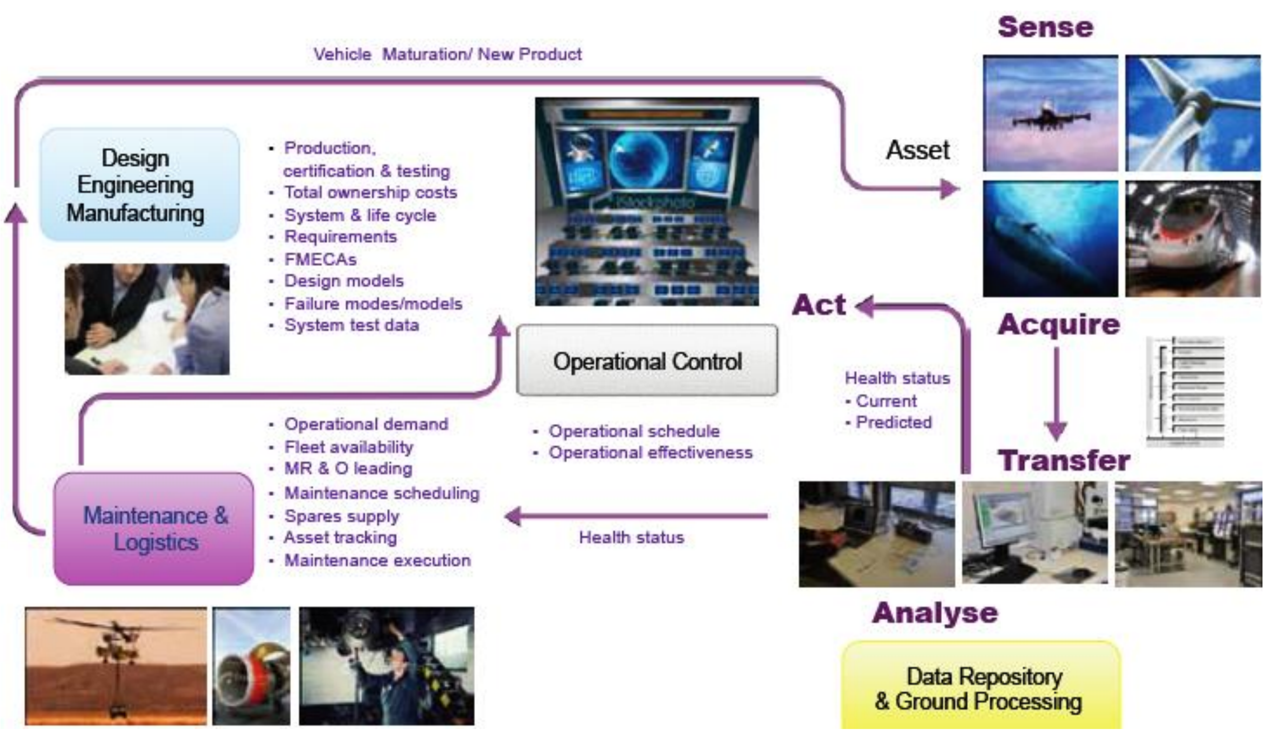

Figure 2.420: Information flow within IVHM (Jennions, 2011)

The concept of IVHM is to address the complete life cycle of a vehicle and not just the current conditions. The system makes full use of embedded sensors with links to other monitoring devices combined for prognostic and diagnostic reasoning. Constant monitoring of the health of the vehicle is maintained and data is processed. The usage of the vehicle can also be matched to the degradation of parts and improve the prognostics prediction accuracy. Moreover, plans for replacements and repairs of parts are made convenient prior to failure. Through maintenance scheduling techniques, optimum timing prior to failure for part repair is achieved. Risk of sudden failure and cost of unscheduled maintenance is eliminated in the process.

2.5. Intelligent System

Artificial intelligence (AI) is the recreation of a human brain. It is defined as the "science of making machines do things that would require intelligence if done by humans" (Jain, Silva., 1998).

Referring to the different generations of computing devices, Artificial Intelligence (AI) is the fifth generation of computing which is still under development. These generations represent major steps in computer development, with each bringing smaller, faster, and more powerful machines. Starting from technology based on vacuums, transistors, ICs, microprocessors, AI and heading towards quantum computing.

Some of the major branch's AI has links to are vision systems, robotics, expert systems, neural networks etc. The goals of AI being to develop devices that can respond naturally, yet, have the capabilities of learning and self-organising. The human brain has features which include pattern recognition, association, complexity, noise tolerance and so much more. Parts of these should be made artificially to recreate intelligence in machines using calculations, precision, and logical operations (Kröse et al., 1993). AI has been used in a wide range of fields including medical diagnosis, stock trading, scientific discoveries, and robotic control. Several methods are used as important tools for the field of intelligence which can learn, adapt, and make decisions on their own (Jain, Silva., 1998). The following sections cover some of the concepts of these methods which are used to replicate human intelligence in machines.

2.5.1. Fuzzy Logic

Rather than the generic "true or false" represented by Boolean logic on which modern computers are constructed, fuzzy logic is the method of computing-based degrees of truth. Essentially, meaning the outputs can have continuous values rather than discrete and concise (Yager, Zadeh 2012).

The idea of fuzzy logic was first advanced by Dr. Lotfi Zadeh of the University of California at Berkeley in the 1960s. He established the method whilst working on a computer problem which could not be represented by an absolute value (1 or 0). A state in between these parameters changes the whole case (Rojas, 2013). Fuzzy logic opened a gate way for situations other than extreme cases of truth where 1 or 0 can be used to represent states of approximate truth – rather than long or short, 0.63 of length (membership functions μ). This allows the description of the behaviour of a system to be dealt with mathematically. Definition for the fuzzy set (A) in the universe X in equation: (Jain, Silva., 1998)

$$A = \{(x, \mu_A(x)); x \in X, \mu_A(x) \in [0,1]\}$$

Where $\mu_A(x)$ is the associate function representing *A*. This function characterises the grade of possibility that an element – denoted as x - belongs to set *A*. The closer this function ($\mu_A(x)$) is to absolute truth (Boolean logic '1'), higher the possibility x is considered to belong to set *A* and vice versa.

To provide informative feedback and for the purpose of monitoring the condition of a system, these different fuzzy model types have been applied to sensory fusion algorithms. A fault detection index has been developed by a fusion approach based on fuzzy logic using the Sugeno model type interface. This system developed by (Boutros, Liang 2007) could link information from four monitoring indicators.

(Ruan, Wang 1997) grouped fuzzy models into three main types based on the following parts:

Table 1: Grouped fuzzy model types

Types of Models	Mamdani model	Tagaki – Sugeno – Kang model	Simplified model
Mathematical Equation	$y = A$	$y = a_0 + \sum a_i x_i$	$y = c$
Definition	A is a fuzzy number	a_i is a constant, x_i is a variable	c is a constant
Description	Defined by membership function. Applicable for knowledge processing, expert systems	Linear combination of weighted input variables, suitable for indirect fuzzy control	Combination of both types, consequent parts are expressed by constant values

Adopted from (Jain, Silva., 1998)

An intelligent condition – based maintenance system was developed using adaptive Mamdani-type fuzzy model by (Kothamasu, Huang 2007). The system is split by four sectors, to be precise: data acquisition, feature extraction, model generation and model deployment. Its functionalities are useful in condition-based applications for predictive maintenance. Figure 2.21 below illustrates the model of a simplified fuzzy logic system.

Fuzzy logic signifies close representation of how a human brain works. It is an adequate artificial intelligence (AI) method that can be used to gather information from several measurement techniques. Humans accumulate data and form several partial truths which we aggregate further into higher truths which in turn results in an outcome. Fuzzy logic follows this principle. A similar kind of process is used in artificial computer neural network mentioned below (Jain, Silva., 1998).

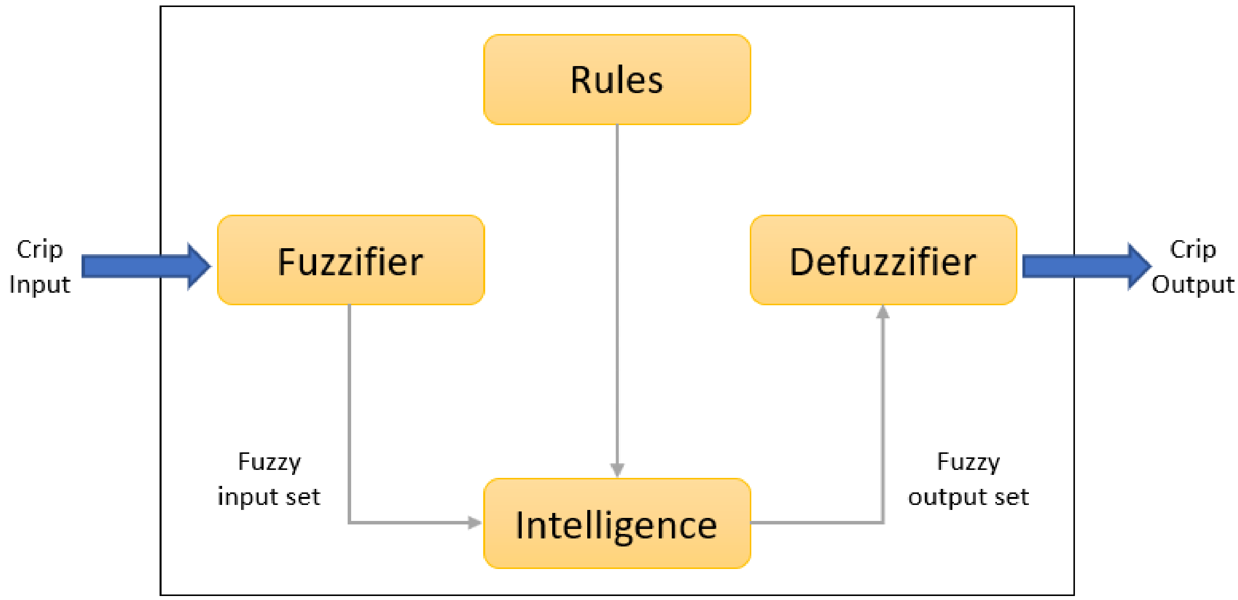

Figure 2.521: Fuzzy Logic System Block Diagram

2.5.2. Artificial Neural Network (ANN)

An artificial neural network is the attempt of recreating a processing system inspired by the biological nervous system. ANNs are used to represents a complex nonlinear function by training a massively connected network of highly interconnected processing elements (neurones) working in unison to solve specific problems. The way in which an ANN functions is by learning the problem by trial and error. The functionality of it is such that it does not process the signal directly, instead, it compares the information gathered from a healthy system and a faulty condition to be pre-processed. Hereby, these features are used to model a systems non-linear behaviour (Stergiou and Siganos, n d).

For the ANN method, there are two main basic network architectures: feed-forward and recurrent:

Feed-forward network signals are unidirectional, from input to output. There is no feedback between layers and previous inputs are not remembered. They tend to be straight forward networks and are extensively used in pattern recognition.

Recurrent or feedback networks involve cognitive layers in between input and outputs. Previous methods can be used to reconstruct memory such as a Kohonen feature map. Feedback networks are immensely powerful and can get extremely complicated. Feedback networks are dynamic, and their 'state' is changing continuously until they reach an equilibrium point – until the input changes and a new equilibrium is found.

The feed-forward propagation network requires supervised training, achieved by providing a target output. The structure of the network working along in parallel means the functions of the neurons can be carried out at the same time. The layers of a neural network are split into three multiple layers: input layer, one or more hidden layer, and the output layer. The input layer acts as a data recorder, which receives the values of a data series from outside the neural networks and then constitutes inputs to the next layer. The hidden layer is the processing layer and eventually the output layer sends the results (Stergiou and Siganos, n d). Figure 2.22 illustrates the transition between the layers.

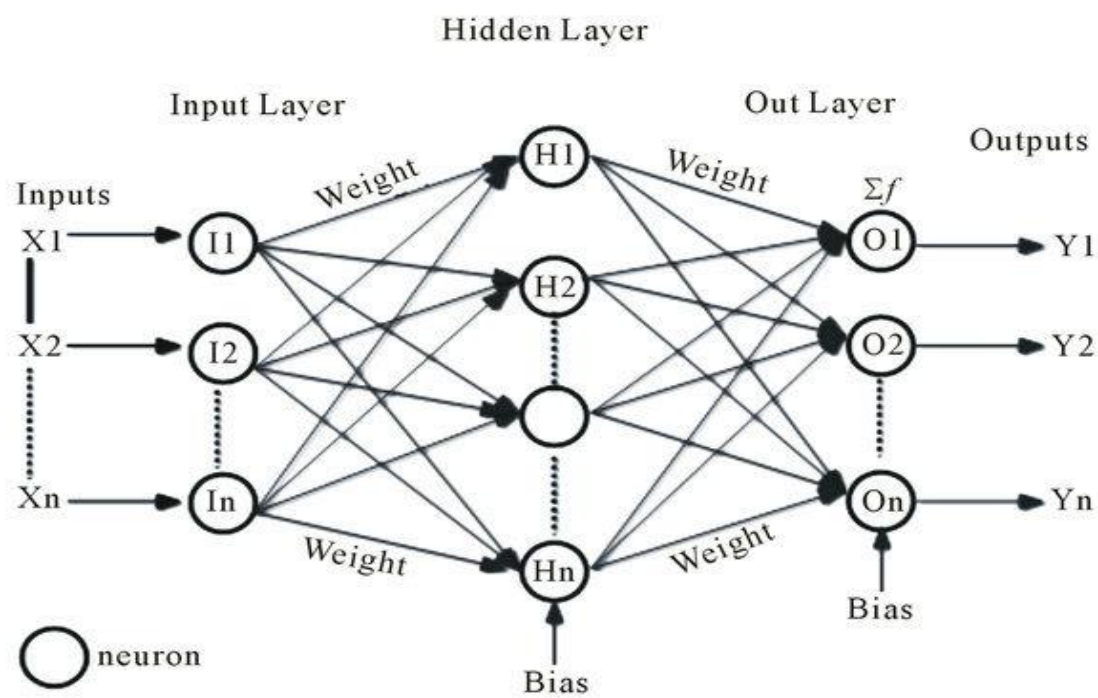

Figure 2.522: An example of neural network architecture (Stergiou and Siganos, n d)

The Kohonen feature map (Figure 2.23), otherwise referred to as Self-Organising Map (SOM) involves training similarly to the feed-forward network, however, unsupervised and determined by the network. It is a 2-Dimensional grid with nodes of input and output layers.

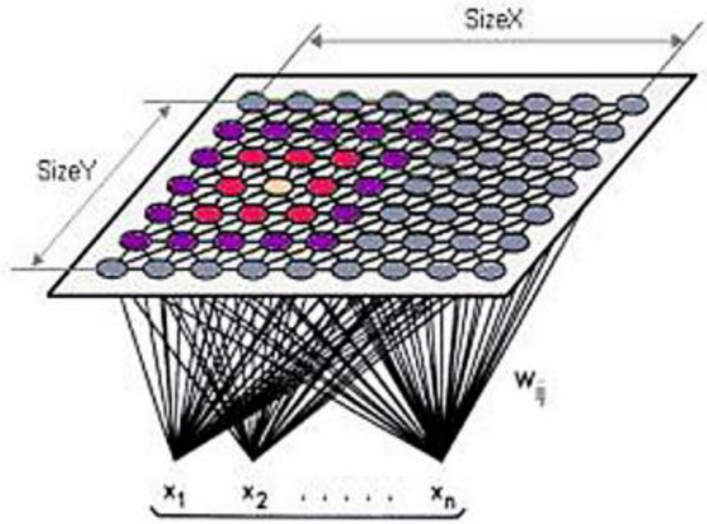

Figure 2.523: Kohoen feature map network (Gorjizadeh, Pasban et al. 2015)

Several researchers have included use of ANN to provide classification of failures in different applications. These include various sub-system applications such as gearboxes for various uses, monitoring of motor faults, bearings etc.

Li and Mechefske utilised both the feed-forward back propagation network as well as the Kohonen map mentioned above for monitoring motor faults. The study summarised feed-forward network contributed results of 99.5% accuracy. On the other hand, SOM classified faults during steady state running. Concluding the study, the authors revealed increase in number of neurons does not necessarily mean improved performances. Although, increase of training data set size increases the diagnostic performance (Li, Mechefske 2006).

2.5.3. Genetic Algorithm (GA)

Genetic algorithm (GA) is an experiential search based on a natural selection process that mimics biological evolution. This method is used for solving both constrained and unconstrained optimisation problems. The functionality of the algorithm is such that it groups a selection of individuals within the existing population and modifies repeatedly for individual solutions. At each step, GA randomly selects individual populates from the current selection and uses them to modify – similarly to the depiction of parents producing children for the next generation. Over successive generations, the population "evolves" towards an optimal solution (Rojas, 2013).

This sort of method applied to solve problems that are not well suited for standard optimization algorithms. Best suited for problems in which the objective function is discontinuous or cut off at some point (Whitley, 1994).

The table below differentiates the two main ways a genetic algorithm differs from a typical, derivation-based optimisation algorithm.

Table 2: Summary of a typical derivation algorithm and genetic algorithm (GA)

Classic Algorithm	Genetic Algorithm
Generates single point at each repetition process. The order of points provides an optimal solution	Population of points are gathered by each iteration - the best points are used to approach an optimal solution
Next point determined by calculation	Next step is selected at random generation by computation

Adopted from (Whitley, 1994)

2.5.4. Expert System

An expert system is an intelligent method which can emulate the ability of human decision making correctly in the absence of a human expert. It is defined as “a software system with high symbolic and descriptive information content, which can simulate the performance of a human expert in a specific field or domain” (Jain, Silva., 1998). In Figure 2.24 below, a typical block diagram for an expert system is illustrated.

User - This is the system that allows a non-expert user to question the expert system, and to receive advice. The user-interface is designed to be a simple to use as possible.

Inference Engine - These acts like a browser, examining the knowledge base for information that matches the user's query. The knowledge base is updated with relevant information.

Knowledge base - This is a collection of facts and rules. The knowledge base is created from information provided by human experts.

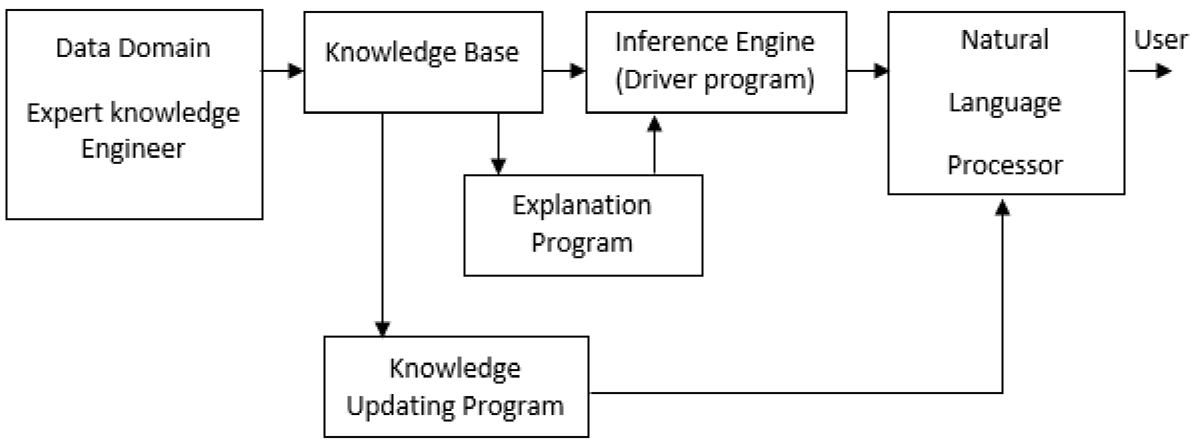

Figure 2.524: Example of a typical block diagram of an expert system (Jain, Silva., 1998)

Expert systems are used in applications to provide information regarding active system conditions. This method of intelligence has been applied to intelligent wind turbine gear box systems to provide knowledge about the maintenance and operation. Though, for a fully functional Intelligent Health Monitoring System (IHM), the need of extensive information regarding the state of the gear box required to use other AI methods such as fuzzy logic and neural network (Garcia et al., 2006).

2.6. Current Issues with Driverless Vehicles

The advance of the new driverless vehicle technology features major advantages for all road users. Safer, faster, more efficient journeys would be in practice with the implementation of road legal autonomous vehicles. Stressful journeys would be outdated. Long, tiresome commutes could be exchanged for productive intervals and a pathway for new sectors of road users will be present. Fundamentally change our transportation infrastructure and provide the opportunity to make our societies better – less dependent on oil, less-resource consuming, with less carnage on the roads and with more freedom for the old, young, and underprivileged (Anderson et al., 2014); an ideal mode of transport for people who have had trouble travelling by themselves previously.

The technology for driverless cars is advancing. Various manufacturing companies are releasing cars with advanced auto-pilot modes (Mercedes-Benz, General Motors, Toyota, Tesla, Audi, and more) and highway autonomy modes. Thus, Google has created a fleet of new fully autonomous cars which have no steering, breaking or acceleration controls where the car drives itself – Level 5 autonomy according to SAE's levels of automation (SAE, 2013). Though still under testing circumstance, Google's self-driving cars are now safe to be tested on multi terrains which include on the road testing. Autonomous vehicles are successfully completing kilometres of test course on urban roads. The complete driverless cars are obeying road traffic laws, dealing with other road users (cars, pedestrians, cyclists), negotiating right of way (Anderson et al., 2014). Despite these successive outcomes, substantial setbacks limit complete use of autonomous vehicles, for consumer use in on-the-road environments. These limiting factors cover some technical, ethical, and legal practices.

The UK is poling position for developing a driverless car. A review of the publishing 'The pathway to driverless cars' was coordinated by the Secretary of State at the Department for Transport. From the review, it was established that the UK is one of the best places in the world to conduct real-world tests of self-driving vehicles for the future. Because according to UK laws, having no restrictions to trials in test-tracks and the opportunity to practice driverless car testing, without any special permit are among the main highlights. As a result, anyone wanting to carryout tests for driverless technology has the right to do so, providing expected compliance of codes of practice are achieved, as well as abidance to the law and maintenance of road safety is consistent (DfT, 2015). Figure 2.25 are photos from tests conducted in UK.

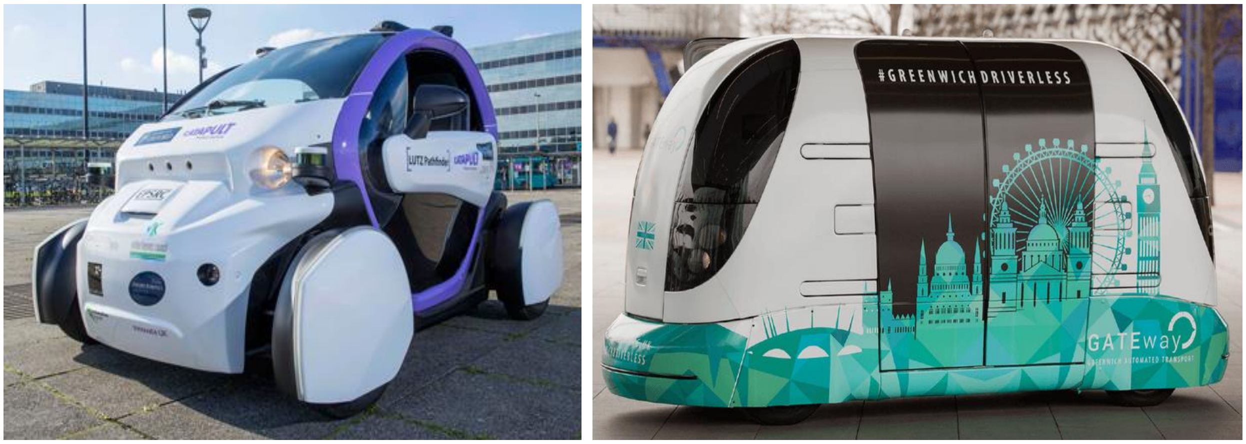

Figure 2.625: Driverless Pod - Milton Keynes Greenwich Automated Transport

Advancing with the international rate of technological advancement in the field, the UK is hoping to create opportunities for the pathway of driverless cars. Currently in the UK, advancements of research are being coordinated in the areas of:

- Safety & Integration (Greenwich) – enable industry, government, and society "to gain critical knowledge, safely accelerate innovation and deliver smart city integration" (DfT, 2015).
- Vehicles on roads (Milton Keynes & Coventry) - consideration of road safety as well as "feasibility from both a technological and societal point of view" (DfT, 2015)
- Legal/insurance (Bristol) – "investigate the legal and insurance aspects of driverless cars and explore how the public react to such vehicles."

In addition to the areas of research covered by the UK, other technical limiting factors include software issues, hardware sensors, mapping and communication and the transition between autonomy and driver take over. Additionally, ethical, and moral factors which leads to legal obligations and safety (Howard, Dai 2014).

Due to recent revelling of the Google car (fully autonomous) and advancements of driver assistance in cars, "the public seems to think that all of the technology issues are solved," says Steven Shladover, a researcher at the University of California, Berkeley's Institute of Transportation Studies. "But that is simply not the case." (Ghose, 2015).

Among several areas which need further advancement for a self-driving car, researchers suggest that the main element to driverless cars is relating to computer science? Currently there is no software which can fully function flawlessly without lag or crashing at some point – regardless, the device or how modern the technology is. If a similar error were to be evident in a self-driving car, the results could be fatal (Ghose, 2015).

Being the most advanced in the field, the way in which the Google's self-driving car works is by having both a backup driver and a second person as a monitor, who can shut off the system at the first hint of a glitch. But producing safety-critical, fail-safe software for complete driverless cars would require reimagining how software is designed. Shladover said "There is no current process to efficiently develop safe software," (Ghose, 2015). For instance, when Boeing develops new airplanes, half of their costs go to checking and validating that the software works correctly, and that is in planes that are mostly operated by humans. On land, there are much more obstacles and challenges.

Hardware implications of a self-driving car require effective technological devices. A self-driving car must be able to differentiate safe and dangerous situations prior to occurrence of such a situation. "Otherwise, it's going to be slamming on the brakes all the time for no reason," Shladover said, (Ghose, 2015).

In the recent advancements, effective sensors have been used to work around these situations. Although, not as well as it should be – especially for the conditions of public environments for consumer use. The current choices of sensors are not equipped to process the data quick enough for on-road scenarios. Without adequate validation, these sensors cannot be used in the vehicles (Ghose, 2015). Although this is not the focus point for the research, prudent review is essential when selecting sensors.

Ethical factors tie in with the data gathered using sensors for use of decision making. In typical on the road conditions, the driver may have to decide to swerve left or right to avoid a collision. For example, a situation of such manner would require ethical reasoning which would require the software in a self-driving car to weigh all the different outcomes and come to a final solution on its own. The dilemma may require killing 1 to save many (Bonnefon et al., 2016).

A review by MIT titled as “Why Self-Driving Cars Must Be Programmed to Kill” covers this issue. How should the car be programmed to act in the event of an unavoidable accident? Should it minimise the loss of life, even if it means sacrificing the occupants, or should it protect the occupants at all costs? Should it choose between these extremes at random? The report stated that carmakers must solve this impossible ethical dilemma of algorithmic morality much before it comes a possible widespread (Bonnefon et al., 2016). As shown in Figure 2.26 below, various states that may be the outcome of algorithmic morality is illustrated.

Figure 2.626: Outcomes of algorithmic morality (Bonnefon et al., 2015)

The answer to these ethical questions plays a tremendous role in self-driving cars and have a significant impact on the way it is accepted in society. In fact, who would buy a car programmed to sacrifice the owner? Although there is no right or no wrong answers to these dilemmas, public opinion is what matters the most as self-driving cars are fundamentally a consumer product (Bonnefon et al., 2015).

Jean-Francois Bonnefon and co. at the Toulouse School of Economics in France discovered the public’s opinion using the new science of experimental ethics. This involved collecting public feedback by posing ethical dilemmas to large numbers of people to see their response. The results from these were intriguing. People were at ease with the idea that self-driving cars should be programmed to minimize the death toll. Nonetheless, here lies in the contradiction. The public were open to the idea of minimizing the number of deaths and saving the maximum number of people but if they did not have to drive one themselves (Bonnefon et al. 2016). Bonnefon and co. pointed out that their work leads the initial steps into the moral maze. They also suggested other issues which will need to be factored for future ease, involving the task of responsibility and who is at fault if a self-driving car was involved in an accident (Bonnefon et al., 2016).

Adding to the increase of questioning the safety factors and integration of driverless vehicles on the roads, Google recently released data showing that its self-driving cars have been involved in 11 minor crashes over the past six years. This has raised considerable attention regarding when these autonomous devices would be released for customer purchase. However, later analysis of the events relating to the accidents revealed that, all the minor accidents were due to human errors and not exactly the driverless car's fault.

2.7. Summary

The progression of the research of self-driving vehicles is ongoing. With the advancement of various technological devices and their use in the autonomous systems, increased requisite of a vehicle management system becomes vital. Additionally, active in-service condition monitoring is also required. This review has shown the importance of vehicle management and to extract useful data, about the current characteristics of the vehicle, in-service condition monitoring is required. Information can be gathered using various sensory and actuator systems. As a result, predictive maintenance techniques should be carried out with the management of the vehicle for optimum use and to avoid uncalculated failures.

Recent research has shown that vehicle management systems can identify faults or maintenance needed in advance via the Controller Area Network (CAN). This is due to the management system acting ahead at a level where the life of the system is fully analysed and monitored from beginning, till when replacement of a specific part, or maintenance of the system is required. Moreover, sensors make adequate use when monitoring is insufficient. The system makes full use of embedded sensors with links to other monitoring devices combined for prognostic and diagnostic reasoning. Furthermore, additional software model interfaces to the vehicle and with the use of multi sensors, they provide overarching services such as data logging and supervisory functionalities. Experimental work by Google, Tesla and other researchers of driverless vehicles examines the practicality of the system.

As the study of self-driving vehicles continues, increased focus of vehicle management is necessary. Study shows that as industry relies more on intelligent systems for passenger safety (collision avoidance mitigation, lane change etc.), these features must readily be available 100% of the time. Hence, the vehicle management system must keep the vehicle up to scratch 100% of the time. Propagation of intelligence techniques provide better information which can be used in intelligent vehicle management systems.

Investigation of artificial intelligence methods as shown in section 2.4 has many benefits and limitations. Depending on the application of the method, the system can be finely tuned to fit relevance. Among the discussed intelligent methods, fuzzy logic signifies close representation of how a human brain works, creating a pathway of possibilities rather than discrete measures. Its capabilities allow it to fuse different measurement techniques and can be adapted to prognostic management systems.

For the development of a vehicle management system intelligence of such manner would be significant. Creating prognostic management methods for the advancement of a fully functional management system is the end goal. A complete system that has the capability of sustaining independently/ autonomously – referring to Level 5 of SAE. This chapter has proved insight to various fields of study within driverless vehicles and has aided the necessary guidance for achieving the contributions of the research.

Subsequent chapters entail the development of an innovative steering system monitoring solution for driverless cars, utilising embedded systems with IoT integration. The new system addresses critical issues, enhances overall vehicle safety, and ensures optimal performance by monitoring steering wheel components at level 5 automation. This new management system significantly improves the efficiency and safety of driverless cars.

CHAPTER 3

DESIGN & DEVELOPMENT OF AN INTELLIGENT MANAGEMENT SYSTEM FOR DRIVERLESS VEHICELS

3.1. Introduction

This chapter address the thesis objective (2): ‘Develop a suitable test bench that includes driverless vehicle subsystem or system’. It will further go onto discuss System Development of a driverless Pod highlighting its hardware elements, electrical, software aspects. Furthermore, detail features that will enable the Pod to have autonomous control through additions such as navigation and localisation, along with its User Interface (UI) developed for the Pod.

3.1.1. Architectural Framework and Diverse Components of the Intelligent Management System in Driverless Vehicles

An autonomous vehicle, also known as driverless vehicles, typically consists of various components that work together to enable autonomous operation. Autonomous vehicles typically adhere to the traditional "Sense-Plan-Act" paradigm in robotics. The sense, plan, act paradigm is often implemented in a continuous loop, where the system continually senses the environment, updates its understanding of the situation, plans the next set of actions, and then executes those actions. This iterative process allows autonomous systems to adapt to changing conditions in real-time. This paradigm is fundamental to the development of autonomous vehicles and robotic systems because it provides a structured approach to handling the complexities of dynamic and unpredictable environments. It helps in achieving the goals of safe and efficient navigation through the integration of sensing technologies, decision-making algorithms, and actuation mechanisms.

Intelligent Management Systems (IMS) in driverless vehicles play a crucial role in ensuring safe, efficient, and reliable operation. While the specific structure and components may vary depending on the vehicle's design and purpose, several key components contribute to their functionality:

- Perception System:
    - Sensors (LiDAR, radar, cameras, ultrasonic) collect environmental data.
- Sensor Fusion:
    - Integrates and processes data from multiple sensors for a comprehensive view.
- Localisation System:
    - GPS and Inertial Navigation Systems (INS) determine the vehicle's position and movement.
- Mapping and Environment Modelling:
    - Uses high-definition maps for detailed road information and real-time updates.
- Decision-Making Module:
    - Path & Behaviour Planning: Determines optimal route considering vehicle state, traffic, and environment and decides vehicle actions in various scenarios for improved safety and efficiency.
- Control System:
    - Vehicle Dynamics Control: Manages steering, acceleration, and braking for path adherence. Collision Avoidance: Adjusts speed for safe following distance and intervenes to prevent collisions.

- Communication Systems:
  - Enables vehicle communication with others and infrastructure.
- Monitoring and Diagnostics:
  - Health Monitoring: Constantly checks vehicle components for potential issues.
  - Diagnostics: Provides information on vehicle state for maintenance and troubleshooting.
- User Interface:
  - HMI: Allows user interaction, displays vehicle status, and enables manual intervention.
- Cybersecurity:
  - security measures to protect vehicle systems from cyber threats.

The integration and design of these components are critical to the overall functionality and safety of a driverless vehicle. Manufacturers and developers continually refine these systems to enhance the efficiency, safety, and user experience of autonomous vehicles. Figure 3.1 below illustrates a typical system overview of an autonomous vehicle.

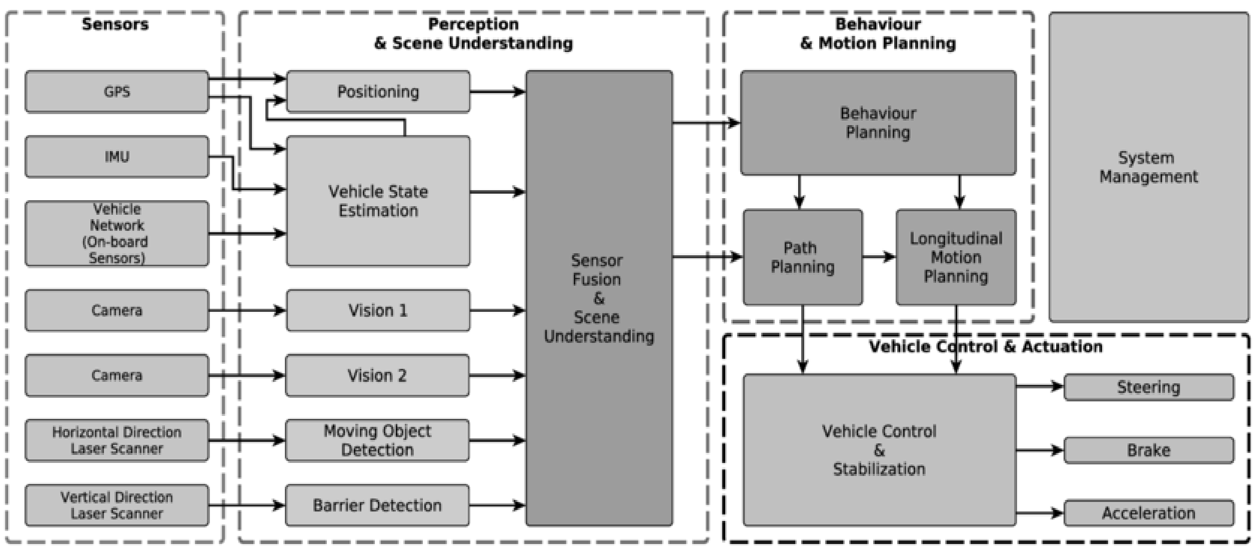

Figure 3.1.11: The information flow between the modules of an automated vehicle (Tas et al., 2016)

The area of focus for the thesis lies mainly in 'Monitoring and Diagnostics' as mentioned in the list above. Subsequent chapters detail the developments of the original contributions to improve reliability, maintainability and safety of driverless vehicles categorised at SAE Level 5 of automation. The specific focus is on the steering system through the introduction of a novel monitoring system.

3.2. Development of an Appropriate Test Bench Arrangement

To simulate the design and critically analyse its effectiveness, the model should be assessed, and the stimulus provided by the test bench becomes essential for one of the many research objectives: 'Develop an appropriate test bench that includes driverless vehicle subsystem or system.'

The research topic 'Driverless Vehicles' being a broad area, which requires various levels of design, development & testing both in and outside of the lab environment; the complete process has been separated accordingly. As part of the development, a Driverless Pod had to be designed and developed to apply different Intelligent Management strategies and to gather real data. Thus, the test bench must be designed in the most applicable way:

- Accessibility: various configurations both in terms of mechanical and electrical are being tried and tested, therefore it should be possible to intervene quickly or regulate changes from all aspects.
- Stiffness: should be able to carry high load and be rigid so that the chassis has enough support to hold moving parts.
- Generate data: real time testing and saving of data for evaluation.

To deeply investigate and develop an Intelligent Management System for Driverless Vehicles (IMSDV), an appropriate test bench that would meet various conditions had to be developed. After brainstorming some major design specifications, as noted above, an IMSDV test bench was developed as shown in the simulation Figure 3.2 below.

The architecture of the bench consists of 4 layers – Figure 3.3. The layers have been laid out in the most optimised manor to suit the design model/ unit. The rigid structure enhanced using the materials allows applying various conditions to the design model to be tested. The dimensions for the architecture are 1000 x 640 x 1100mm (length l, width w, and height h).

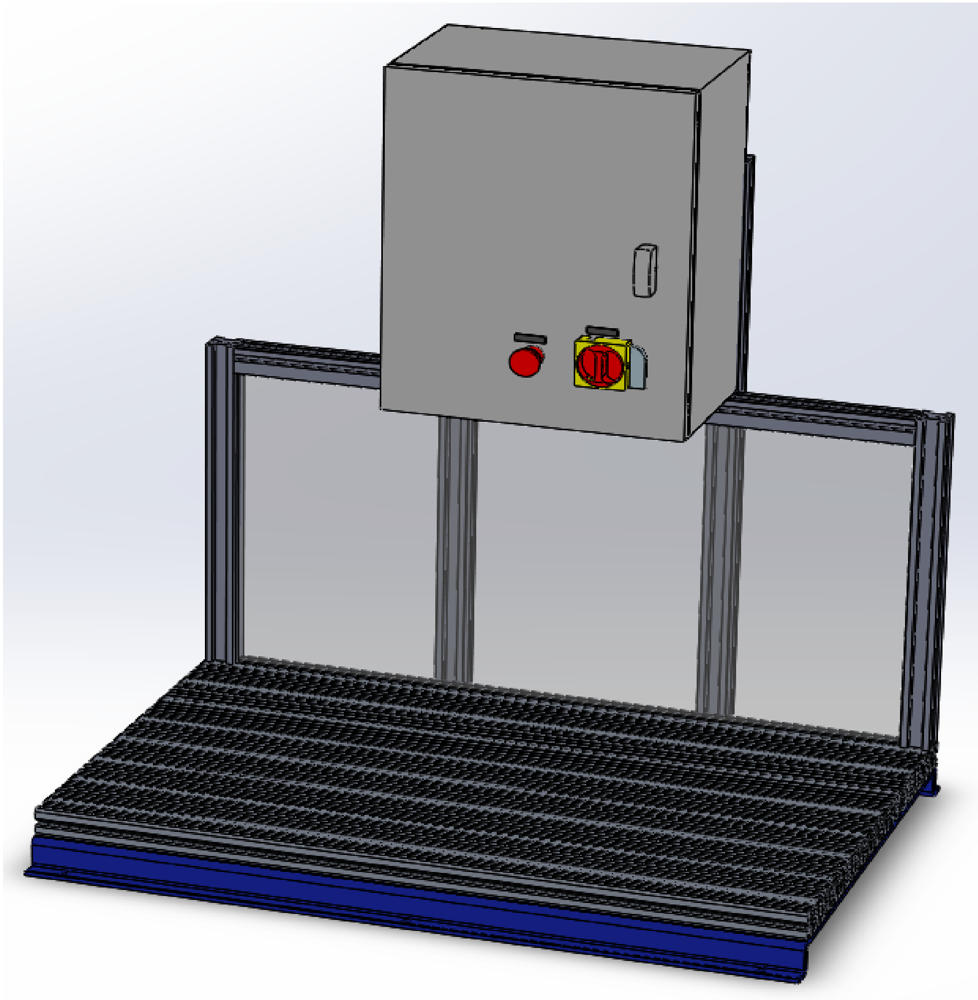

Figure 3.2: In-Lab test bench design which suits the capabilities of evaluating a Driverless Pod. Additional mounting frames were installed on the test bench to create an elevated platform to secure the Pod at working height.

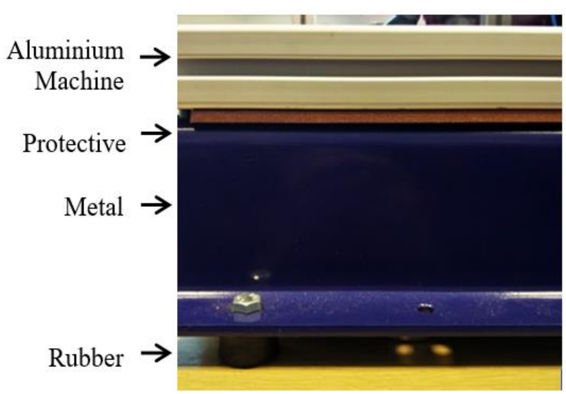

Figure 3.3: Four Layer architecture of the test bench

Figure 3.4: Pod on the Elevated Platform

3.3. Description of a Newly Proposed Driverless Pod Platform

The 'Driverless Pod' would be a multi-disciplinary system including mechanical, electrical, control features. In view of the mechanical structure of the Pod, some design requirements are listed:

- Dimensions: structure of the Pod needs to be within the test bench architecture for ease of access and testing within lab environment.
- Pre-Existing structure or build from scratch: rather than creating a structure/ chassis from scratch, a system which is pre-existing that could be ambiguously fitted with the driverless capabilities would be ideal.
- Mounting: numerous sensors should be able to be mounted around the Pod. Monitor various parameters such as acceleration, movement through sensory fusion, actuators, and data processors.

Weighing Pros and Cons of design possibilities a pre-existing electrically powered structure was selected, that could be modified accordingly. To design and build a 'Pod' would require a great amount of time and attention to detail, budgeting issues (purchasing raw material). However, the ability to construct a well-suited design was the major highlight - shape, size, and layout. Another option was a pre-existing structure closely related to design specifications which could be modified - go kart, golf buggy etc. This means less time spent on design/ build, more time for controllability and testing.

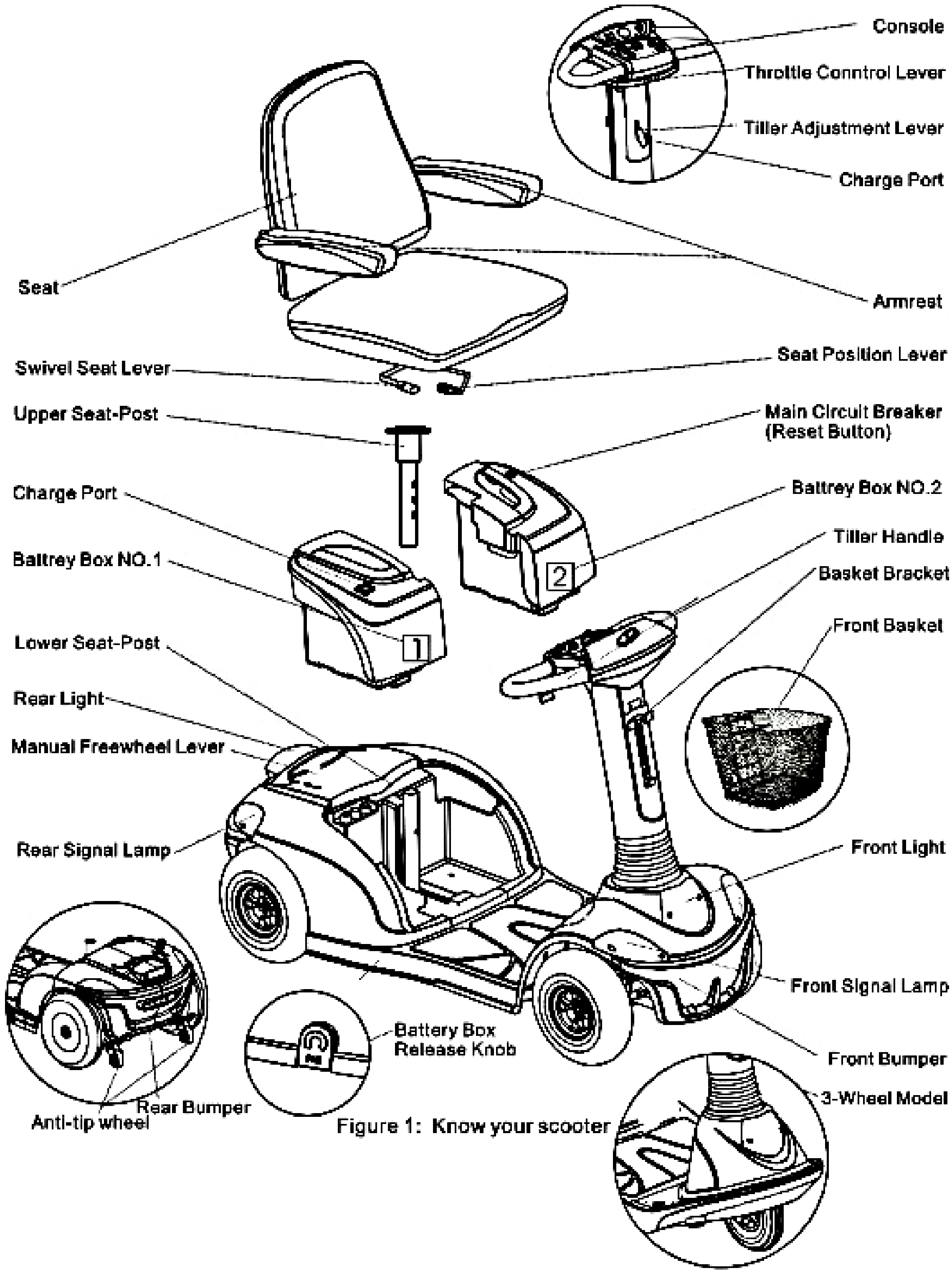

Figure 3.5: Landlex RS Broadway Mobility Scooter (Landlex User Manual)

A second-hand mobility scooter was purchased, to be modified accordingly. The Landlex Broadway mobility scooter shown in Figure 3.5 was purchased and entirely reconstructed. The scooter itself has various running conditions and features: User Console, Adjustable Tiller, Light Sensor, Status Light Emitting Diode (LED), Hazard Lights Button, Adjustable Speed Dial etc. which complement the unit highly for its intended customers (Landlex User Manual). Although, when choosing this scooter, the portability of the 24 V battery source, the robust chassis, multi terrain tyres and the straightforward design with automatic breaking are features that were most complementary concerning this research development. The transformation has meant manual controls over steering has been reformed, user interface (UI) entirely modified, onboard electronics including wiring changed. Section 3.4 details the transformation from a regular mobility scooter to the newly formed Driverless Pod.

3.4. Conversion of a Conventional Mobility Scooter to an Autonomous Personal Mobility Pod

This section covers the development phase of an autonomous Personal Mobility Pod (PMP) detailing the conversion from a standard mobility scooter to an autonomous platform which will satisfy 'Research Objective (2)'. The proposed system will be focused on a low-cost platform, which will be at level 5 automation of the SAE standards, featuring self-navigation between multi points safely without any human interaction: demonstrating the 3 principals of any fully autonomous system - sense, plan, and act.

The autonomous PMP includes multidisciplinary sensory actuation to achieve these tasks, thus, the running conditions and suitability with the research would be tested and validated. The Pod will contribute to developing the IMSDV and used as a test apparatus to gather real data. Succeeding testing and validation of the Pod, feedback from multi-sensors, actuators will enable gathering raw data for constructing a management system for the Driverless Pod.

3.4.2. System Design and Architecture

To provide localization and monitor the vehicle and its surrounding environment, a set of sensors were used in this stage to provide surrounding information about the vehicle. This data used to feed the vehicle planner which interact with user to specify the desired location with the suitable operating conditions. The main brain of the vehicle embeds a Google Maps API system to map the vehicle in the real road map and provide a tracking of the vehicle along this map. Google Maps provides direction information of the Pod to reach a user desired location. Trajectory tracking controller converts this path into control points for the steering and speed controllers and minimise the error between the actual path and planned path. Steering and speed controllers tune the setting points and overcome the dynamics disturbances that avoid the vehicle smooth movements.

A complete Personal Mobility Pod (PMP) consist of multi systems including user interface, vision system, and obstacle detection and mapping system, planning and motion control system etc. However, this chapter focuses on the user interface with vehicle and the motion control system. Some of the main components used in the autonomous Pod are noted below – each will be discussed in related sections. A system overview of is illustrated in Figure 3.6.

- National Instruments myRIO-1900 FPGA: Main Control/ Management
- ATmega328P – Arduino Nano: Slave Controller
- CYTON 30A 5-30V Single Brushed DC Motor Driver
- Adafruit Industries 746 GPS Module: GPS receiver for position data
- Adafruit 1946 FONA Mini Cellular GSM Breakout uFL Version
- Adafruit 2472 9-DOF Absolute Orientation Inertial Measurement Unit: IMU Breakout
- Inductive Motor Speed Sensor
- Absolute Encoder: Measure Steering Angles
- Laptop to Interface and Monitor the System: Onboard
- Electric Power Steering Motor GM 13136674 001407140

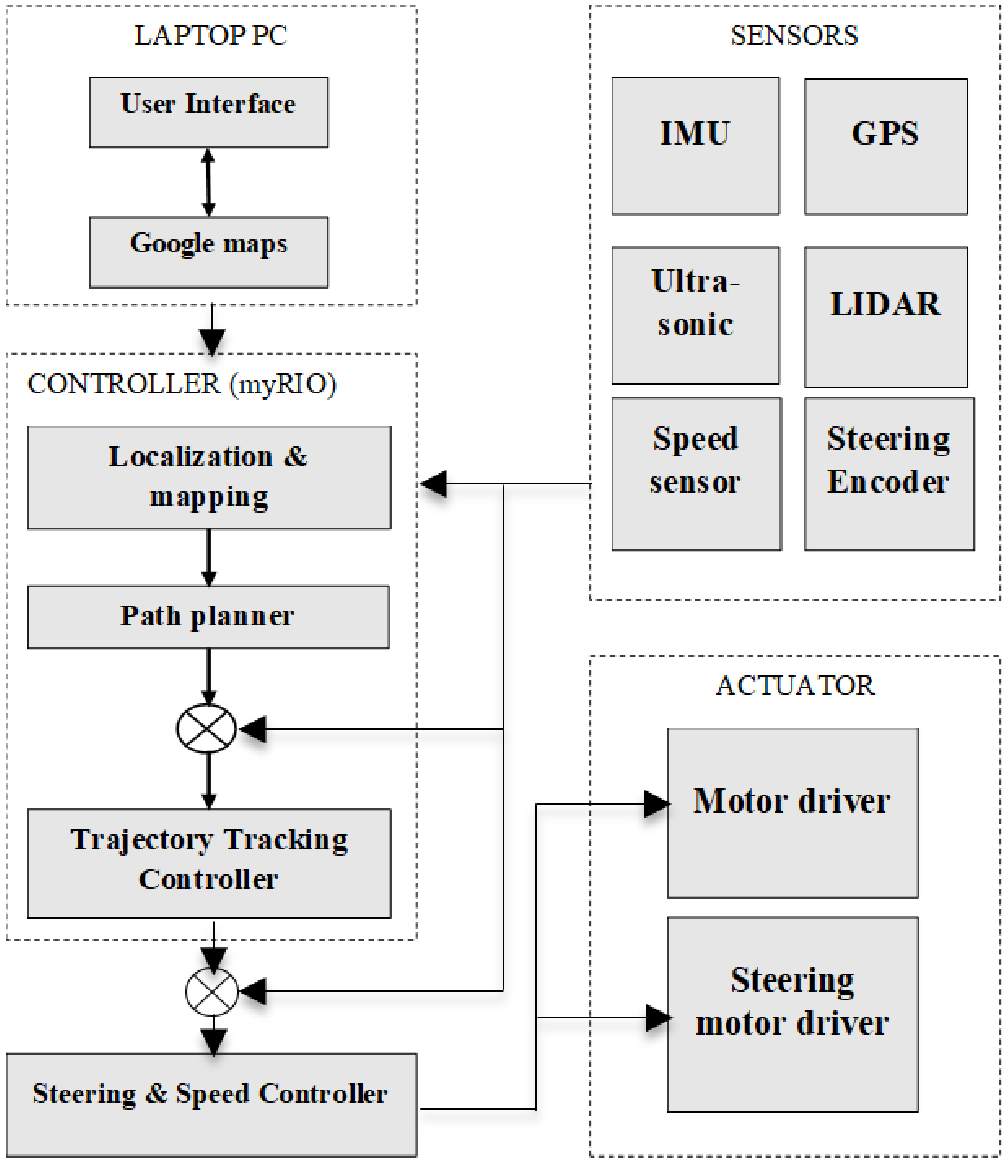

Figure 3.6: System Overview

3.4.3. Design and Development of Hardware

The base platform for the personal mobility pod is Landlex Broadway RS. It has been modified and retro fitted where necessary to accommodate the various sensory actuation systems, power systems, computing units and other features used in the process of automating the Pod. The original scooter chassis was preserved during conversion and kept as non-destructive as possible with minor cutting, drilling. Any modification and custom-built parts were specific to the scooter type, utilising existing mounting points. Similar method may be used to recreate the described pod using other scooter platforms.

From the original design of the scooter, various features that were admired as a part of the original scooter were not necessary for the development of a PMP. I.e., the controls and steering of the scooter were the console attached to the tiller handle – Figure 3.7 would no longer be used; instead, an actuator was used for controllability.

Figure 3.7: Tiller Console (Landlex User Manual)

In terms of what is required of the system, the PMP should be fully autonomous at Level 5 of SAE standards. It should be able to manage various conditions, navigate itself to a requested destination without the intervention of any manual controls; much like other test driverless vehicles at level 5 automation. Prove the concept of accommodating a monitoring system that could identify varying conditions of wheel, tyre systems. For such a system, various sensory elements would be predominant, leading to a sensory fusion system that actuates an outcome comparatively with the controller through an algorithm of decision making.

3.4.4. Steering Control System

The manual tiller control used for the front axle steering linkage system from the original scooter structure had to be removed and replaced by a suitable actuator with the capability of carrying the payload for the newly remodelled driverless system. Different actuators were investigated, tried, and tested for the application, including heavy duty servo motors. Though, following a subsequent amount of testing on servo motors, with custom built mounting brackets designed and installed, it proved to be incapable of carrying the load and functioning as anticipated. This led to continuous research for an apt actuator.

Succeeding testing of various compact actuators, a reoccurring issue was raised each time - none of the compact designed motors could produce the required torque. Therefore, the expected outcome was not achievable. Thus, replicating an actual car, an electric power steering system was fixed upon with the reasoning of high load and torque capabilities. A used Vauxhall Corsa C Electric Power Steering (EPS) module was purchased and modelled to suit the Driverless Pod. The EPS system was mounted in a vertical fashion directly to the steering column on the Pod as shown in Figure 3.8. The actuator was mounted directly along its shaft, to the steering column of the Pod. Metal assemblies were used to hold its position. This setup sufficed the steering criteria and allowed rotary movement of the steering.

Nonetheless, succeeding initial testing it was found that the mounting of the actuator was not practical. As the steering actuator operates its course of drive, the non-rigidness fit proved to be an issue; mounting jitters and make the movement look/ feel uncomfortable.

Leading to the steering system being further modified to be rigid and robust. The design structure of the chassis itself was re-modelled to accommodate the new unique layout. Progression of the design and construction of the new layout is exemplified in Appendix. A complete SolidWorks illustration of the before and after the updated design is shown in, Figures 3.9 and 3.10.

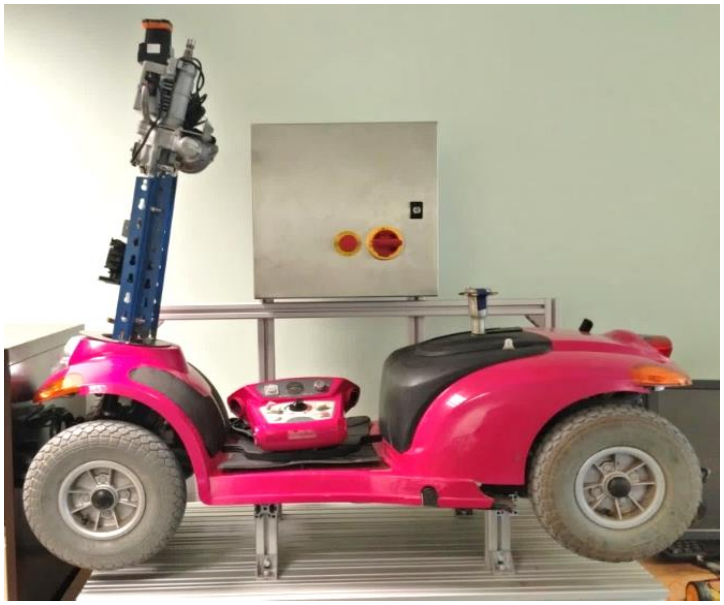

Figure 3.8: Developed driverless pod on the laboratory testbench setup with the initial design of the steering mount

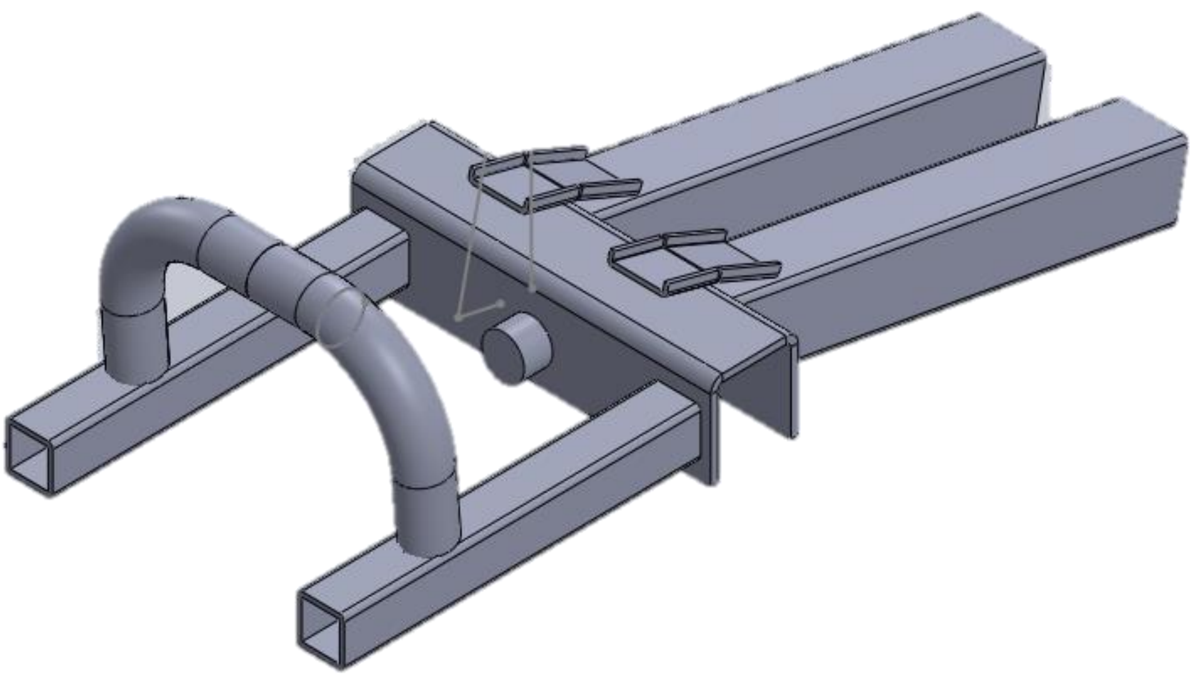

Figure 3.9: A SolidWorks Representation of the Scooter Chassis before Modification

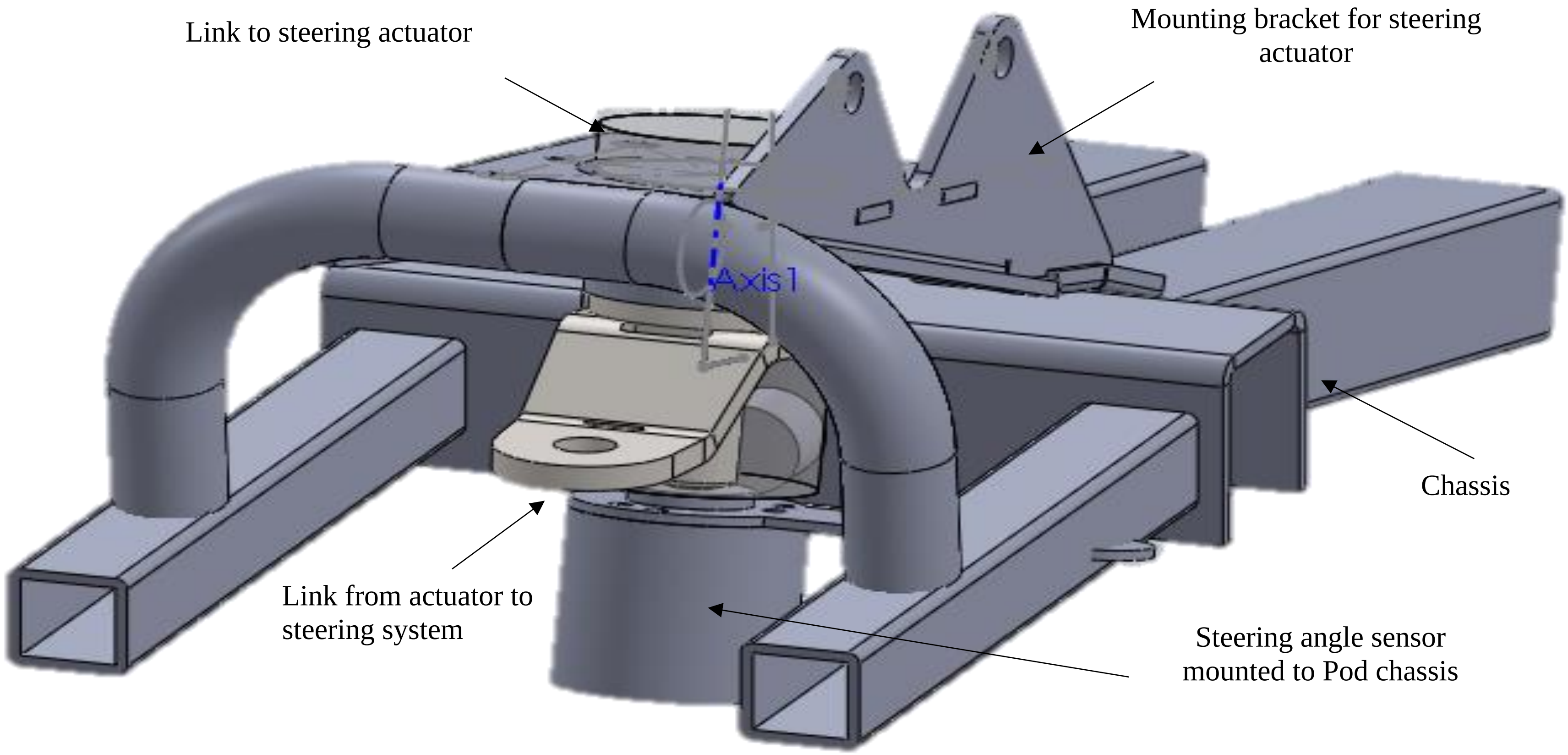

Figure 3.10: Re-Modelled Design of the Chassis w/ New Steering Actuator Mounting for the Pod

The chassis of the original scooter has been modified to make the new mounting and the old steering system completely remodelled to accommodate the actuator. The original scooter chassis was preserved during conversion with minor cutting/ drilling to minimise damage the structure. Design of the mounting bracket has been completed through Computer Aided Design (CAD - SolidWorks) and built specific to the original scooter type. All subsequent parts, including welding has been completed within the University workshop with the aid of workshop technicians. Final installation and assembly were carried out in the Tribology lab.

With the updated design, the EPS actuator has been mounted directly onto the Pod's chassis. Upon initial testing, re-modelling the chassis to accommodate the actuator has proved to be much better than initial design. The structure is robust and rigid with truly little jitter and further visually pleasing.

Initial tests conducted following the new build using a power source demonstrated the capacity of the motor. The necessary current stands at 20 A, dependent on the load. Consequently, connecting the motor directly to the controller (NI myRIO) or linking it directly to the battery may result in inadequate power due to myRIO's output limitations or could potentially cause damage.

Moreover, bi-directional control of the motor's movement is required for optimal use of the automated steering system. Thus, for controlling the steering, there is a need of additional circuitry that can act as a bridge to the motor. There are various methods for triggering this process: transistors, ICs, or relay. The specifications of the motor being highly rated, 12 VDC with a current rating of approximately 20 A depending on the load, a relays circuit was opted. Relays are commonly used in applications involving electronic switching. Implementing such a system would be advantageous for the steering system of the Driverless Pod.

In this case, two distinct types of relays have been combined to drive the steering actuator: general purpose SRM-1C-SL-5VDC non-latching relay, automotive 0 – 728 - 12 relay. The need of these two relays come into action due to the differences in characteristics. The NI myRIO controller's output voltage is 3.3V and 5V fixed. At this voltage, the automotive relay cannot be switched, but is required to control the EPS motor. Therefore, the general-purpose Single Pole Double Throw (SPDT) relay switch has been set in place to bypass the incapability of the automotive relay to function with the controller and instead 2 general purpose relays have been used to switch. The resultant of the SPDT switching leads to the automotive relays which drive the motor. A detailed circuit diagram of the circuit board is shown in the following figure. ‘Proteus Design Suite’ software was used to create schematics and electronic prints for manufacturing the printed relay circuit board as shown in below Figure 3.11.

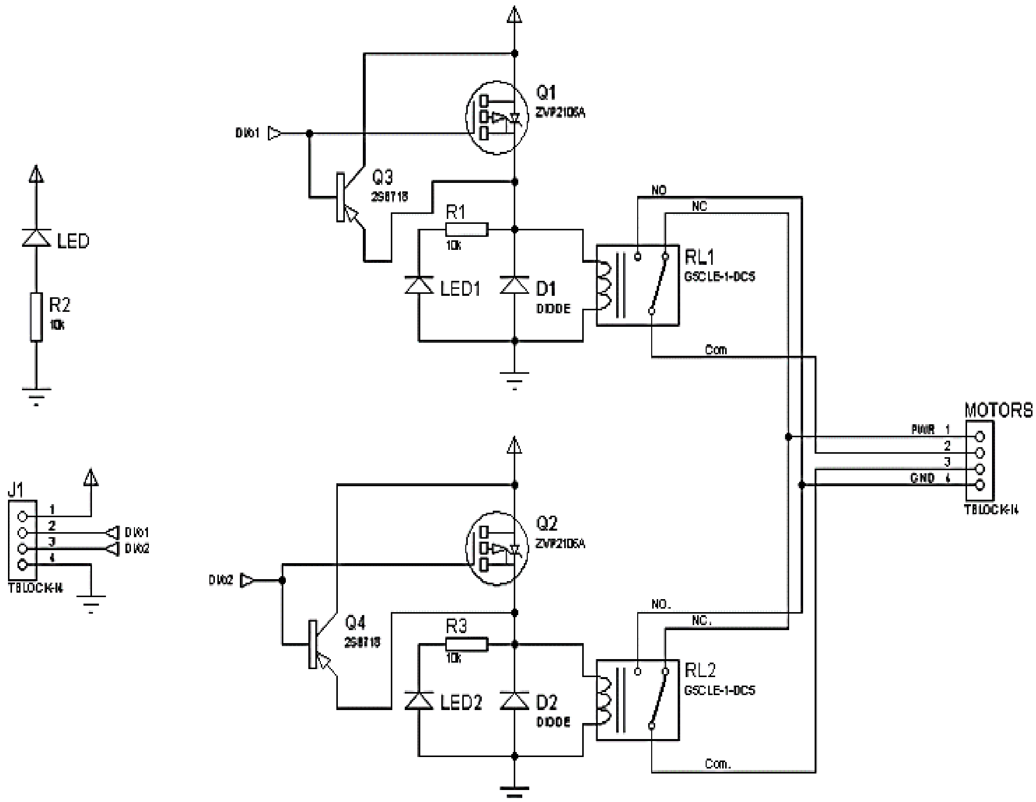

Figure 3.11: ESP – Relay Circuit Connection to myRIO and Automotive Relay

The steering motor was controlled through analogue I/O pins of the controller (NI myRIO) using the circuit board via LabVIEW software. A Graphical User Interface (GUI) designed through the software allowed commanding left or right, replicating steering movement. Though the circuit suffices intended functionality, the board’s build quality being low, as it was printed with available material in University Laboratory environment health and safety, thus, quality of outcome were factors which opposed.

Outsourcing to electronic circuit board manufacturers to find similar design, several companies were found. CYTON 30A 5 - 30 V DC Motor Driver circuit board was purchased and replaced for both the relay circuit connection from the controller and the automotive relay circuit controlling the EPS actuator. CYTON Motor Driver board has the capability to work with the low output voltage of the controller but still generate enough power to control the actuator, cancelling the need of a bypass circuit between the controller and the motor.

The control over steering position was achieved using a rotary position sensor. Details of sensory actuation, calibration of the sensor with actual steering position are detailed in the succeeding chapter.

3.4.5. PMP Main Drive System

The forward and backward movements of the original scooter were triggered using a throttle potentiometer, where fluctuations in the throttle voltage result in actuation. A RHINO controller has been factory fitted and pre-programmed by the manufacturer to acknowledge the throttle potentiometer as a proportional system. The same concept was opted for the Pod by controlling the voltage send to the RHINO controller programmed with the driving motor. The pre-programmed working principle of the controller was not altered. Thus, NI myRIO controller has been used to surpass the system and automate the drive process as intended.

The logic behind the program: voltage range being between 0 V – 5 V DC, at start-up the signal connection of the throttle control should receive a voltage which is proportionally in between 0 V and 5 V DC. At this state, the controller actuates a halt/ stop/ brake. If at the start-up, the signal is not at such a proportional state, the main motor will not operate - as a safety measure. This fault is indicated on the original scooter interface by a status LED immediately after ignition key is turned. To resolve this occurrence, ignition should be turned OFF, voltage applied corrected, and ignition turned ON again. For forward movement, the voltage should be increased from 2.5 V – 5 V DC max speed, for reverse movements from 2.5 V down to 0 V DC. Using the voltage output from the myRIO controller, the signal to the throttle potentiometer was manipulated accordingly to achieve drive.

This manipulation of signal voltage would suffice controlling the main scooter motor. However, inconsistency is caused with varying voltage ranges. I.e., low battery, slight differences in range. For an optimal design of the Pod, complete control of the drive system is key; such compensation cannot be tolerated in an optimal design. To eliminate uncertainty, the actuator was disengaged from pre-set RHINO throttle program and detached from the Pod. In a familiar fashion to the steering control system, a DC motor driver circuit was purchased and implemented. Direct control of main drive motor through myRIO controller - via CYTRON motor driver board – limitations caused by RHINO controller were eliminated from the PMP system.

Whilst in motion, a crucial aspect is continuously modulated control of speed. The system implements use of a PID controller using an efficient algorithm in a simple manner. A set point specifying the desired process variable being controlled, compared with a process variable specifying the measured value of the variable. This method of control algorithm maintains a fixed speed while the Pod is in motion with regards to external factors i.e., differences in terrain.

3.4.6. On-Board Electrical Power

Main power source for the PMP is produced by two 12V battery packs connected in series to make 24V. The main drive motor of the Pod as well as accompanying circuitry are powered from the 24V power supply. An additional 12V 34AH/ 20hr battery is used specifically for the steering motor and associated circuitry. Both power sources have been equipped with circuit breakers and fuses to provide additional protection/ power cut off to components.

3.4.7. PMP Software Development

The original mobility scooter was pre-programmed by the scooter manufacturer to function with basic UI controls – forward/ backward, ignition, speed control and indicator lights. The on-board RHINO scooter controller allowed optimal control for the scooter.

For the development of a new Driverless Pod, a new unified controller was opted. National Instruments myRIO FPGA module acts as the main control/ management system for the PMP. NI myRIO-1900 (Figure 3.12) chosen as it is a reconfigurable I/O device which is a portable, multifunctional unit used in various multidisciplinary applications: including robotic and mechatronic systems. It features the Xilinx Zynq-7010 all-programmable system on a chip, which includes a dual-core ARM Cortex-A9 processor and an Artix-7 FPGA. The dual-core ARM Cortex-A9 processor on NI myRIO runs the NI Linux Real-Time OS. Additionally, it provides the option to program the processor in either LabVIEW or C/C++.

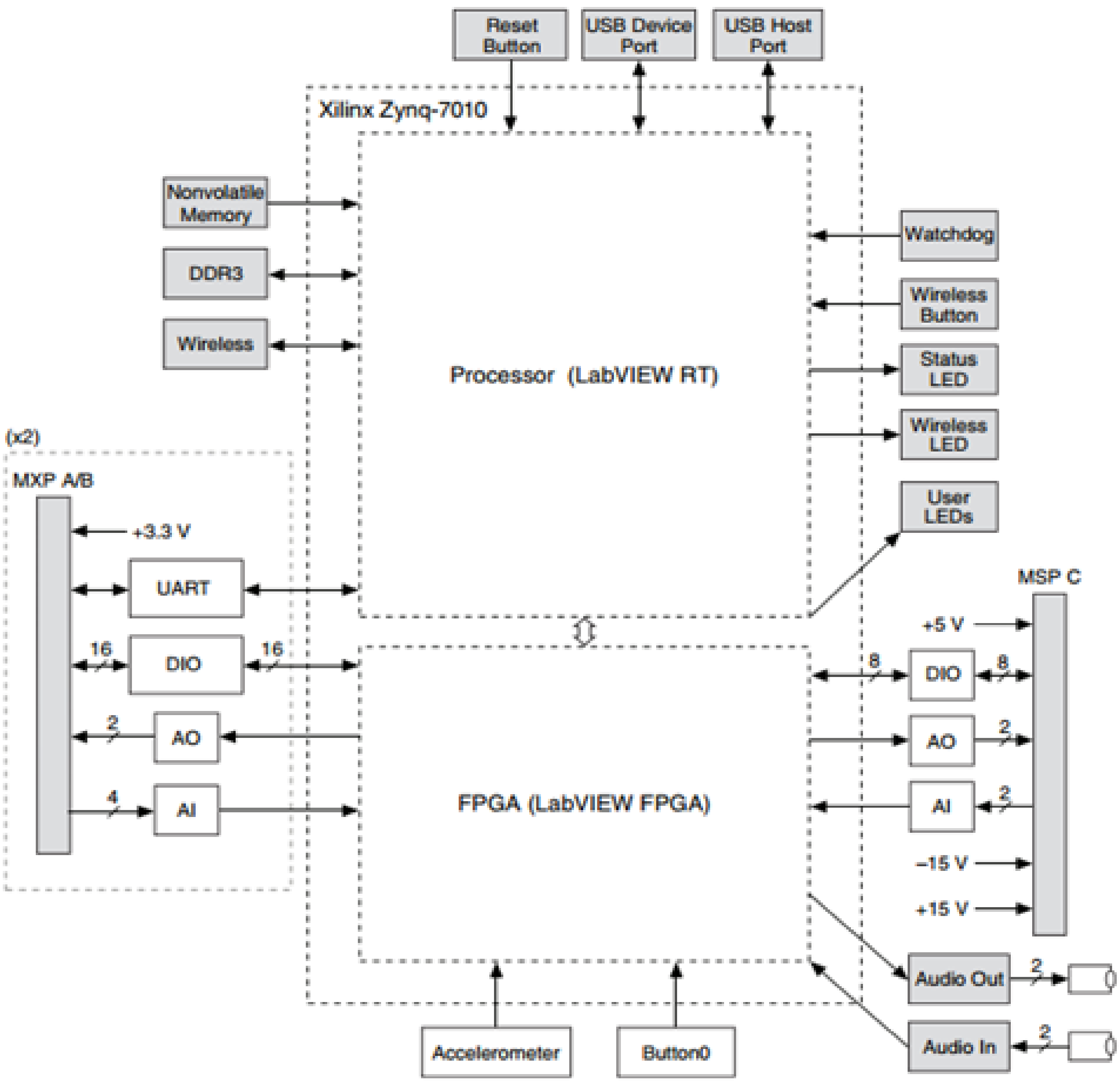

Figure 3.12: Overview of NI myRIO-1900 (Source: ni.com)

The module has been used with LabVIEW software which is an object orientated language. The programme includes various sub-VI's each including the required objects and libraries. For navigation, the robotics library was used to create the map and find the optimum path with search techniques. By using ActiveX object an interaction between the browser and LabVIEW was established to send and receive map data. Associated sensors were all programmed using myRIO communication library. Additionally, Arduino Nano ATmega328P (Figure 3.13) has been used as a slave controller which interfaces with the main myRIO controller.

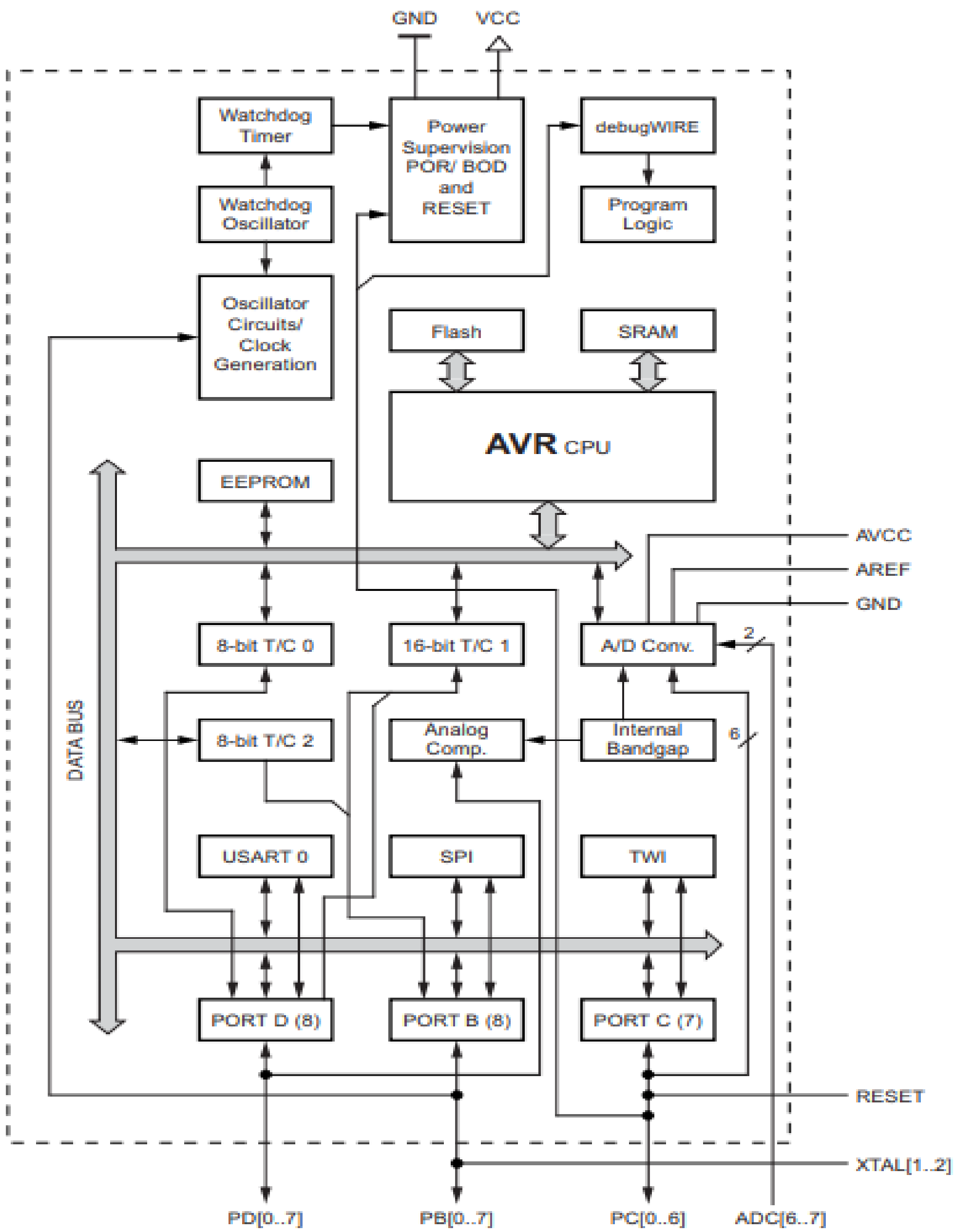

Figure 3.13: ATmega328P Block Diagram (Source: Atmel Datasheet)

The PMP has been designed to have two modes of driving: Autonomous Mode & Manual Mode. In autonomous mode level 5 of SAE standards is followed i.e., no driver - PMP determines steering, actuation. In manual mode, the driver has manual software driven control of steering and drive - no decision making is carried out by the PMP.

A low-cost Atmel microcontroller has been used as the controller for initial testing purposes of the various associated sensors. The software programming for the system was developed using C. Concerning the complete construction of the software development, the programming for the system is achieved using LabVIEW. The design software uses graphical programming language (G) through dataflow models instead of the conventional lines of text code. It is an integrated development environment designed specifically for engineers and scientists. LabVIEW being highly graphical, creating a user interface which displays, Maps, location, controls were made effortless.

3.5. Mapping and Navigation

This section discusses localisation and planning for the vehicle using GPS, IMU sensor and Google maps to define the desired route that the vehicle must follow. Various research suggests how to make real time data logging using low-cost systems that uses the controller to send and receive location data through a server and monitor it using google maps or other mapping tools. The UI software will communicate with google maps using Google Maps APIs service. This service uses HTTP request to calculate direction between given locations and return the data as an image to be displayed along with waypoints to target location.

To track the vehicle on maps, The Google Static Maps API provides the UI with updated map image according to the specified location by the GPS feedback. Map parameters including zooming, format, map type, markers, and path visualization which enhance user experience can also be controlled. Thus, the user specifies a target location and request the direction from Google maps Direction API to return the path: waypoints, travel duration and distance is returned in an xml format. Thereafter, waypoints are used to update local map. This command is used by LABVIEW ActiveX object to interact with a browser to send HTTP commands and then receives the google maps results – illustrated in following Figure 3.14.

Additional features to improve the Maps UI could be having the ability to search for nearby locations such as hospitals, workshops etc. Such additions would be beneficial as part of further improvement to the GUI and user experience.

3.5.1. Google Maps

In the mapping and planning layer of the vehicle considered as the main layer that deploy the autonomous technique of the vehicle, google maps plays this role and performs the necessary tasks.

Google Maps has been established and incorporated in the UI of the Pod using LabVIEW for live monitoring of the Pod along with other discussed parameters. The interactive map feature maps display in various modes, trip information, zoom, marker etc.

The communication between the vehicle platform and the google maps service was established using HTTP commands. These commands provide the key functions to the maps platform to return the desired information. The function set built in LABVIEW is attached in appendix.

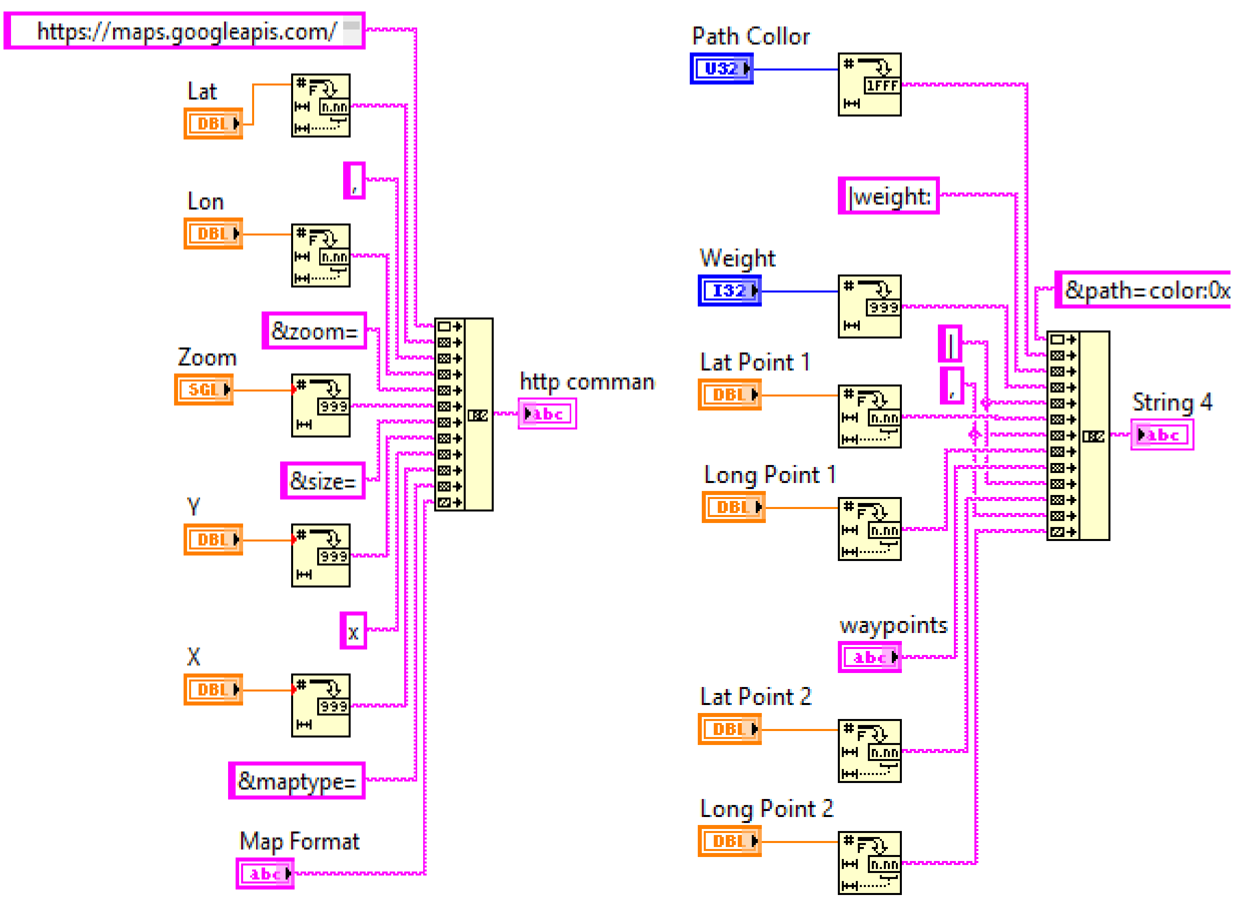

Figure 3.14: Snippet of LabVIEW Illustrating Commands Providing the Key Functions to Google Maps Platform

3.5.2. Vehicle Orientation using IMU

An Inertial Measurement Unit (IMU) is an electronic device that measures a body's specific force, angular rate and the magnetic field surrounding it. The mentioned Adafruit 2472 9-DOF Absolute Orientation IMU incorporates 3 sensors (L3GD20H - gyroscope, LSM303 - accelerometer, BMP180 - magnetometer) to give nine distinct types of inertial measurement. The outputs of all sensors are processed by an on-board microcontroller and output over I2C interface.

Some description of each sensor is specified:

- L3GD20H 3-axis gyroscope: ±250, ±500, or ±2000 degree-per-second scale
- LSM303 3-axis accelerometer: ±2g/±4g/±8g/±16g selectable scale
- LSM303 3-axis compass: ±1.3 to ±8.1 gauss magnetic field scale

For gathering the autonomous PMP's orientation, raw data is collected and delivered through I2C to ATmega328P – Arduino Nano which is extracted and send to the main NI myRIO controller via serial communication. This data details orientation of the vehicle which is used in the tracking control program and main monitoring program of the Pod using shared variable technique.

Furthermore, using the gathered acceleration data could be used in calculating the velocity and displacement of the vehicle to tune the GPS data and localize the vehicle for indoor environments; or when the GPS signal is lost to enhance system performance.

3.5.3. Localisation of the PMP using GPS Sensors

Global Positioning Sensor (GPS) is a network of 30 satellites orbiting the Earth. Though originally developed for military navigation, with current technology, any device with a GPS can receive a radio signal any satellites broadcast. At least 4 GPS signals are visible at any given time around the globe providing 3-D coordinates (latitude, longitude, and altitude) with high precision and accuracy.

The way in which the data is extracted is that the GPS module generates NMEA sentences which consist of ASCII text strings terminated by a carriage returned line feed combination. NMEA

(National Marine Electronics Association) sentences accommodate wide range of navigation information of which the GPS sentences form much small subset. Each sentence begins with “$” followed a two-character “talker ID” (“GP” for a GPS sentence) and a three-character sentence type. The sentence body contains comma-delimited fields and ends with a checksum. By default, the Gms-u1LP emits ASCII characters at 9600 baud (8-bit, 1-stop) and generates a cluster of four sentences (and occasionally more) every second.

In the main program, extracted longitude and latitude information are send to the planning program using shared variable technique in LabVIEW. The steps covered by the sensor module to extract GPS data is: Capture the NMEA sentences (ASCII text strings) generated by the Gms-u1LP as an array of strings in LabVIEW, Parse the sentence to extract individual data fields, and finally, extract information from the data fields using LabVIEW scan from String and format into String VI programs. The given coordinates update the location of the vehicle in real time on the map which monitor the vehicle movement and position.

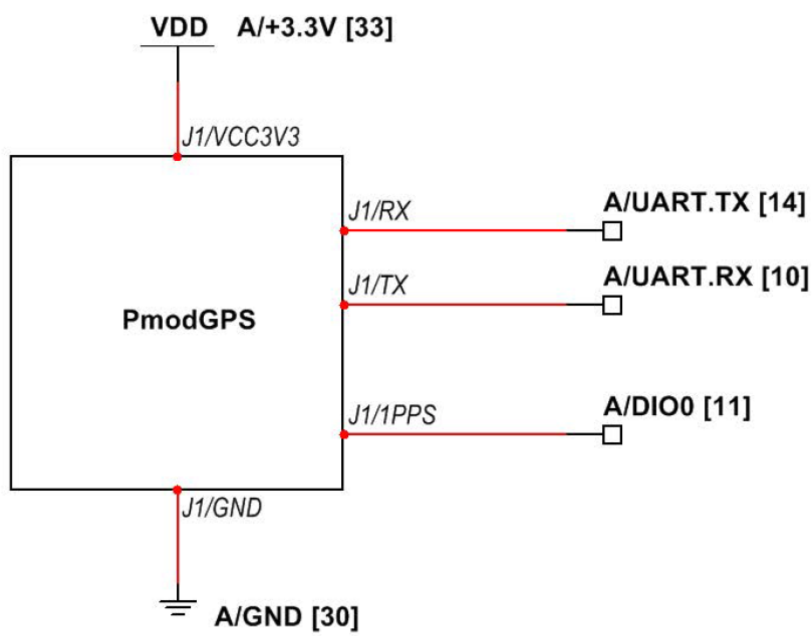

Figure 3.15: Pinout Connection of a GPS Module

3.6. Motion Control System

The purpose of the trajectory tracking controller is to provide the setting points for the steering and speed controllers, aiming to follow the pre-defined path given by the planner considering the desired speed and orientation of the Pod. According to De Luca et al., three steps can be identified for a tracking controller, namely:

- Point-To-Point Motion - navigate from initial position to a desired target point
- Path Following - using a geometrical path from origin to the desired location
- Trajectory Tracking - locating end point with the determined velocity

There are several types of controllers developed to handle the tracking task based on the vehicle model. Pure Pursuit is a tracking algorithm for path planning purposes which computes angular velocity and calculates the steering angle, thus, moves the robot from a position to reach a target point ahead by a list of waypoint coordinates (coordinates from origin to end target). The nearest point on the given path from the Pod's current position is always calculated – point to point. The algorithm then updates the look-ahead point on the path based on the current position of the robot from the last position until the last point of the path is reached. Given the position and orientation of the Pod as an input, the linear and angular velocities commands for the Pod are calculated. This method ensures the smooth steering and reduce the oscillations during movement.

3.6.1. Geometrical Modelling of the Pod

Scooters that are considered as car like robot vehicles can be described as a rigid body with concentrated mass in the centre of gravity and classified as a non-holonomic system (TÖRŐ, 2016). Geometrical model is considered as a simplest modelling technique; based on Ackerman steering configuration, it only uses the dimension and position of the vehicle regardless its velocity and acceleration. The importance of this method is come from evaluating the path tracking performance and developing the pure pursuit controller (WIT et al., 2004 & Wang et al., 2009). In this method, it is considered that the vehicle moves with low speed and has moderate steering angles. If operating at higher speed and larger steering angles, the curvature would be much greater. i.e., increased area of turning point. So, there are two main assumptions:

1. *The four-wheel scooter is simplified into a two-wheel bicycle model by combining the two front wheels together and the two rear wheels together to form a two wheeled model neglecting the dynamics effect.*
2. *Only move along a plane*

As in the Figure 3.16 below, the geometrical relationship between steering angle and the curvature where the vehicle move along can be driven as:

$$\tan \boldsymbol{\delta} = \frac{L}{R} \qquad (1)$$

Where:

$\boldsymbol{\delta}$: steering angle, L: wheelbase length, R: radius of the curvature the Pod move

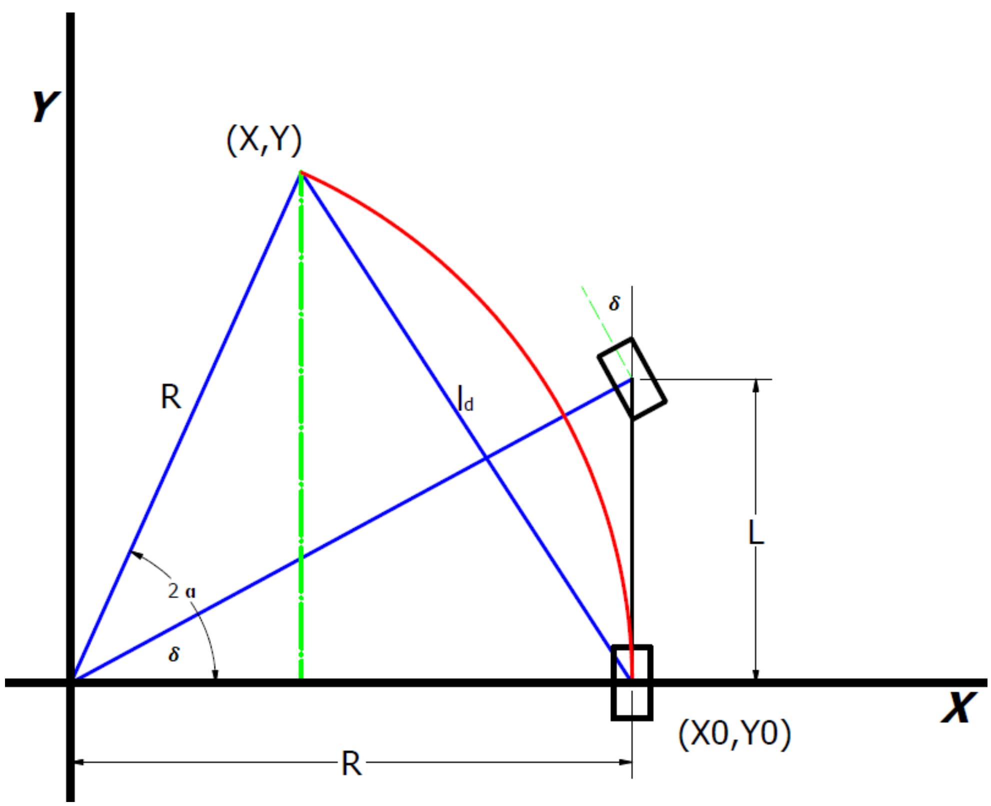

Figure 3.16: Representation of the Pod as a Bicycle Model

3.6.2. Tracking Algorithm

Using Pure Pursuit method, a circular curvature is calculated between start and end points according to the look-ahead distance. By applying the sines law in the geometry model as shown in Figure 3.16, steering angle $\boldsymbol{\delta}$ can be calculated using the look-ahead distance l_d for each point and the angle α derived from the below equations:

$$\frac{l_d}{\sin 2\alpha} = \frac{R}{\sin\left(\frac{\pi}{2} - \alpha\right)} \tag{2}$$

$$\frac{l_d}{2\sin\alpha\cos\alpha} = \frac{R}{\cos\alpha} \tag{3}$$

$$R = \frac{l_d}{2\sin\alpha} \tag{4}$$

$$\gamma = \frac{2\sin\alpha}{l_d} \tag{5}$$

Where: γ is the curvature between start and end points; by substituting in Eq.1, the steering angle will be as:

$$\delta = \tan^{-1}(\gamma . L) \tag{6}$$

$$\delta = \tan^{-1}\left(\frac{2\,\mathrm{L}\sin\alpha}{l_d}\right) \tag{7}$$

From Eq.7, the Pure Pursuit controller is a function of the look-ahead distance l_d in front of the vehicle. Small look-ahead distance provides more accurate tracking while large distance provides more stable and smoother tracking. To tune the Pure Pursuit controller, the look-ahead distance is scaled with the longitudinal velocity of the Pod.

$$l_d = K . v_x \tag{8}$$

As shown in the Figure 3.17, the controller is calculating the steering angle using current position of the Pod and end point given by the planner which constrained by the speed provided that scales the look-ahead distance. The next step is to control steering and speed of the vehicle by a simple PID controller for tracking the desired steering angle and speed provided with tracking controller. This low-level controller is tuned by the steer angle sensor and speed sensor's feedback. By implementing the PID method for both steering and main drive motor, the Pod can withstand deviation/ varying differences in terrain and minimise any error whilst in motion. Latter Chapter details further testing and experimental results.

- The Pod's steering system consisting of three main elements; actuator, angular sensor, and controller. In this study, the steering actuator is a DC EPS motor controlled through the DC motor driver which control direction and voltage to the motor.
- Speed control (referring to the main drive motor positioned at the back of the Pod) uses the PID method to maintain a fixed speed whilst in motion.

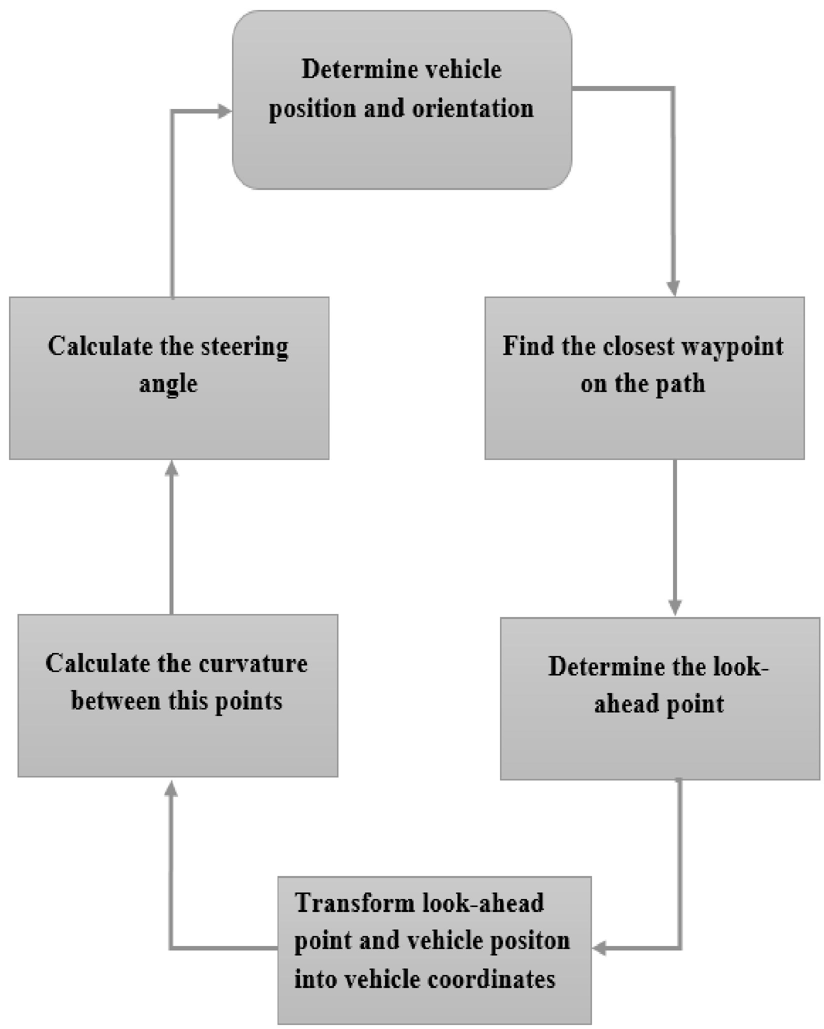

Figure 3.17: Tracking Algorithm Flowchart

3.7. Summary

The contents of Chapter 3 cover the principal design and layout of a test apparatus that supports the developed autonomous pod. The chapter details the use of equipment (various sensors and actuators), fitting, design, manufacturing, and manual control set up of the designed pod. It goes onto discussing the conversion from a standard mobility scooter into an autonomous PMP. Including Mapping and navigation, localisation and tracking, the steps to achieving a fully autonomous device is illustrated.

Chapter 4 details the methodology for a newly proposed monitoring system that will contribute towards maintenance management of driverless vehicles, specifically focusing on safety and reliability of the steering system component.

CHAPTER 4

EXPERIMENTAL DESIGN AND IMPLEMENTATION OF AN IOT BASED REMOTE MONITORING SYSTEM FOR DRIVERLESS VEHICLES

4.1. Introduction

Having introduced the aim & objectives, literature study and developments of a test platform in the preceding chapters, subsequent chapters go onto detail the design, development and implementation of the proposed sub-system that would help improve the reliability, maintainability and safety of driverless vehicle steering components.

This chapter will detail the design of the proposed monitoring system. Detailing the strategies and parameters used to monitor the steering component's health condition through the sub-system arrangement.

4.1.1. Overview of System Structure

The Internet of Things (IoT) refers to the network of physical devices, vehicles, appliances, and other items embedded with sensors, software, and network connectivity that enable them to collect and exchange data. IoT architecture is the framework that defines how these devices communicate, process data, and interact within the IoT ecosystem. The architecture typically consists of several layers, each serving a specific purpose. Figure 4.1 below, provides and overview of a high level IoT architecture.

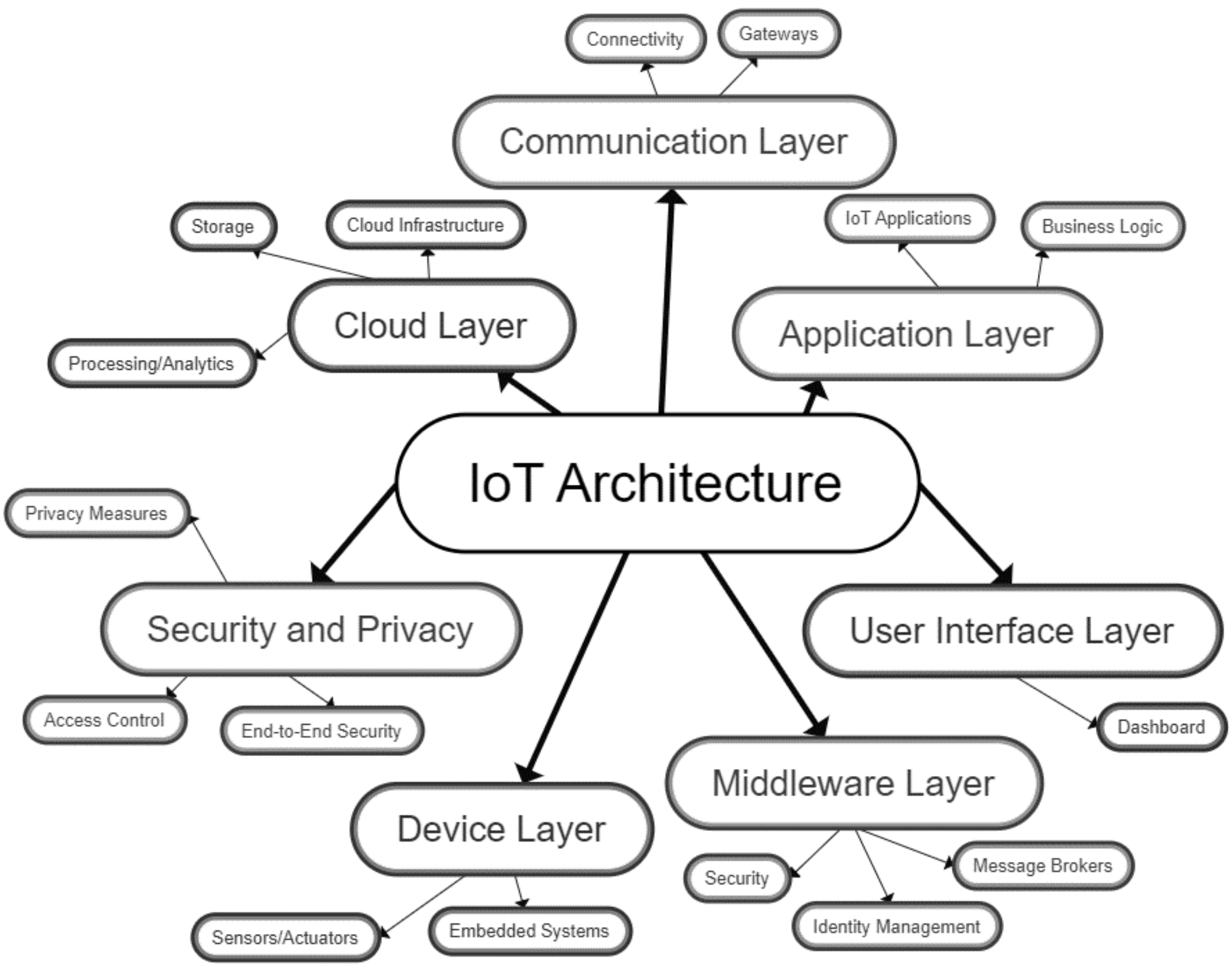

Figure 4.1.11: Overview of A High Level IoT Architecture

This architecture provides an overall system structure overview to designing and implementing IoT solutions, ensuring scalability, flexibility, and security. Different IoT applications may have variations in their architecture based on specific requirements and use cases.

In the evolution of autonomous vehicle capabilities, the integration of an IoT - based remote monitoring system stands as a pivotal advancement. Going beyond traditional methodologies, this advanced approach aims to detect, assess, and respond to real-time conditions within the vehicle.

At the centre of this technological advance is the seamless integration of robust "Monitoring and Diagnostics" protocols, ensuring continuous monitoring of vital vehicle components. This includes the propulsion system, sensors, and communication modules, creating a proactive framework for the identification of potential issues and the monitoring of wear and tear on essential parts.

In line with the broader trend of leveraging connectivity and data analytics, the integration of an IoT-based remote wheel bearing monitoring system proposed in this research, seeks to enhance the safety, efficiency, and reliability of modern transportation systems. This strategic alignment emphasises proactive measures, leveraging connectivity and data analytics to detect emerging issues. Fully autonomous vehicle fleet management companies can then implement timely maintenance routines and replace components as needed, averting potential damage/ safety implications to the vehicle.

The ramifications of this integration extend beyond merely preventive measures. The incorporation of an IoT-based system is crucial for improving the overall lifespan, maintainability, reliability, and safety of driverless vehicles. By leveraging the capabilities of IoT, this system not only addresses the current requirements of the vehicle but also establishes the groundwork for a future where autonomous vehicles operate with exceptional efficiency and resilience.

The following diagrams depict the structure of the full system. Figure 4.2 provides an overview of the entire system, showcasing the progression of the pod and the IoT-based remote monitoring system.

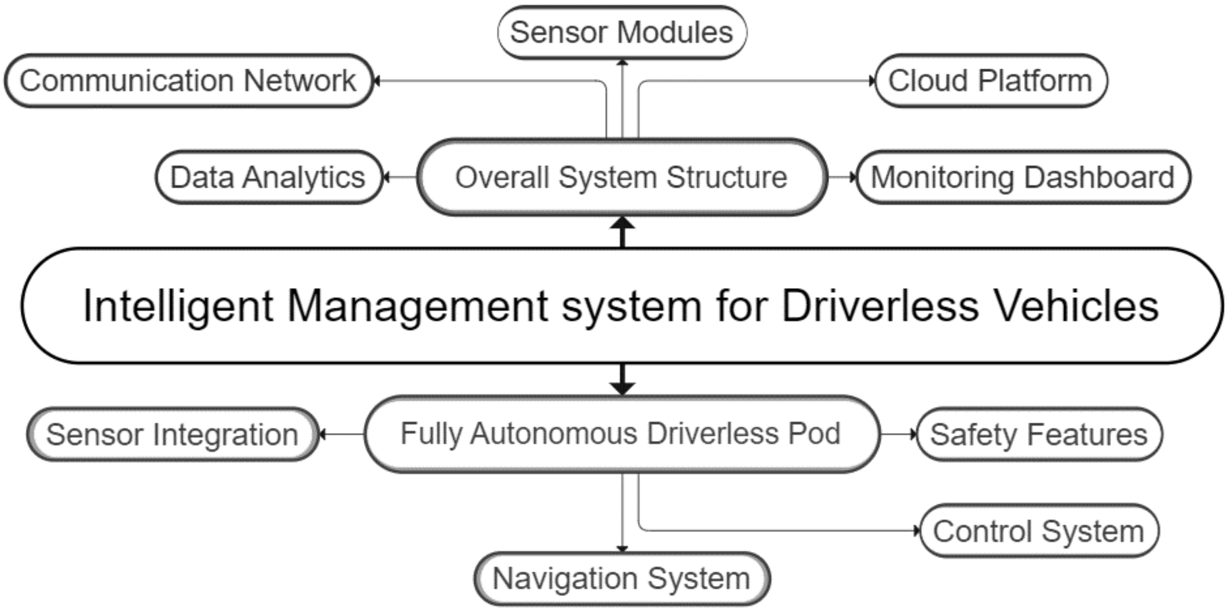

Figure 4.1.12: System Overview Inclusive of Developed Pod with IoT

Figure 4.3 delves deeper into the intricacies of the evolved IoT system framework for the monitoring system.

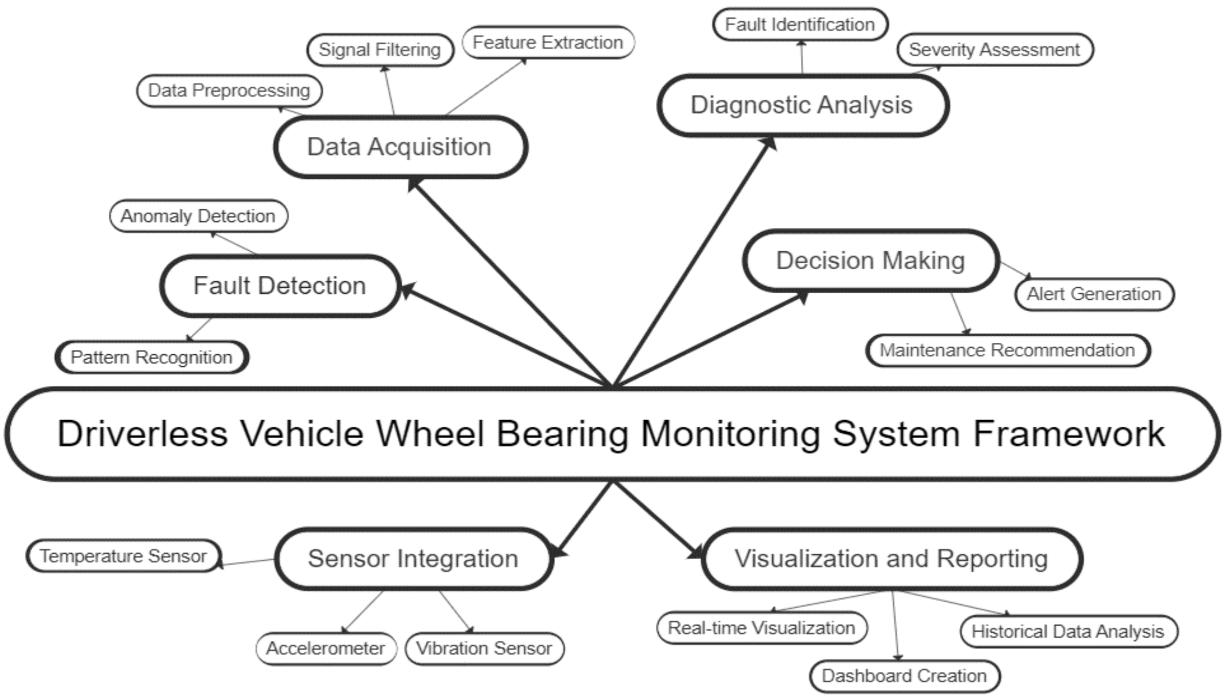

Figure 4.1.13: System Overview of the IoT Based Remote Monitoring System for Driverless Vehicles

In the evaluation of the overall system as described, the testing procedure was divided into several stages as shown in Figure 4.4. Initially, within laboratory environments, individual components of the Pod and their functionalities underwent testing. Following the successful completion of component-level tests, comprehensive functionality tests for the fully autonomous personal mobility pod, including mapping features and the user interface, were conducted in a controlled field environment. Subsequently, wheel bearing severity tests were performed on the developed Pod. The testing process then proceeded to assess the monitoring system utilizing IoT, with separate tests for each section. The testing culminated with the comprehensive evaluation of the fully integrated system. Further detail concerning the tests conducted are explicated upon in subsequent chapters.

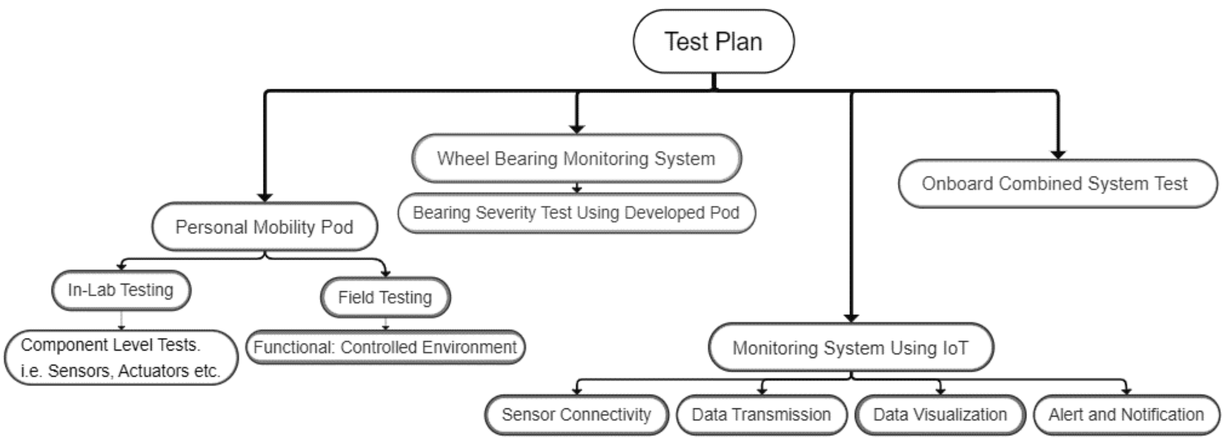

Figure 4.1.14: System Overview of The Test Scenarios for The Full System

4.2. Case Study

According to SAE (SAE, 2013), the development of the steering system is a significant focus in driverless vehicles. The autonomous vehicle steering falls under level 2 of the SAE J3016 automotive automation standard, which involves human interaction in decision-making. Currently fully automated, power assisted, or semi-assisted steering systems utilise feedback signals using various sensory arrangements. However, this does not provide information concerning the real time onboard steering system disruptions. Previous studies on vehicle management systems have neglected to consider real-time steering disruptions caused by component health issues.

This research aims to investigate and address these considerations to enhance the reliability and safety of driverless vehicles, with a specific focus on the vehicle wheel. By monitoring wheel bearing vibrations in real-time, it becomes possible to detect excessive or irregular vibrations that indicate problems with the bearings - like worn bearings, misalignment, or other bearing defects. This monitoring system can create an active alarm system, trigger alerts or warnings, prompting maintenance actions before the issues worsen or impact other interconnected components. Such proactive measures would minimise downtime, reduce maintenance costs, and improve overall vehicle reliability.

4.3. Discussion

When ‘Level 5 Full automation’ is achieved in the automotive industry, car sharing will undergo a revolutionary transformation. With vehicles capable of complete autonomous operation, the concept of car sharing will become even more convenient and accessible. People will no longer need to physically drive or own a car; instead, they will be able to summon a self-driving vehicle through the likes of mobile applications or other webservices, which will pick up and drop off consumers to and from their desired destinations.

Prominent manufacturers of autonomous vehicles, who specialise in Level 5 automation, strongly advocate the societal advantages of car-sharing over the personal preferences of individual car owners. These autonomous car-sharing services will optimise traffic flow, reduce congestion, and minimise the need for parking spaces, resulting in improved urban mobility. A fleet of autonomous vehicles would work based on an ‘availability on-demand,’ returning to base, charging, and redeploying as needed.

To achieve these goals to improve transportation from its current state, the integration of added monitoring systems through advanced driver assistive systems (ADAS) is the approach that would lead to seamless and sustainable transportation solutions to full automation.

An area of ADAS that could lead to full automation suggested by SAE standards is the vehicle steering system. In conventional vehicles, a disturbance in a vehicle’s health condition can be identified by the driver, in most cases. For instance, if the vehicle’s alignment is disturbed, it becomes noticeable through several indications such as on the steering wheel, the vehicle's drive or through visual checks in extreme cases. To rectify such issues, various methods would be opted by an approved mechanic, including string method, laser correction, or use of wheel alignment apparatus (Grossman, January 1983, Lee, Leve 2014). These techniques assist in making an accurate diagnosis to resolve issues arising and assist by maintaining the integrity of the vehicles steering system.

In driverless vehicles however, where there would be no human driver at 'Level 5 Full Automation', the passenger would not need to worry about such operational steering system issues. Monitoring and routine maintenance would expect to be handled independently. The need for an advanced intelligent maintenance system cannot be overstated, respectively to enhancing the steering system. By dedicating further research and development, enhanced level of safety through steering system health monitoring could assist in evolving demands to achieve full autonomous vehicles.

It is proposed using multi-sensory fusion and monitoring techniques, interfaced with a Vehicle Management System (VMS), such factors (discussed above) could be identified and provide warnings to take an action on an individual basis. Furthermore, information could be transmitted through online services to the fleet management/vehicle maintenance team, incorporating additional features based on the research of (Sulaiman et al., 2016).

Current developments of driverless research by vehicle manufactures and other researchers (such as Google, UK's Department of Transport, other private research companies) features development of driverless cars and testing in various conditions, for best commercial use.

4.3.1. Industry Standard Testing of Commercial Vehicles

Vehicle testing is a crucial step in the automotive development process. It refers to the process of evaluating and validating the performance of the vehicles in compliance with agreed industry standards, regulations, ensuring safety and customer expectations. The aim of having strict testing standards is to allow manufacturers to identify and address any potential risks/ hazards, address arising issues, carry out any design/ set-up implications to minimise defects prior to being released for production and commercial use. Vehicle testing also plays a vital role in innovation and incorporation of modern technology. Through testing manufacturers can gather test data which can be used to refine and improve their vehicles, furthering areas of improvement. General vehicle testing typically covers a wide range of aspects. General areas of testing but not limited to:

1. Performance:

    - Acceleration and Top Speed Testing
    - Braking Testing: braking performance, including stopping distances and brake fade characteristics.
    - Handling and Stability Testing: ability, stability control, and manoeuvrability.

2. Durability and Reliability:

    - Road Load Data Acquisition (RLDA): Collects data on the loads experienced by the vehicle during real-world driving conditions to simulate long-term wear and tear.
    - Suspension and Chassis Testing: durability and performance of suspension systems, chassis components, and frame structures under various road conditions.
    - Fatigue Testing: stress cycles to ensure long-term durability.

3. Emissions:

   - Exhaust Emissions Testing: quantity and composition of pollutants emitted from the vehicle's exhaust, compliance with emission standards.
   - Onboard Diagnostics (OBD) Testing: functionality of the vehicle's diagnostic systems.

4. Crash Testing:

   - Frontal Impact Testing: Simulates a head-on collision to evaluate occupant safety, structural integrity, and the effectiveness of restraint systems i.e., airbags and seat belts.
   - Side Impact Testing: occupant safety in a side collision scenario.
   - Rollover Testing: vehicle's stability and rollover resistance through dynamic manoeuvres and simulations.

5. Environmental Testing:

   - Climate Chamber Testing: vehicle's performance, materials, and systems under extreme temperature, humidity, and weather conditions.
   - Water Ingress Testing: resistance to water penetration, ensuring protection against leaks and corrosion.
   - Dust and Sand Testing: ability to withstand dust and sand ingress, particularly for off-road vehicles.

6. Electrical and Electronics Testing:

   - Electromagnetic Compatibility (EMC): ensures electrical and electronic systems do not interfere with each other or external devices.
   - Functional Testing: electrical systems, lighting, infotainment, communication, and driver assistance systems.

7. Noise Vibration and Harshness (NVH) Testing:

    - Noise Testing: noise levels produced by the vehicle's engine, drivetrain, wind, and other sources, aiming to reduce noise and vibration levels.
    - Vibration Testing: vehicle's response to vibrations caused by road irregularities or engine operation, ensuring optimal comfort and reliability.

Test methods and areas of focus differ upon manufacturers and testing criteria. Nonetheless, rigorous testing is crucial to ensure that vehicles can safely operate in real world conditions.

‘Durability and Reliability’ is amongst the most crucial phases in testing and development as it evaluates the long-term performance of vehicles. This form of testing assists in better understanding the vehicles maintenance intervals, component lifespan, and potential wear and tear patterns. This information aids in establishing appropriate service schedules and recommendations for owners, ensuring the vehicle's long-term reliability and minimising unexpected breakdowns or failures.

Amongst various other test methods of ‘Durability and Reliability’ testing, Road Load Data Acquisition (RLDA), Fatigue Testing, and Vibration Testing are most relevant to this research. Car manufacturers conduct these types of tests on a road simulator test rig with various parameters applied for the mode of testing.

A road simulator test rig is an advanced equipment used to mimic real-world road conditions and assess the performance and durability of vehicles. Performance data of vehicles is collected through tests conducted in real-world driving conditions, using test tracks that simulate different road types, speeds, and load. Road simulator test rigs can reproduce the vertical, longitudinal, and lateral forces that act on the vehicle under the real-world conditions. Apply force and motion in six degrees of freedom through vehicle spindles to replicate the effects of real-world road loads on the vehicle and test subsystem durability. The vehicle being tested would be securely positioned on the rig, and a range of simulated road inputs, including forces, vibrations, and irregularities, are applied. The primary objective of the tests is to ensure the vehicle can withstand the lift expectancy without failure.

Various sensors such as Wheel Force Transducer (WFT), Linear Variable Displacement Transformer (LVDT), strain gauges, thermocouples, ride height sensors, accelerometers etc are used to measure various parameters of the vehicle components to collect the data. The collected data can be analysed to create a load spectrum that represents the cumulative loads experienced by the vehicle. The Figures 4.5 and 4.6 below illustrates road simulator test rigs used throughout the industry for vehicle testing. Various rigs from different manufacturers are available. Kistler, MTS are industry leaders for producing these test rigs.

Figure 4.5: Road Simulator Test Rig Used for Vehicle Durability Testing (Source: MTS Systems)

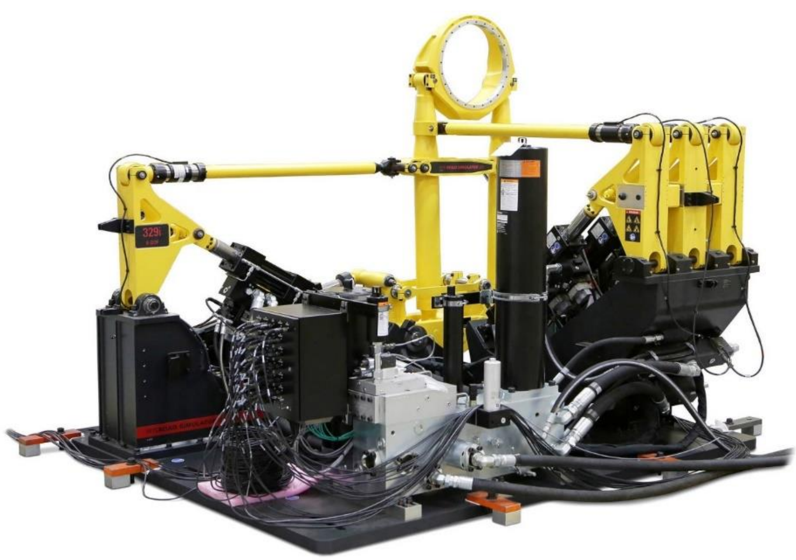

Figure 4.6: Model 329i Spindle-couple Road Simulator (Source: MTS Systems)

Component focus of the durability tests in fatigue testing cover engine components, suspension, chassis & frame, drivetrain, wheels & tyres. All of fatigue testing involves retention under different loading parameters. Vibration testing look at structural health, chassis, electronic systems, mounts etc. By subjecting these critical components to RLDA, fatigue and vibration testing, manufacturers can identify design weaknesses, improve materials and construction techniques, and optimise the overall durability and performance of the vehicle. This helps ensure that the vehicle meets quality standards, enhances safety, and provides a comfortable and reliable driving experience.

The mentioned are testing and research methods to improve vehicle quality, reliability, and durability prior to commercialisation. Real world condition testing has limitations as unpredictable scenarios can affect the vehicle health differently. Real time monitoring systems were introduced to aid progressive improvements through ADAS technology. With the increasing use of onboard sensors and monitoring systems, some have the capability to collect and analyse data in real time to monitor various components and systems: Engine Monitoring, Braking System Monitoring, Exhaust System Monitoring, Tyre Pressure Monitoring System (TPMS). By monitoring these mechanical components in real time, maintenance schedules could be optimised, allowing timely intervention could reduce downtime and maximise efficiency.

In addition to monitoring tire pressure, wheel speed and other related parameters, there are other mechanical components associated with the vehicle's wheel and tire that could be monitored in real time to enhance safety, performance, and longevity of related components.

4.4. Plan of Action

This research is built on the study of real time health monitoring for AV with the key focus being vehicle wheel and tyre components. Even through rigorous testing of vehicles and its subsystems on test rigs, bearing monitoring is not considered by vehicle manufacturers testing prior to commercial release. Bearing health monitoring system is currently not an area of focus within driverless vehicle research or an added feature of ADAS.

Monitoring early bearing failures can lead to early detection of arising issues prior to other components breaking down. Bearings are over designed as they are built to last. Excessive amounts of vibration at bearings translate to other components which can cause other components to fail first. Real time monitoring of bearings has been previously researched and have proved it is possible to detect health conditions of bearings at initial stages of fatigue. None of these previous studies have provided an advanced monitoring system that features an onboard real time wheel bearing/ misalignment monitoring system that utilises vibration analysis to issue health condition in severity levels. Utilising IoT protocols, alerts are sent to maintenance teams for the application of driverless vehicles. This work addresses and resolves the shortcomings of previous studies.

The original contributions mentioned in this research delivers a capsulated sub-system configuration, for the focus point. The sub-system may be replicated as a retro fitted ADAS for conventional vehicles.

It is expected the proposed Intelligent Vehicle Health Management (IVHM) system would enhance the development of driverless vehicles research, by developing (1) Steering Monitoring System, (2) Wheel and Tyre Monitoring System:

1. Steering Monitoring System

In a conventional car, with disturbance in wheel alignment, the driver would be able to feel the difference in drive on the steering system. Thus, toe in/out, camber angels, caster angles identified. Hereby, the driver would take the vehicle to a service centre or drive in a particular manner until the problem is repaired. In a driverless vehicle, disturbance in alignment could not be corrected by the passenger. Further focus is essential to this area to improve reliability and safety of driverless vehicles. This system would monitor and analyse the performance of the developed driverless pod's steering system during testing phase by monitoring the wheel and tyre components.

The system would include multisensory fusion algorithm including steering angle sensor (rotary potentiometer/ shaft encoder), Inertial Measurement Unit to measure orientation/ angular rate with a wireless controller capsulated with the steering system. Real time data from a steering system would be collected using the developed driverless pod testing apparatus.

2. Wheel and Tyre Monitoring System

Usually, the first sign of imbalanced wheels is a wobbly steering wheel when driving above a certain speed. Vibration of the steering wheel often suggests that front wheels are unbalanced. Incorrectly balanced wheels affect vehicle handling, stability and cause premature wear. Thus, monitoring of the wheel is crucial. Correctly balanced wheels provide better handling and more comfort.

Defected wheel bearings are additionally a cause of uncomfortable driving. Monitoring the conditions of wheel bearings could contribute to developing advanced maintenance strategies for driverless vehicles using wireless monitoring systems and included in the capsulation. Wheel bearing defects will create excessive vibration, such signals could be monitored through using piezo electric elements and provide warning systems. Built of the study of (Onsy 2013).

Additionally, tyre pressure has a significant effect on vehicle performance and tyre life; therefore, the correct tyre pressure and temperature should always be revised. By monitoring tyres using pressure sensors, the life of the tyre can be extended by making sure, pressure is always maintained at the criterion limits. ADAS systems such as TPMS are currently available on commercial vehicles.

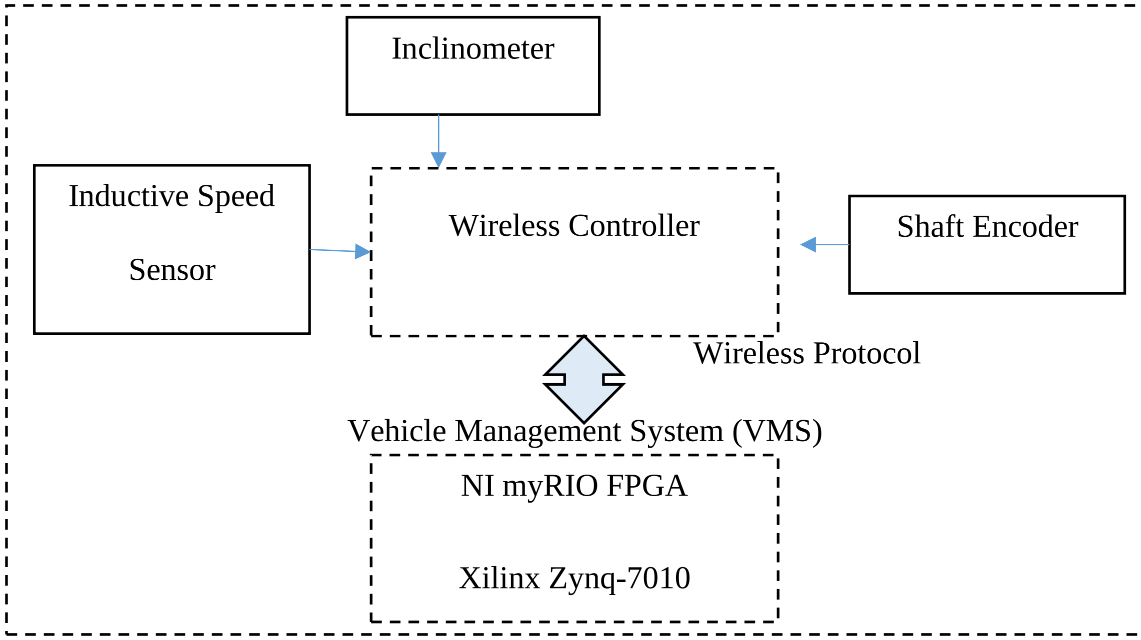

Figure 4.7: Overview of Wheel Alignment Monitoring System

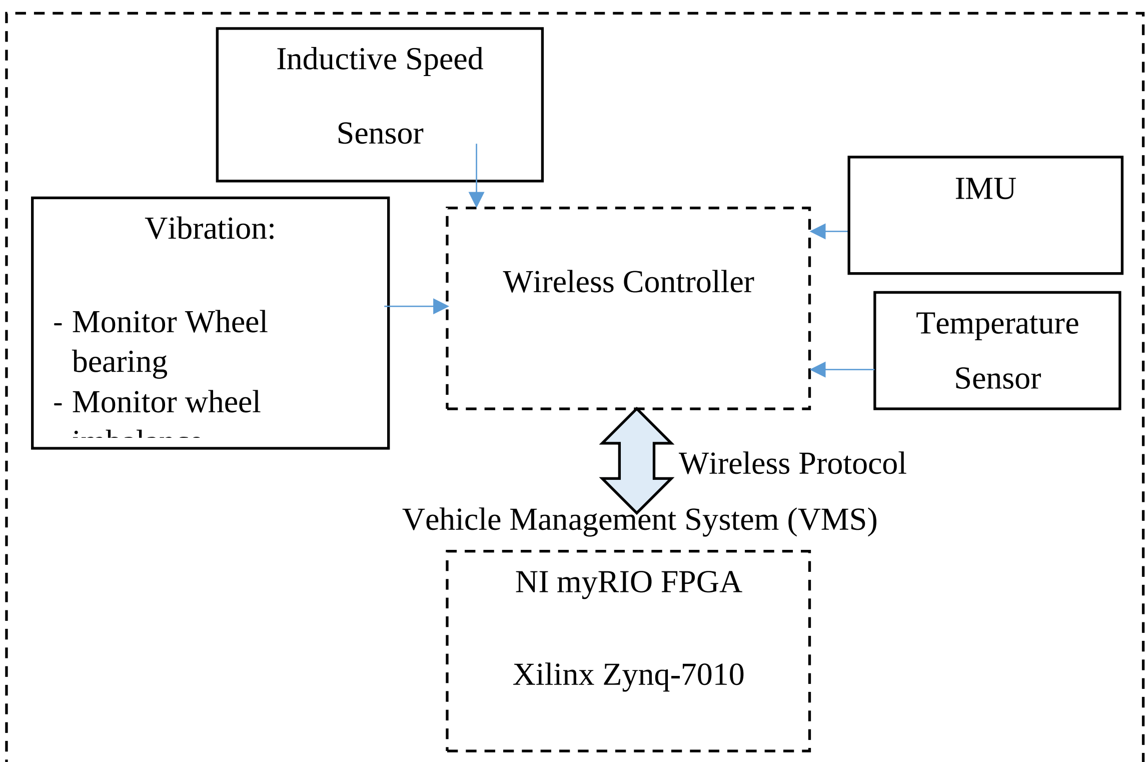

Figure 4.8: Overview of Wheel and Tyre Monitoring System

4.5. Design And Implementation of a Monitoring System Using IoT

Following trials of designing and building a bespoke capsulated sub-system with multi sensing elements featuring various microcontrollers proficient for the mentioned configurations, it was noted a prebuilt kit that maintains industry standards would be more suited, and more reliable. Thus, selection requirement being an easy to use, multi-sensory device that was small but has capabilities to work wirelessly with IoT protocols.

BOSCH XDK 110 applied here is a powerful development tool capable for multipurpose use in the fields of testing, development of new devices, and is widely used in IoT (Internet of Things) applications including environmental, smart agriculture, smart home, smart manufacturing, health monitoring, transportation. Taking advantage of monitoring, control and analyse applications remotely over Bluetooth or Wireless Networks, it allows projects to become smart and be connected. The XDK is a powerful tool for industry standard data collection. It was selected for the implementation of the sub-system that would contribute towards creating an intelligent condition-based monitoring system for driverless vehicle’s steering system.

Concurrently, LabVIEW is an environment where engineers can program graphically and can be advantageously used to develop automated research, validation, and production test systems. It allows to visualise results measured immediately with built in UI creation tools and integrated data viewers. The programming environment simplifies hardware integration for engineering applications so that you can establish a consistent way to acquire data. Additionally, LabVIEW can inter-operate with and reuse libraries from other software and open-source languages to guarantee compatibility with other engineering tools.

This work partly focused on connecting the mentioned two tools (LabVIEW and XDK 110) with IoT protocols for creating a user-friendly monitoring system which would encompass gathered data provided by available sensors on the XDK device and exhibit the developed system through GUI based features of LabVIEW and on an IoT monitoring platform. Design and implementation of the BOSCH XDK 110 device as well as monitoring via IoT platform, the LabVIEW application were simultaneously tested.

The system design would be such that the XDK device reads data from the sensors. The XDK workspace, which is based on Eclipse IDE, is used for executing the overall program of the project to the XDK110 device. The data is sent wirelessly to an online database where it can be viewed via a dashboard. Data is also sent to the LabVIEW application via HTTP REST client where they are also displayed, stored, or otherwise processed. WLAN with MQTT protocol is used with XDK110 to communicate to the IoT application, which enables to access stored data and monitor it from any other device with the correct credentials. i.e., data stored on the database can be monitored from multiple entities. Subsequent sections of the chapter will shed light on the different steps followed to create the described monitoring system.

4.5.1. Hardware Configuration – XDK110

The XDK110 device from BOSCH (Figure 4.9) selected for the application is an all-in-one device that combines sensor data, connectivity, and software development interface in one package. It can be used in scenarios that requires real-time data collection, connectivity to the internet or cloud, and program customization, making it a versatile tool for IoT innovations.

Figure 4.9: BOSCH XDK110 The product dimensions are: 60 mm x 42 mm x 22 mm. Weight: 43g.

The device is inclusive of multiple built-in Micro-Electromechanical Systems (MEMS) of 8 various sensor types and means of connectivity, with the possibility of extending with the ‘XDK Gateway’ extension bus. Additional individual sensors and various parameters for condition monitoring or predictive maintenance methods can be implemented.

The user interface of the XDK has a power switch, and green system LED to display the state of charging, three programmable LEDs (red, orange, yellow), two programmable pushbuttons, Interface for J-Link Debug-probe, Interface for extension board.

The XDK110 comes with an open-source software development (SDK) that makes easy to develop applications and program the device to suit requirements. The XDK can be programmed using C language in its programming environment (IDE) which is an eclipse-based IDE, and or using its own programming language, Eclipse Mita which is focused on making IoT boards easier to program for developers without an embedded development background.

4.5.2. XDK's Onboard Sensor Selection

The built-in components of the XDK are MCU: 32-bit ARM Cortex M3, communication interfaces, internal Li-Ion rechargeable battery, integrated antennas, user interface components and 8 various sensors which include, environmental sensors and the focus for this research, its inertial sensors. This includes Accelerometer BMA280, Gyroscope BMG160, Magnetometer BMM150 and Inertial measurement unit BMI160.

Table 3: Bosch XDK110 Onboard Sensors

Sensors	Range	Rate	Connectivity	Buses / IO
Accelerometer	Programmable ±2 g to ±16 g (G-forced = g)	2000 Hz	LED	GPIO / SD Card
Gyroscope	Programmable ±125 °/s to ±2000 °/s	2000 Hz	ADC	I2C
Magnetometer	±1300 µT (micro-Tesla) (X, Y-Axis); ±2500µT (Z-Axis)	300 Hz	BLE	
Humidity	10% to 90%rh (percentage relative humidity)	182 Hz	WLAN	
Light	0.045 lux to 188,000 lux (22 bit)	-		
Pressure	300 hPa to 1100 hPa (Pascal)	182 Hz	MQTT	
Temperature	-20 °C to 60 °C (Degree Centigrade)	182 Hz	Eclipse Hono over MQTT	
Noise sensor	60 Hz 500-700 mV (Mega Volt)	-	REST over HTTP	
Two buttons			LoRa	

Adopted from (eclipse.dev, n.d.)

The BMA280 (Figure 4.10) is a highly advanced and compact triaxial (X, Y, Z) acceleration sensor designed for low-power consumer electronics applications. It incorporates digital interfaces and offers a 14-bit digital resolution, enabling precise and low-noise measurements of accelerations in three perpendicular axes. It is also noteworthy the temperature range in which the sensor can be operated, from -40 °C to +85 °C. This sensor is particularly suitable for detecting tilt, motion, shock, and vibration in various devices. Although the multiple other sensors available on board, such as environmental, geomagnetic, and ambient magnetic light sensors are exploited, the research specifically focuses on the use of its vibration sensor.

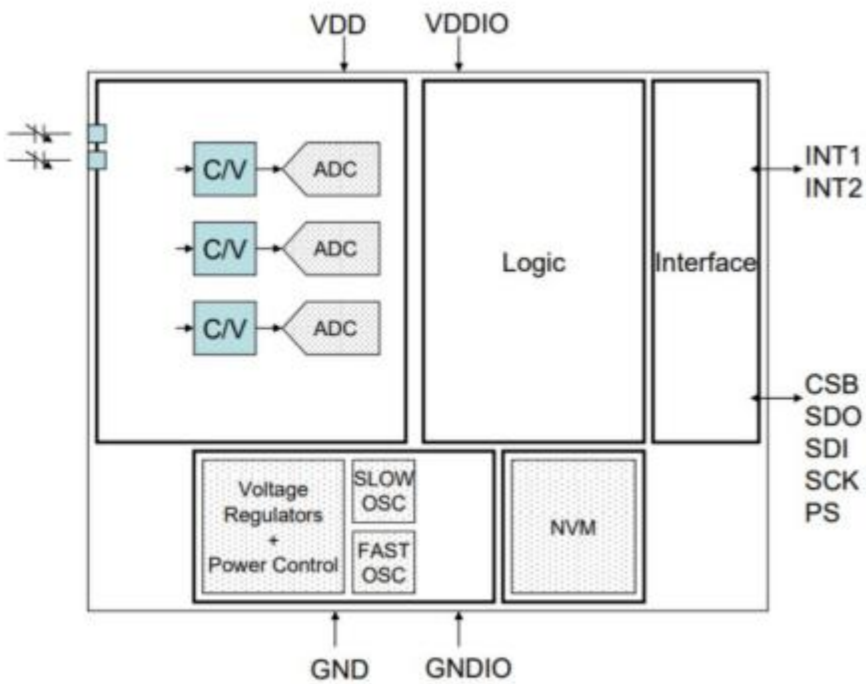

Figure 4.10: Block Diagram for BMA280 (Source: Bosch)

4.5.3. Communication Interface

The XDK consists of various communication techniques to facilitate data transfer and connectivity. Having these multiple communication options provide flexibility and connectivity to different networks, devices and applications depending on requirements. This key feature enables the possibility of IoT. The communication techniques supported by XDK110 are detailed in this section.

Universal Serial Bus (USB) Video Camera

The Bosch XDK 110 development board includes a Micro-USB connector for connecting to a PC. This USB 2.0 interface is available for data transfer, charging or for flashing the device with the programmed firmware.

JTAG

JTAG stands for ‘Joint Test Action Group’ also known as IEEE 1149.1, it is a standard interface used for testing and debugging circuits in the electronic industry - integrated circuits (ICs), printed circuit boards (PCBs) in particular. JTAG allows communication between a testing device and the device being tested. With the XDK, it is possible to programme the device via JTAG as well as carry out the standard tasks. Unused for the research application.

Expansion board

Additionally, also included with XDK is an expansion board called ‘XDK Gateway’ with additional pinouts which allow easy implementation for additional functions. Works at a voltage level of 2.5V with several setting for current (0.5 mA, 2 mA, 6 mA, 20mA). While all pins can handle 20mA, the maximum amount for the expansion board is 50mA. Unused for the research application.

Bluetooth

Bluetooth enables wireless communication between devices such as smartphone, tablets, or other Bluetooth-enabled devices within a closer proximity range. It was published in 1999 and adopted as the IEEE 802.15.1 standard. Numerous versions are available with the newer versions of Bluetooth having reduced consumption – Bluetooth Low Energy (BLE). he commonly used frequency band is 2.4 GHz and the range varies depending on the version, most often between 50 and 200 meters. Unused for the research application.

LoRa

LoRA, short for Long Range, is a wireless protocol designed for long-range transmission of data between devices with low power consumption. It uses a modulation technique called Chirp Spread Spectrum (CSS) to achieve long range capabilities. LoRa in the XDK110 enables the kit to communicate with other LoRa devices or LoRaWAN networks, providing extended coverage and connectivity options for IoT applications. Unused for the research application.

WLAN

Wireless Local Area Network (WLAN) is the network standard used by the device, also known as WiFi. This capability allows the XDK110 wireless communication and connectivity via internet. IoT is made possible for this research by connecting to the internet to be able to send sensor data via MQTT onto Akenza.io database. Akenza is an IoT platform which allows to connect, control, and manage IoT devices from one space, utilising its database for storage in this application. The data is required to be read instantly without further delays; hence, the higher data flow is preferable to power consumption and WLAN selected for wireless communication.

4.5.4. Communication Protocol

The XDK Workspace development environment provides libraries for various wireless communication protocols. These protocols include HTTP (Hypertext Transfer Protocol), UDP (User Datagram Protocol), CoAP (Constrained Application Protocol), MQTT (Message Queuing Telemetry Transport). HTTP is used for communication with web servers, while UDP is a lightweight protocol commonly used for real-time multimedia services. CoAP is a lightweight protocol designed for resource-constrained devices in IoT networks. It follows a client/server model and provides communication for constrained devices over UDP or SMS transport. MQTT is a machine-to-machine (M2M) protocol based on publish/subscribe communication, widely used in IoT applications. The firmware development for the XDK will utilise the Eclipse Mita language, implementing functions for MQTT protocol.

Originally developed in 1999, MQTT began as a proprietary protocol designed to communicate with supervisory control and data acquisition (SCADA) in the oil and gas industry systems over satellite. In 2010, MQTT was released as a royalty-free protocol, allowing widespread adoption and usage. Furthermore, in 2014, it became an OASIS (Organization for the Advancement of Structured Information Standards) standard, further solidifying its status as an open and widely accepted messaging protocol. This transition has facilitated the broad application of MQTT across various industries and use cases beyond its original scope (Hunkeler et al., 2008).

MQTT follows a publish/ subscribe pattern, where devices or applications can take the role of a publisher that sends information or collected data as messages to a broker, and other devices or applications acting as subscribers receive these messages from the broker as illustrated in Figure 4.11. Once a connection is established, the broker will keep it active as long as the client does not perform a disconnect or the connect is lost.

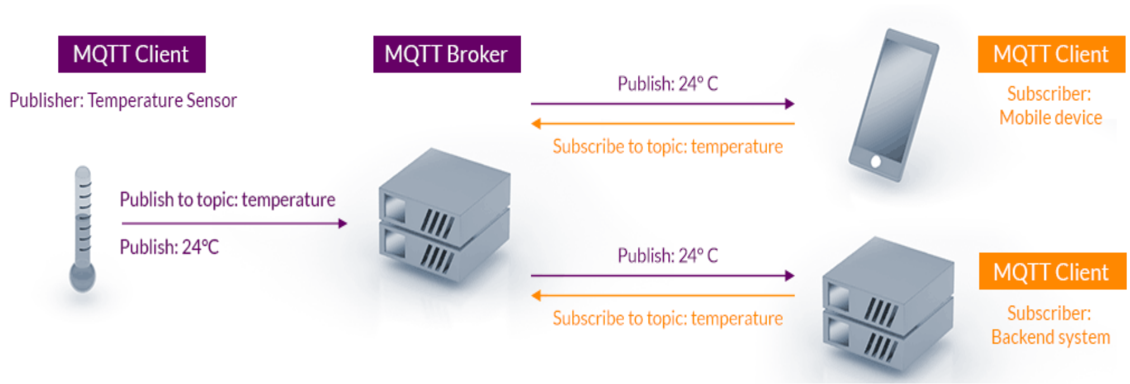

Figure 4.11: MQTT Publish/ Subscribe Architecture (Source: mqtt.org)

Publishing: Publishers send messages to the MQTT broker by specifying a topic and the content of the message. The broker receives these messages and forwards them to interested subscribers based on their topic subscriptions.

Subscribing: Subscribers connect to the MQTT broker and subscribe to specific topics of interest. The broker delivers messages to subscribers based on their topic subscriptions. Subscribers can subscribe to specific topics or use wildcard patterns to receive messages selectively.

Key features of MQTT pub/sub:

1. Lightweight: MQTT is designed to be lightweight and efficient, making it suitable for constrained environments with limited bandwidth and resources.
2. Asynchronous: Messages are sent and received asynchronously, allowing devices to communicate efficiently without waiting for responses.
3. Quality of Service (QoS): MQTT supports different QoS levels to ensure message delivery reliability. QoS levels range from "at most once" (where messages can be lost) to "exactly once" (ensuring message delivery without duplicates).
4. Scalability: MQTT pub/sub can scale to handle large-scale deployments and high message loads, allowing for the seamless integration of numerous devices and applications.
5. Reliability: MQTT brokers often provide mechanisms for persistent connections and message persistence, ensuring reliable message delivery even during network disruptions or device failures.

MQTT is currently one of the most used protocols in IoT projects. It is known for its lightweight nature which enables it to be implemented on small microcontrollers and devices with constrained capabilities making it ideal for connecting remote devices with limited resources and low network bandwidth.

MQTT supports bidirectional messaging between device to cloud and cloud to device, facilitating easy broadcasting of messages to groups of devices. This capability is particularly valuable when large-scale communication and coordination are required. With the ability to scale and connect with millions of IoT devices, MQTT offers a robust solution for deployments of varying sizes and complexities.

In IoT environments, security is of utmost importance, and MQTT provides mechanisms to address this concern. The protocol facilitates seamless integration with Transport Layer Security (TLS) for message encryption, guaranteeing confidentiality and integrity. Moreover, MQTT supports contemporary authentication protocols such as OAuth, enabling secure client authentication (Figure 4.12). This ensures the protection of communication between MQTT clients and brokers.

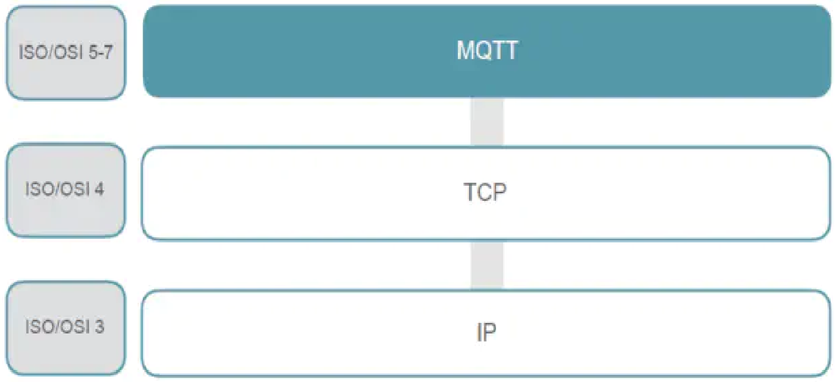

Figure 4.12: MQTT protocol is based on TCP/IP, and all clients and the broker need to have a TCP/IP Stack (Source: mqtt.org)

Overall, MQTT pub/sub provides a flexible and efficient communication model, allowing devices and applications to exchange data in a decentralised and scalable manner. It is widely adopted in IoT and M2M scenarios due to its lightweight nature and support for reliable messaging. The use of this communication method is well suited for the application of predictive maintenance and monitoring in the automation industry as described. Therefore, MQTT was chosen as the IoT protocol for wireless communication of the IMSDV.

4.5.4.1. Implementation of A Broker

In the MQTT protocol, a broker acts as a central intermediary or hub that facilitates the communication between publishers and subscribers. It receives messages from publishers and sends them to subscribers who are interested in those messages based on the topics they have subscribed to. The broker manages the routing and delivery of messages, ensuring that they reach the intended recipients. It also handles security, session management, and QoS levels to ensure reliable communication. Essentially, the broker facilitates the exchange of messages between publishers and subscribers in the MQTT network.

There are several MQTT brokers available on the market, both open-source and commercial that could be used for implementing MQTT-based communication. Eclipse Mosquitto, HiveMQ, RabbitMQ are few examples of specifically dedicated MQTT brokers. The choice of broker depends on factors such as scalability, required features, deployment environments and so forth as required for specified projects.

Eclipse Mosquitto which is an open-source MQTT broker that is widely used and highly regarded for its scalability and ease of deployment. It is available for various platforms including Windows, Linux, mac as well as other options of embedded systems.

Eclipse Mosquitto Broker

For this approach, the broker is linked with the XDK110 device to read acquired data. The XDK 110 device is supported with its own software platform – XDK Workspace which is programmable using C or Eclipse Mita which is a new programming language for embedded IoT. Code written using the Workspace will be debugged and flashed to the XDK device itself which will collect the data from the sensors and send to the Mosquitto broker.

To begin with, the Eclipse Mosquitto Broker was downloaded and installed. Variants of the version depended on the operating system are available. After the installation, a configuration file needs to be created to customise the MQTT setup. The configuration file should include two important commands. The first command, "listener 1883," specifies the port on which the MQTT broker should listen for incoming connections. The second command, "allow_anonymous true," enables anonymous devices to connect to the broker without requiring a name and password for authentication.

For prefer of secure communication, an alternative option is to username and password authentication. This involves creating a file that lists the name and password pairs on separate lines, with each pair separated by a colon. The file can include multiple pairs for multiple secure connections. Once the file is created, it needs to be encrypted using the "mosquitto_passwd -U passwordfile" command in the command line.

In the configuration file, set "allow_anonymous" to false and provide the path to the password file using the line "password_file c:\mosquitto\passwords.txt" (replace the path with the actual path to password file). The configuration file should have the extension "conf" and can be named something like "myConfFile.conf." Ensure that the configuration file is placed in the installation directory of Mosquitto.

To start the MQTT broker, use the command "mosquitto -v -c myConfFile.conf" in the command line. The "-v" option enables verbose mode, and the "-c" option specifies the path to the configuration file. Check if the broker has successfully started by using the "netstat -a" command and verifying if it is running on the specified port mentioned in the configuration file.

To publish messages, execute the command "mosquitto_pub -h 127.0.0.1 -p 1883 -m 'test message' -t test" in the command line. In this command, the IP address of the MQTT broker can be specified using "-h," the port using "-p," the content of the message using "-m," and the topic using "-t." The message entered will be displayed in the command line where the subscriber is running.

Implementing wireless communication over MQTT using Eclipse Mosquitto provides an easy and cost-effective solution for reading data from the XDK 110 device. By following the installation steps, configuring the MQTT broker, and publishing messages, a wireless communication was established quickly and efficiently. Further customisation and exploration to connecting the broker with the specified Akenza.io IoT platform and other clients were achieved, here after.

4.5.4.2. MQTT Client Publisher

The role of a publisher is commissioned to the XDK110 device itself as it is used for acquiring data.

To utilise MQTT a network connection needs to be established with the target server. WiFi is commonly employed to establish this connection with the XDK. A personal hotspot set up for the PMP’s WiFi requirements has been shared for the MQTT requirements.

```
// resource for WiFi connectivity
setup wifi : WLAN {

    //shared hotspot with PMP
    ssid = 'mySSID';
    authentication = Personal(psk = 'myPassword');

}
```

The next required step was setting up an MQTT resource. Typically, essential parameters such as url, clientId and transport are required. The url configuration-item represents the MQTT broker's address, for example, mqtt://mqtt.broker.url.com:1883. The clientId configuration-item serves as a unique identifier for the XDK device. Lastly, the transport configuration-item refers to the Wi-Fi resource responsible for transmitting the MQTT messages. It establishes the communication channel through which the messages are sent to the MQTT broker.

'keepAliveInterval' of type 'unit32' can also be configured to define how long the destination broker will keep the session between the broker (mosquitto) and the XDK alive for. The timer for this is reset every time the XDK sends a control packet message or a ping. The default value for this configuration is 60 seconds. The broker session is stopped when the keep alive period times out.

```
// resource for MQTT Broker
setup Broker : MQTT {
    transport = wifi;
    cleanSession = true;
    url = 'mqtt://mqtt.broker.url:1883'; //broker url/ip
    clientId = 'myXDK'; // clientId should be unique for each broker. Device ID recommended
    authentication = Login('Username', 'Password');         // if authentication is required
    var nameTopic = topic('XDK110/myXDK/nameTopic', 0);     // "nameTopic" is a variable of type signal.
                                                            //can have multiple topics signals as desired
}
```

Following setup of the WiFi resource and MQTT, acquired data can be published. For the purpose of the model being tested, an event on the XDK's code was created for reading accelerometer data. Acquired every 1 millisecond and sent to the broker as JSON string. The data being sent could also be monitored on XDK Device Console as shown in Figure 4.13.

```
Connecting to XDK device 'XDK Device 1' in port 'COM4'...
Connection to port 'COM4' established
XDK DEVICE 1: [INFO, C:/Users/[redacted]/XDK-Workspace/XDK_MQTTonakenza_EclipseMitaApp/src-gen/base/ConnectivityWLANWifi.c:98] init WlanNetworkConnect succeeded
XDK DEVICE 1: [INFO, C:/Users/[redacted]XDK-Workspace/XDK_MQTTonakenza_EclipseMitaApp/src-gen/base/ConnectivityWLANWifi.c:113] setting DHCP succeeded
XDK DEVICE 1: [INFO, C:/Users/[redacted]/XDK-Workspace/XDK_MQTTonakenza_EclipseMitaApp/src-gen/base/ConnectivityWLANWifi.c:121] Connecting to personal network: [redacted]
XDK DEVICE 1: [INFO, C:/Users/[redacted]XDK-Workspace/XDK_MQTTonakenza_EclipseMitaApp/src-gen/base/ConnectivityWLANWifi.c:155] Connected to WLAN. IP address of this device is: 192.
XDK DEVICE 1: [INFO, C:/Users/[redacted]/XDK-Workspace/XDK_MQTTonakenza_EclipseMitaApp/src-gen/main.c:216] enable ConnectivityWLANWifi succeeded
XDK DEVICE 1: [INFO, C:/Users/[redacted]/XDK-Workspace/XDK_MQTTonakenza_EclipseMitaApp/src-gen/main.c:226] enable ConnectivityMQTTAkenzaBroker succeeded
XDK DEVICE 1: [INFO, C:/Users/[redacted]DK-Workspace/XDK_MQTTonakenza_EclipseMitaApp/src-gen/main.c:236] enable PlatformXDK110 succeeded
XDK DEVICE 1: [INFO, C:/Users/[redacted]XDK-Workspace/XDK_MQTTonakenza_EclipseMitaApp/src-gen/main.c:246] enable SensorAccelerometer succeeded
XDK DEVICE 1: [INFO, C:/Users/[redacted]/XDK-Workspace/XDK_MQTTonakenza_EclipseMitaApp/src-gen/main.c:256] enable SensorEnvironment succeeded
XDK DEVICE 1: [INFO, C:/Users/[redacted]/XDK-Workspace/XDK_MQTTonakenza_EclipseMitaApp/src-gen/main.c:266] enable SensorButton_one succeeded
XDK DEVICE 1: {
XDK DEVICE 1:         "accx": 20, "accy": 7, "accz": 540,
XDK DEVICE 1:        "temperature": 14.9025
XDK DEVICE 1:
XDK DEVICE 1:     }
XDK DEVICE 1: {
XDK DEVICE 1:         "accx": 22, "accy": 5, "accz": 540,
XDK DEVICE 1:        "temperature": 14.9025
XDK DEVICE 1:
XDK DEVICE 1:     }
XDK DEVICE 1: {
XDK DEVICE 1:         "accx": 18, "accy": 8, "accz": 542,
XDK DEVICE 1:        "temperature": 14.9025
XDK DEVICE 1:
XDK DEVICE 1:     }
XDK DEVICE 1: {
XDK DEVICE 1:         "accx": 21, "accy": 6, "accz": 543,
XDK DEVICE 1:        "temperature": 14.9025
XDK DEVICE 1:
XDK DEVICE 1:     }
XDK DEVICE 1: {
```

Figure 4.13: Data from XDK110 device

4.5.4.3. MQTT Client Subscriber

As shown in Figure 4.14, MQTT allows the possibility of multiple subscribe clients. 1000+ clients can be easily handled by the major MQTT brokers. For the purpose of IMSDV, there will mainly be two subscriber clients: LabVIEW, Akenza.io.

Subscriber: LabVIEW

All individual MQTT Client Subscribers require MQTT resources to be set up on their own source. For LabVIEW, to be able to use the protocol, it was necessary to install appropriate plugins. The LabVIEW open-source MQTT project and associated modules were installed from the VIPM (Visual Instruments Package Manager) add-ons management program. The open-source projects consist of prepared example applications that can be found in the attached libraries for subscriber, publisher, or broker along with its relevant packages. To create the required subscriber client for receiving messages, an example client within the library was deployed, modified to display plotted data, and extended to meet the requirements of the designed application.

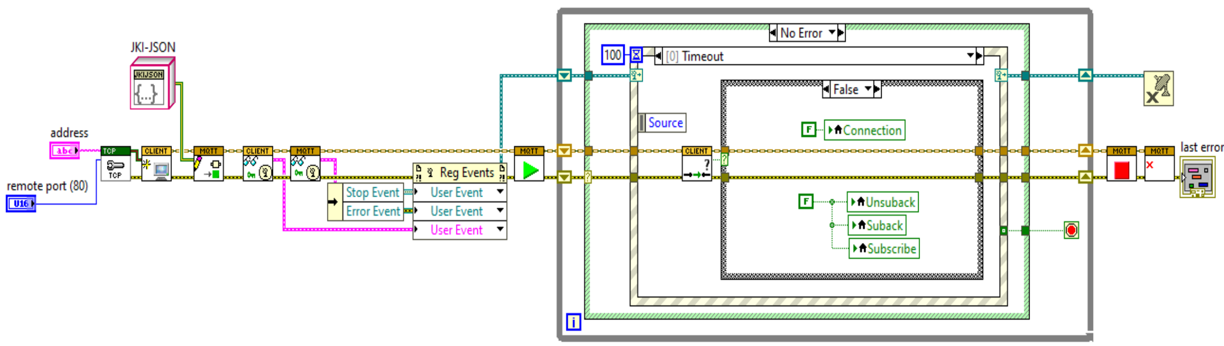

Figure 4.14: MQTT Subscriber sample from plugin modified to suit requirements for client

Subscriber: Akenza.io

Akenza.io platform where device provisioning, data visualisation, data analytics, remote device management, and integration with other IoT services can be benefitted. Collected data is analysed and actions upon collected data is transmitted.

Akenza.io is an IoT platform that provides tools and services for managing and deploying IoT solutions. While it offers device provisioning, data visualization, data analytics, remote device management, and integration with other IoT services, it also includes MQTT functionality.

The Akenza.io platform was connected to the selected MQTT broker, Eclipse Mosquitto by configuring the MQTT settings within the Akenza platform. This typically involves specifying the broker's host, port, and necessary authentication credentials. Once connected, the published topics were able to be subscribed to on the Mosquitto broker and receive message from the XDK publisher.

Akenza.io provides a user-friendly interface and tools for managing MQTT connections, viewing received messages, and integrating MQTT data into the IoT solution. It can serve as a convenient way to leverage the capabilities of an MQTT broker like Eclipse Mosquitto while benefiting from the additional features and services provided by the Akenza.io platform. A key feature that benefits the research is the availability of the data visualisation tool – dashboard, and the rule engine.

During the research, the XDK110 device was helped to be set up in partnership with Akena.io in turn to benefit access from the full version of the Akenza.io IoT platform. Additionally, a form of marketing was also contributed with the company as part of the agreement. This aided the research to make full use of available features on the platform that would normally be charged on a subscription fee.

Additionally, another option which was explored for interacting with Akenza.io is through rest API with HTTP GET. In this set up, XDK was linked directly with the Akenza.io platform following all previous steps of setup. Only changes with setup were rather than the XDK device MQTT protocol being programmed to be linked to mosquito broker, data was directly sent to Akenza.io. Hereby, the acquired data is also sent from Akenza's database to the LabVIEW application as shown in Figure 4.15, 4.16.

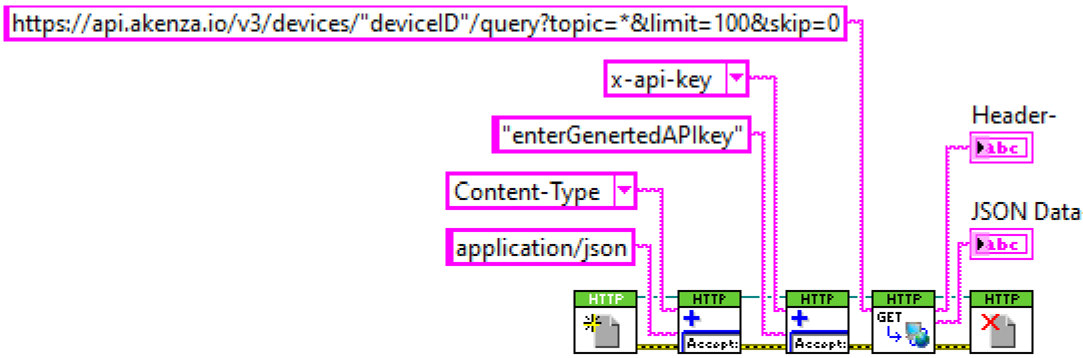

Figure 4.15: HTTP GET request from LabVIEW via REST API to Akenza.io platform

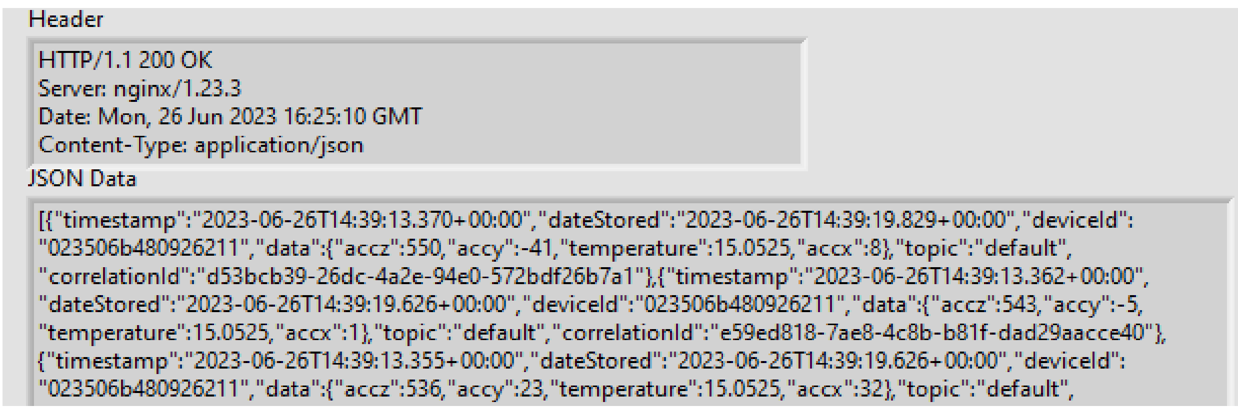

Figure 4.16: Received data from Akenza.io through REST API as JSON string

This section of the chapter explained the possible use of IoT communication protocols to enable monitoring and diagnosis of autonomous vehicle components using an XDK110 device integrated with cloud monitoring enabled. Akenza.io platform is consequently utilised to enable its dashboard viewing properties which can be accessible from anywhere in the world using the correct credentials.

For the application of diagnostics where the device will be attached to the PMP under investigation and data from the accelerometer and other relevant sensors the developed system proves to be sufficient.

4.6. Personal Mobility Pod's Wheel

Wheel bearings play a vital role in the optimal performance of a vehicle by facilitating smooth wheel rotation. Their significance lies in ensuring the healthy functioning of the vehicle and minimising friction caused by other components within the drivetrain system. However, when wheel bearings sustain damage or require replacement, it can affect linked elements and lead to other significant issues.

There are several signs that indicate a wheel bearing in a vehicle is failing. While it is uncommon for wheel bearings to fail suddenly and catastrophically once the initial warning sign are noticed, it is highly advisable to refraining from driving with failing wheel bearings. As mentioned in the preceding, wheel bearings play a critical role in linking the wheel to the vehicle and driving with worn wheel bearings can cause serious damage to the steering assembly and the drive axel and ultimately be a major safety hazard.

Some common indicators of damaged wheel bearings are:

- Unusual noise in the form of humming / growling / clunking that becomes more pronounced with increase in speed.
- Vibration on the steering wheel or the floor that may change with speed and/ or as the vehicle turns.
- Loose wheel or excessive play in the steering wheel. However, this could also be induced by other suspension or steering components.
- ABS Malfunctioning which could be related to ABS sensor that is mounted in the wheel end bearing.

The mentioned signs server as warnings to the driver/ owner, indicating the need for timely intervention by a qualified automotive technician who can conduct proper diagnostic procedures. However, for a fully autonomous vehicle classified at Level 5 of automation, where human attention or interaction is not required for any dynamic driving tasks, a monitoring system that would trigger alerts depending on health conditions of vehicle components is suggested to contribute towards developing an Intelligent Management System for Driverless Vehicles. These reasonings pointed to wheel bearing as being a main focus point for the design application.

4.6.1. Experimental Bearing Type

Most automotive wheel bearings fall into two main designs: ball bearings and tapered roller bearings. Ball bearings are commonly found in passenger cars due to their low friction and suitability for high engine speeds. However, they are not as effective in handling severe side loads as tapered roller bearings.

Tapered roller bearings, on the other hand, are typically used in commercial vehicles or vehicles that experience higher side loading. They have a larger contact area between the rolling elements and the races, allowing them to absorb high radial forces. However, they are not as suitable for high engine speeds.

The choice between ball bearings and tapered roller bearings depends on the specific application and the trade-offs between high engine speeds and severe side loads. Various settings rolling elements, rows, fittings are modified for different use cases.

The wheel bearings being a focus group for the research, preparation for testing and testing was carried out on the developed PMP. The small machine's intended use being for personal mobility, the mechanics of the set up was different to that of a road legal car. PMP's original form being intended for mobility scooter usage, manufacturers fitted roller bearings. The forces acting on the wheel bearing for the PMP would be mainly radially due to the steering system difference in comparison.

The bearing type evident on the original scooter were checked to review its viability for the study. The scooter wheels were fitted with 6202 - deep groove ball bearings (Figure 4.17) with seals fitted on both sides.

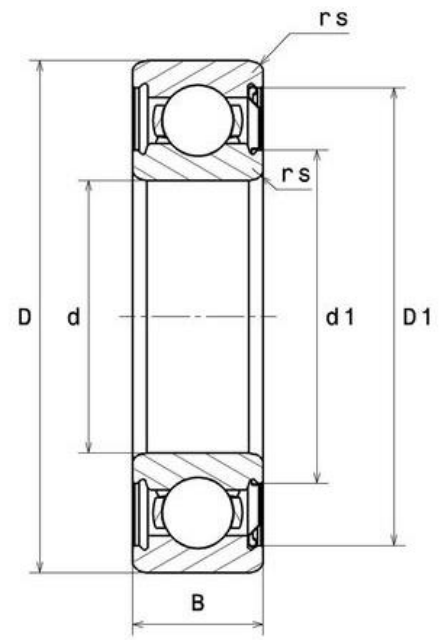

Figure 4.17: Deep groove ball bearing 6202

Table 4: NTN 6202 Product Definition

Brand	NTN
d - Internal Diameter	15 mm
D - External Diameter	35 mm
B - Bearing/Inner Ring Width	11 mm
rs - Min Fillet Radius	0,6 mm
Radial Clearance Class	CN
Mass	0,045 kg

Table 5: NTN 6202 Product Performance

C - Dynamic Load	8,6 kN
C0 - Static Load	3,6 kN
Cu - Fatigue Limit Load	0,279 kN
f0 - Coefficient	12.7
Nlim - Oil Lubrication Limit Speed	23000 tr/min
Nlim - Grease Lubrication Limit Speed	19000 tr/min
Tmin - Min Operating Temperature	-40 °C
Tmax - Max Operating Temperature	120 °C

This type of bearings is particularly versatile, have low friction and are optimized for low noise and low vibration, which enables high rotational speeds. They accommodate radial and axial loads in both directions, are easy to mount, and require less maintenance than other bearing types. The integral sealing can significantly prolong bearing service life because it keeps lubricant in the bearings and contaminants out. This existing bearing type used or the original sooter meets the criteria for the proposed test application. Therefore, new bearings of the same type were purchased and purposed for the proposed tests to aid developments of an IMSDV.

4.6.2. Diagnosis Method

Many publications have addressed the effectiveness of monitoring wheel bearings. Defected wheel bearings could lead to catastrophic failures if not maintained. In driverless vehicles, this is an area which needs further investigation. Level 5 of SAE’s automation standards classify fully autonomous vehicles that can handle all driving tasks under all conditions. No human intervention is required. Consequently, to take ownership of arising problems such a monitoring system would aid the maintenance strategies to improve safety and efficiency of the vehicles.

Monitoring the life of wheel bearings could be used to develop advanced maintenance strategies for driverless vehicles using wireless monitoring system. Wheel bearing defects will create excessive vibration, such signals could be monitored through using vibration sensor and provide warning systems.

There are several techniques available which can be used for detection and diagnosis to monitor the health of a bearing. Namely they may be broadly classified as acoustic measurements, temperature monitoring, wear debris analysis and vibration measurements. Previous studies that have carried out extensive review of the different detection techniques used for rolling bearing defects have concluded the most effective method of them all to be vibration monitoring. Vibration analysis is highly reliable and sensitive to the severity of faults, offering clear indications of the bearing's condition. By analysing the level and frequency of vibrations, it becomes possible to pinpoint the precise location and assess the potential severity of any defects. Therefore, due to its ease of application and effectiveness, vibration analysis is widely recognized as the preferred technique for bearing assessment. (Karakaş, 2022).

Fault detection methods using vibration analysis can be done in different formats. Time domain and frequency-domain analyses are among the most frequently used. Amongst other choices, selection of a method depends on factors such as the specific machinery and fault types to be detected, the available computational resources, and the required speed and accuracy of the fault detection system. For the current settings of the system, time domain analysis has been selected.

Time-domain analysis involves analysing the vibration data as a function of time. It focuses on extracting waveform indices or parameters that are calculated from the vibration signal. These indices provide numerical values that can be used for data comparison and trend analysis. By monitoring the trends of these waveform signals over time, deviations from normal behaviour can be identified, allowing for timely fault detection and maintenance actions.

In the context of wheel bearings, the consequences of a failure can be significant, affecting both vehicle safety and operational efficiency. Therefore, a proactive approach to monitoring and addressing even small deviations in vibration levels is often recommended. Regular vibration analysis, combined with other forms of inspection and monitoring, can help ensure the reliability and safety of wheel bearings in automotive applications.

Some commonly used waveform indices in time-domain analysis for fault detection include:

1. Peak-to-peak value: This index indicates the difference between the maximum and minimum amplitudes within a given time interval. This indicator is particularly useful for assessing the dynamic behaviour of the vibration and identifying significant variations or anomalies. Sudden increases or deviations from the normal range may indicate the presence of faults or abnormal operating conditions by comparing the peak-to-peak amplitudes of vibration signals.
2. Kurtosis: Kurtosis is a statistical measure that assesses the shape of the vibration signal's distribution. High kurtosis values indicate a more peaked or heavy-tailed distribution, which can be associated with certain fault conditions.

$$\text{Kurtosis} = \frac{N\sum_{i=1}^{n}(\text{xi}-\bar{\text{x}})^4}{[\sum_{i=1}^{n}\ (\text{xi}-\bar{\text{x}})^2\ ]^2} \tag{9}$$

Kurtosis is indeed an indicator of peakedness and is sensitive to the impulsive content of the signal, making it useful for detecting localised bearing faults. Its sensitivity to impulsive vibrations, often associated with early-stage faults, makes kurtosis widely employed for fault detection, especially in the initial stages.

However, it is important to note that kurtosis is not suitable for tracking the condition of a bearing as it worsens over time. As the bearing condition deteriorates, the vibration data becomes more random, and the impulsive nature of the signal diminishes while noise increases. Consequently, the kurtosis value, which initially increases during the early stages of a fault, will start to decrease.

In fact, the kurtosis value of vibration signals generated by bearings in good condition is typically around three. Deviations from this baseline value can indicate the presence of fault conditions. Therefore, kurtosis can be an effective tool for early fault detection, but its usefulness diminishes as the bearing condition progresses and becomes more severe.

3. RMS (Root Mean Square): RMS represents the square root of the mean of the squared amplitudes of the vibration signal. It provides a measure of the overall energy or magnitude of the signal and can help identify changes in vibration levels, illustrated in Figure 4.18.

$$\text{Root Mean- Square (RMS)} = \sqrt{\frac{1}{N}\left[\sum_{i=1}^{n} (X_i)^2\right]} \quad (10)$$

Since the RMS value considers both the positive and negative portions of the waveform, it provides a comprehensive assessment of the vibration magnitude. It is particularly useful in evaluating the destructive potential of the vibration, as higher RMS values indicate higher energy content, which can lead to increased wear, fatigue, or damage in mechanical systems.

Therefore, the RMS value is a valuable parameter for assessing vibration severity and determining appropriate maintenance or corrective actions based on the energy content of the vibration signal.

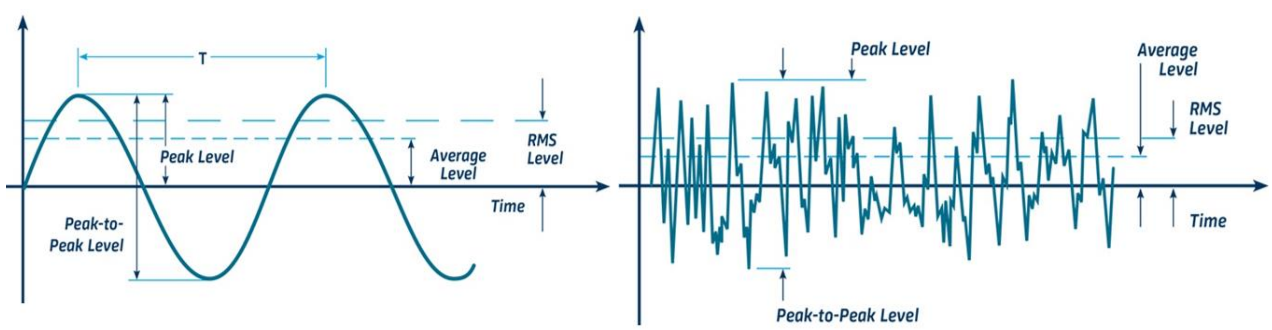

Figure 4.18: Root Mean Square (RMS) and Peak to Peak definition (Brüel & Kjær)

4.7. Summary

In the earlier sections of the chapter, a case study style approach is used to explain the possible area of improvement/ contribution to improve reliability and safety for driverless vehicles. A discussion of some background literature and current developments according UK's development tracks is summarised. Leading to the methodology, the current industry standard testing in the automotive industry is also explained. Road simulator test rigs used for the durability testing is explained. In 'Plan of Action' part of the chapter explains how a similar concept is ought to be used and the area of further improvement is explained in more detail.

Second sections of the chapter detail the design and implementation of a monitoring system using IoT. The proposed sensing device is explained and how IoT based communication - MQTT protocol is a viable option for the experimentation is detailed. Further description of how the device can be implemented with the described MQTT protocol is illustrated with the necessary MQTT client subscriber – Akenza.io and LabVIEW.

Finally, go onto detail the design, development and implementation of the proposed sub-system that would evaluate health conditions & safety of the steering components – wheel bearing. The diagnosis method to be used as part of the testing is explained. The experimental bearing type used on the developed PMP is explained and reviewed for its suitability with the current set up.

The next chapter, '5. Testing and Validation' will detail the experimental set up and results testing, and validation carried out on the PMP system as well as the developed sub-system individually and go onto validating the developed sub-system using the test platform (PMP).

CHAPTER 5

TESTING AND VALIDATION

5.1. Introduction

This chapter details the testing & validations strategies carried out due course. The stages of testing were split into sections, where initial stages of testing involved the developed PMP. Followed by testing of the developed sub-system. Latter stages concluded the testing and validation of the complete system applicability where the sub-system was mounted on the developed test platform (PMP) to operate in autonomous mode and provide real time feedback from the system.

5.2. Testing of The Developed Personal Mobility Pod (PMP)

To evaluate how well the developed PMP performs under different conditions and to validate its accuracy using analytical approaches, a series of test procedures were carried out. These tests employed a two-step process that thoroughly examined and confirmed the functionality of the Pod ensuring its alignment with the original contributions by aiding in the development of the IMSDV.

5.2.1. Experimental Test Bench Setup for Laboratory Testing of Personal Mobility Pod

Testing of the PMP were split to distinct categories. Components at an individual level were initially tested to evaluate the design in lab and later grouped tests carried out in field testing. Individual component testing covered the PMP's drive actuator, steering actuator, battery packs, GPS, IMU, object detection and other associated circuitry and sensors. Field testing for the pod included manual mode operation tests and focused on the autonomous features such as localisation of the Pod, motion control systems.

Following preparations of components with subsequent software development through the LabVIEW platform, a complete system run was the next step within the lab. These tests were carried out within the laboratory environment utilising the test bench arrangement as mentioned in Chapter 3. Reproducing purpose-built industry standard test rig setups mentioned in Figure 4.5, an elevated test setup arrangement was created for the PMP, shown in Figure 3.4.

User Interface

As the UI a portable laptop is mounted the PMP which allows the user to interact with the LabVIEW GUI to specify a desired location and run PMP (Path Planning) program and visually monitor onboard vehicle status. The PMP could also be controlled via the UI in admin, manual mode.

1. User Interaction: The user utilises the LabVIEW GUI on the PMP to specify the desired location. This could be done by inputting an address or coordinates.

2. Google Maps API Integration: The PMP program interacts with the Google Maps API by sending an HTTP command. This command includes the desired location specified by the user. After sending the HTTP command to the Google Maps API, the PMP program receives an image map with waypoints to the desired location. This map may display the recommended route to the destination.
3. Distance and Travel Time Calculation: The GUI interface informs the user about the calculated distance between the current location and the desired location, as well as the estimated travel time. These values are obtained from the Google Maps API in conjunction with onboard sensors response.
4. Vehicle Monitoring: The user can also monitor various aspects of the vehicle's status and environment through the GUI. This includes the vehicle's position, speed, and heading angle. Additionally, other user beneficial information regarding the pod.

A portable laptop served as the user interface (UI) shown in Figure 5.1, enabling remote access and control. Wireless control of subsequent circuitry, sensors, and actuators for the operation of the PMP was made possible by establishing wireless communication through the NI myRIO FPGA module. Wireless connectivity was used during testing for most component. Although, the complete autonomous PMP features wired connections for more efficiency and reduced latency and any connectivity issues.

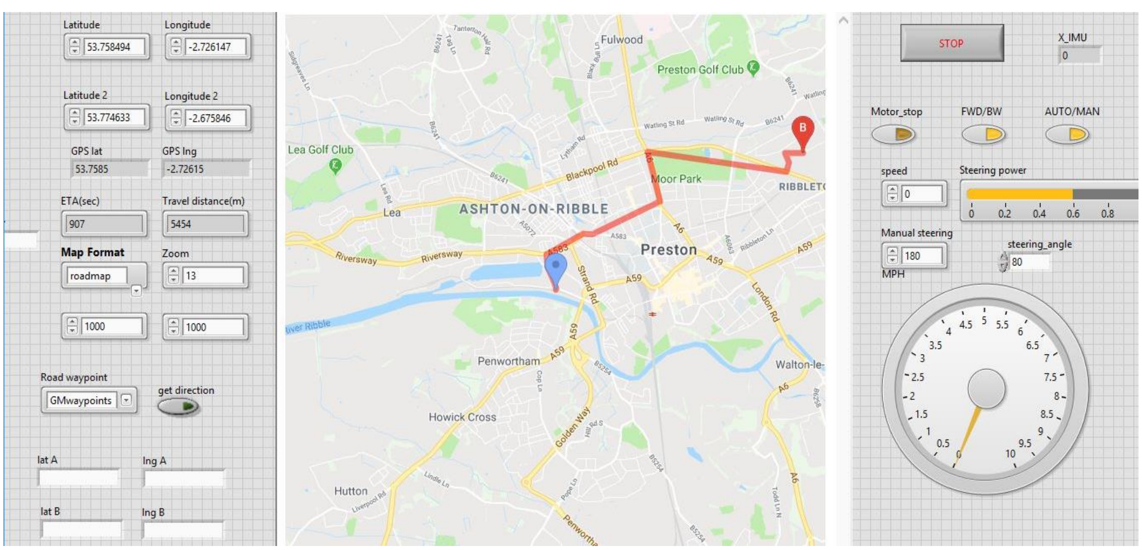

Figure 5.1: User Interface for PMP

Drive Motor Control Testing

To test the motor operation, timely stop/ start functionality, a pre-programmed sequence was created, placing structured loops and case structures consisting of various moves creating a sequence, each lasting up to specified time delays. Thus, real-time sensory feedback was used to stop the Pod from crashing. For comparison of case structure, the motor outputs were recorded, as shown in Figure 5.2. The graph plots the acquired data from the main drive motor. It illustrates two critical functions - Forward/Reverses movements. The Pod was wirelessly controlled using the FPGA controller using digital I/O with additional motor control circuitry for this test to evaluate its operation through LabVIEW.

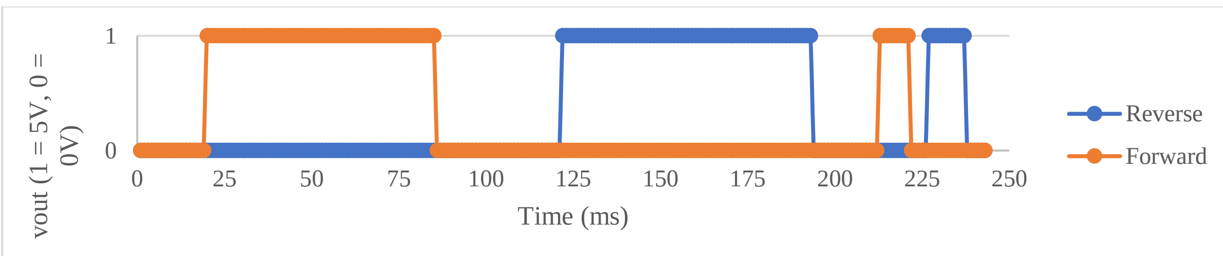

Figure 5.2: Drive Motor Operational Test Data - Logged During Sequence Trials with Object Avoidance

From this test, the expected results were obtained. The motor was controlled wirelessly, and the onboard controller was able to acquire, display and log data. The logged data could be plotted to analyse the trend-line. Similar data collection methods could be utilised during full deployment to monitor movement/ speed/ location in conjunction with other onboard sensors.

Inductive speed sensors (Figure 5.3) were mounted to the chassis to measure revolutions. Numerical tools within LabVIEW were used to convert the measured inputs to get miles per hour (MPH).

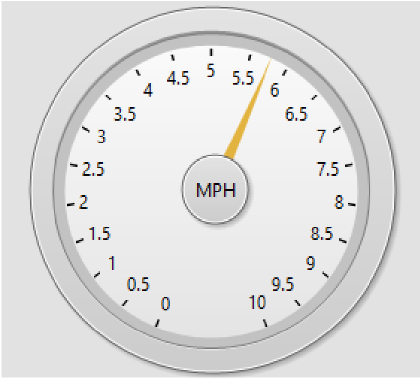

Figure 5.3: Snippet of speed indication during trials from PMP's UI

Steering Control System

In preparation for preliminary testing and validation, it was necessary to ensure the proper alignment of the steering system in the pod, as well as address any wheel imbalances that needed correction. This was a vital requirement as part of the experimental setup.

Wheel alignment was attained by manually correcting the steering alignment, making sure there are no caster angle, camber angle or toe-in / toe-out angles using string method and levelling tools. The string method can provide a good indication of wheel alignment; however, it may not be as precise as using professional alignment equipment. The limitation being the size of the pod, garages with specialist equipment could not accommodate. Although, additional levelling tools were used to assist string method corrections to improve accuracy.

Wheel imbalance is a major factor of premature wearing of tyres, suspension, and steering components. The pods wheels were taken to an approved garage to check and correct imbalance by a qualified technician using wheel balancing machines. Correct tyre pressures were applied and checked with manufacturer specifications.

The Pod's steering is achieved by using Electric Power Steering (EPS) together with an angle sensor (Figure 5.4). A rotary potentiometer has been used for preliminary testing and the relationship between the acquired voltage and the position angles was noted. Therefore, the sensitivity equation was generated to identify the variation between central position/left/right angles.

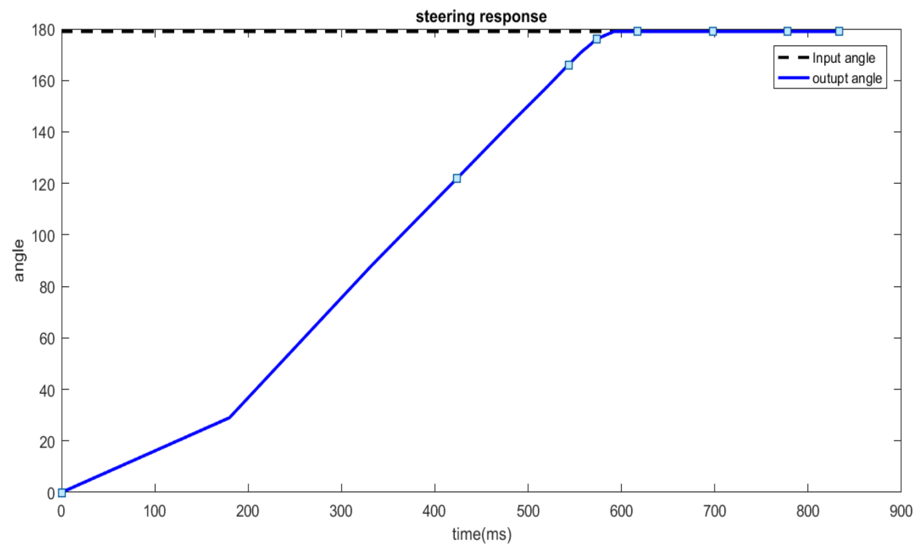

Figure 5.4: The steering response of the vehicle to reach 180 degrees from 0 is illustrated, indicates the high response of the steering.

Succeeding the preparations, in laboratory, the steering was tested separately to ensure the response of the controller. Initial tests carried out whilst elevated on a test bench. Following fast and accurate responses in combination with the sensor used for angular position, to verify the performance of the system, further tests were carried out in a trained ground during field testing. Scattered objects were located randomly to test the obstacle avoidance algorithm; the vehicle successfully went through the field without hitting any objects. This test was monitored and recorded to verify that the vehicle will pass through google maps waypoints and reach the target.

GPS Localisation

NI LabVIEW platform was used for interacting with the GPS, Figure 5.5. The sensor operates several tasks to localise the Pod by acquiring its coordinates and other data as follows:

- Capture the NMEA sentences (ASCII text strings) generated by the Gms-u1LP as an array of strings in LabVIEW,
- Parse the sentence to extract individual data fields,
- Extract information from the data fields using LabVIEW scan from String and format into String VI programs.

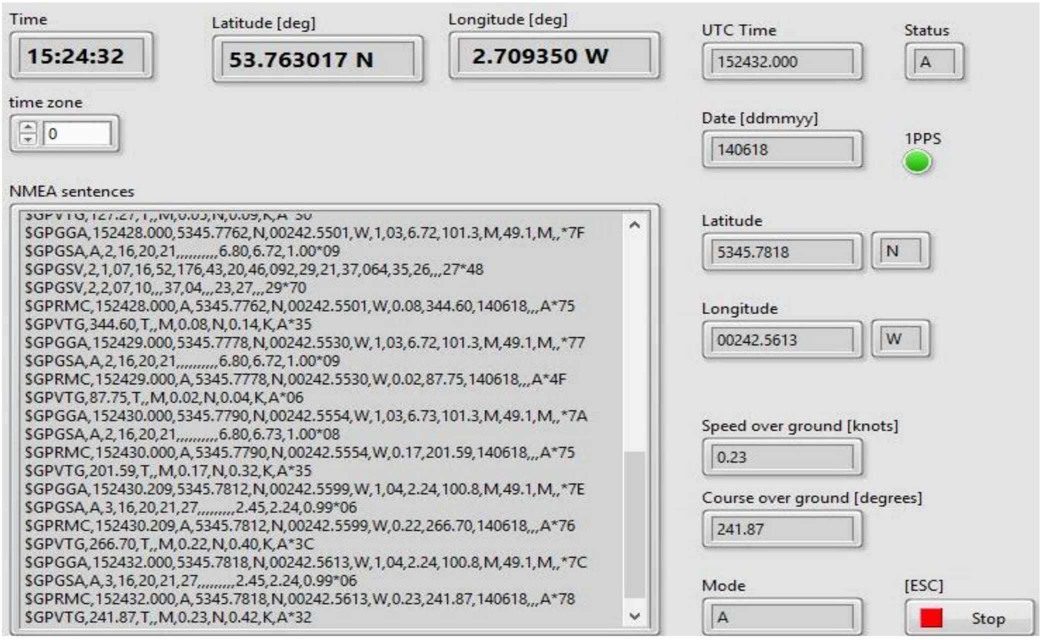

Figure 5.5: LabView Snippet of Acquired GPS Coordinates

Proximity Sensors

As part of the object avoidance and controlled stoppage mechanism, multiple sensors were tested and strategically placed around the PMP to prevent collisions. The sensors underwent individual testing using the controller, were calibrated, and then mounted to the pod before conducting field tests. To achieve the ability to detect and avoid objects, a combination of sensor types, including infrared, ultrasonic, and LiDAR sensors were considered and utilised. Each of these sensors have different range, meaning as a combined sensor fusion, they operate in low and high ranges and assist with providing better accuracy. The sensor data is processed by the PMP's NI myRIO controller through the LabVIEW program to make the real time decisions and navigate safely in the controlled environments.

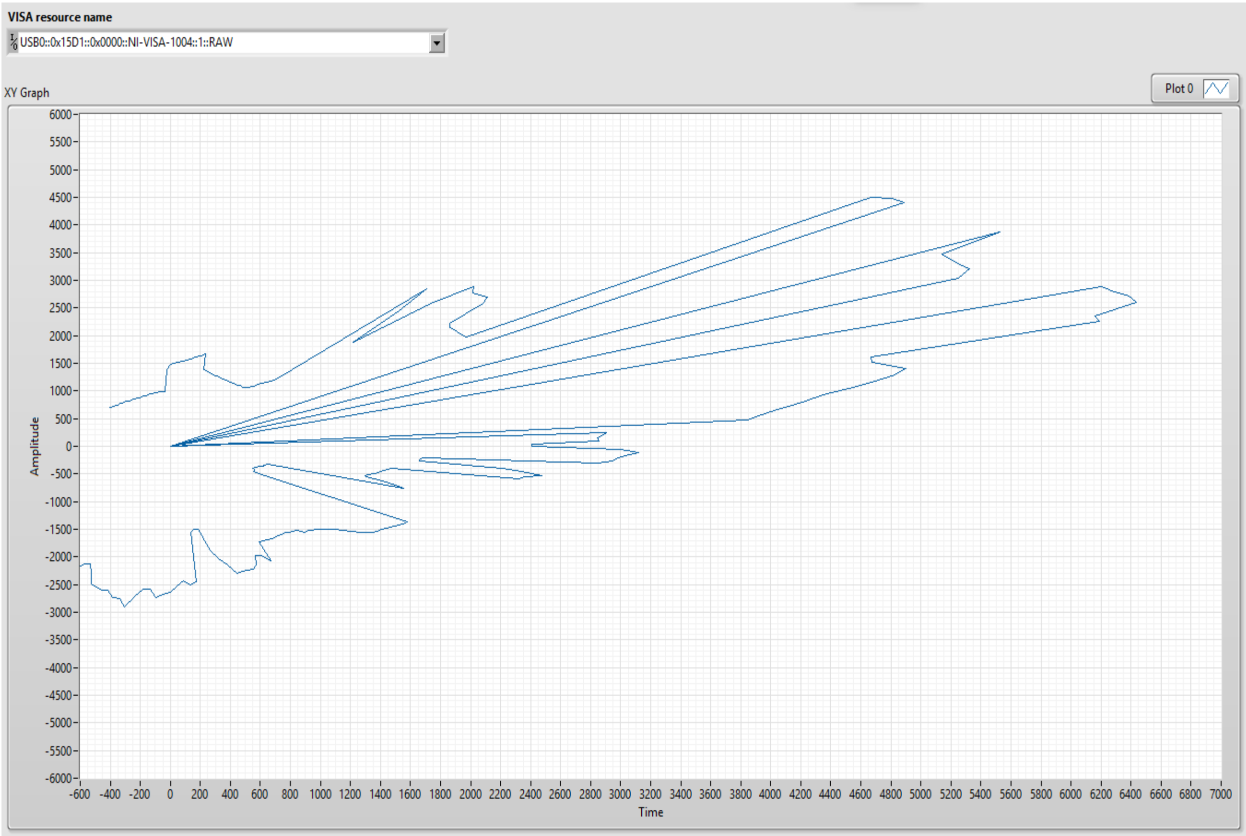

Figure 5.6: This figure shows sample results extracted from the LiDAR sensor. It was interfaced with LabVIEW using NI myRIO with the purpose of mapping/ localising the surrounded area as a 2-Dimensional graph. Further developments may include additional sensors linked within the management system of the Pod, interfaced with the LiDAR to monitor the surrounds more effectively.

5.2.2. Field Testing: Personal Mobility Pod (PMP)

Field testing of the Personal Mobility Pod was carried out at the UCLan (University of Central Lancashire) Sports Arena in a safe controlled environment. A controlled environment was necessary to be in accordance with safety regulations, as the Pod could breach health & safety in a busy environment. Initial field testing comprised of validating the PMPs physical capability in a controlled even terrain. Hardware tests, mapping and navigation, motion control, emergency shut off were the key focus points for this experiment.

During the field tests, the PMP utilised the on-board systems and travelled to its desired location specified by the user from LabVIEW GUI initiating autonomous mode. The program begins by interacting with Google Maps API by sending the HTTP command and then receives the direction as waypoints to the desired locations. The interface displays the calculated distance and estimated time of travel. The onboard controller, circuitry with associated input sensors, drive motor and steering actuators worked in harmony to provide navigation and motion controls effectively to replicate an autonomous driverless vehicle suited for the IMSDV system.

5.2.3. Summary of Tests: Personal Mobility Pod (PMP)

In this work, a low cost driverless PMP was developed with its system architecture and components. This platform was designed to achieve high reliability and integrity with different systems as shown in the connection between individual systems such as google maps, on-line planner, trajectory tracking, and low-level controller. Although, the Pure Pursuit technique does not consider the dynamic effects, it could be tuned using intelligent control system such as Fuzzy controller or Neural Network controller to achieve the system stability.

Through successful testing, the PMP has demonstrated its capabilities in integrating the with the planned vehicle monitoring systems to aid IMSDV development. These systems focus on steering monitoring, including wheel imbalance, vehicle alignment, and early stages of failures, using proactive maintenance techniques. Furthermore, the testing concluded it is possible to use the developed PMP for enhancing developments of the IMSDV and additional areas.

5.3. Testing of the Wheel Bearing Monitoring System on The Test Bench

The system takes multiple tracks to validate effectiveness and reliability of the system:

- Validating sub-systems on test bench – Prior to creating a complete system, each of the sub-systems were validated individuality to check its working status within laboratory environments.
- Validate wheel alignment and imbalance prior to testing - Pod taken to a workshop, machine tested and corrected.
- Final validation – The combination of the sub-system in its intended capsulated form validated on the PMP itself by gathering actual data and creating alarms through the IoT based monitoring system whilst carrying out autonomous driving tasks.

5.3.1 Preliminary Phase Experimental Test Setup

As part of the preliminary testing phase of the monitoring sub-system focused on wheel bearings in time domain using vibration analysis, baseline data of the test bearings needed to be established. Measurement of the vibration levels for the undamaged or healthy bearings serves as a reference point for comparison and helps identify abnormal vibration patterns associated with different levels of damage.

A test setup was established on the in-lab test bench as illustrated below.

This setup allowed to classify the different levels of damage severity for the selected bearing. This includes categories such as no damage/ light damage, moderate damage, and severe damage. To clearly define and document the severity levels ensures consistency in the analysis, vibration parameters were discussed in preceding section. Overall vibration levels through RMS and peak were used to define the levels as they consider historical data and changes can be cleared identified. Following sections illustrate the results gathered, Figure 5.7.

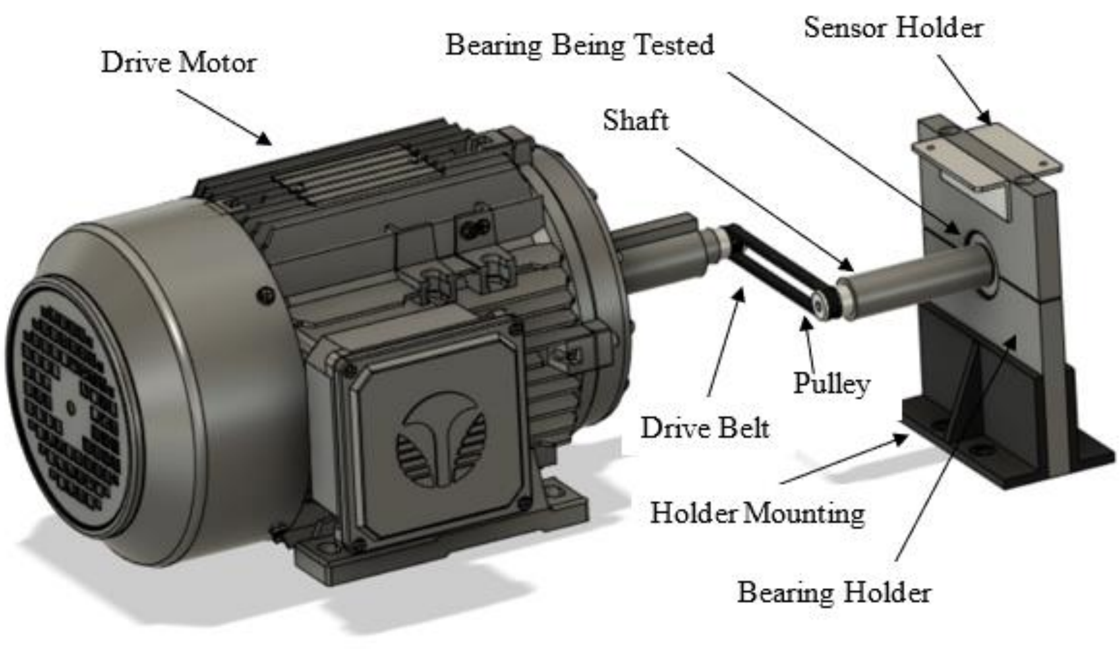

Figure 5.7: Design model of the test bench arrangement to test/ validate the sub-system for bearing monitoring using vibration analysis.

The instrumental set up for the tests utilised a National Instruments DAQ (9191 & 9234) and an industrial grade accelerometer (Model 608A11) shown in Figure 5.8.

Figure 5.8: National Instruments DAQ 9191 & 9234

This NI DAQ specialises in the field of sound and vibration. It has the ability to transit analogue input / output, digital Input / output counter / timer and sensors measurements. The communication protocol with the host PC is via either Wi-Fi or Ethernet. For the purpose of the test bench setup, wired connections were sufficient. It has the ability to transmit / receive the data with a high speed of sampling rate – 127 samples. This device is often used in industry to monitor several parameters including thermocouples, RTDs, strain gauges, load, and pressure (National Instruments, 2014a). It is suitable for remote or distributed sensors and electrical measurement including use in a laboratory testing environment.

Figure 5.9: Low- Cost industrial ICP Accelerometer Model 608A11

The selected is a low-cost accelerometer for general purpose used in industrial applications for vibration measurements (Figure 5.9). Sufficient sensitivity and frequency range were key features that were carefully considered when selecting this sensor as detailed in Table 6 below.

Table 6: Sensor Performance Specifications

PERFORMANCE		
Sensitivity (±15 %)	100 mV/g	10.2 mV/(m/s²)
Measurement Range	±50 g	±490 m/s²
Frequency Range (±3 dB)	30 to 600000 cpm	0.5 to 10000 Hz
Resonant Frequency	1320 kcpm	22 kHz
Broadband Resolution (1)	350 µg	3434 µm/sec^2
Non-Linearity	±1 %	±1 %
Transverse Sensitivity	≤7 %	≤7 %
Conversion FActor	1g = 9.81 m/s².	

During the tests, to ensure consistent and repeatable results special care was taken especially as different levels of damage were being tested, for more reliable comparisons. Maintaining a tight agenda to follow all tasks in the planned order prior to each test. Some parameters that were maintained throughout the experimental stages were speed – 500 RPM or 8.3 hz, same manufacturer bearing types were consistently used, the duration of data collection, sampling rate, and the number of measurement points. Adequate data collection ensures a comprehensive analysis and provides a reliable basis for comparison.

The LabVIEW platform was used to create the software for the setup. LabVIEW supports hardware items, including sensors, data acquisition DAQ. Add-ons are available for further interaction. Sound and vibration toolkits were employed for the analysis. Figure 5.10 below illustrates the LabVIEW back panel.

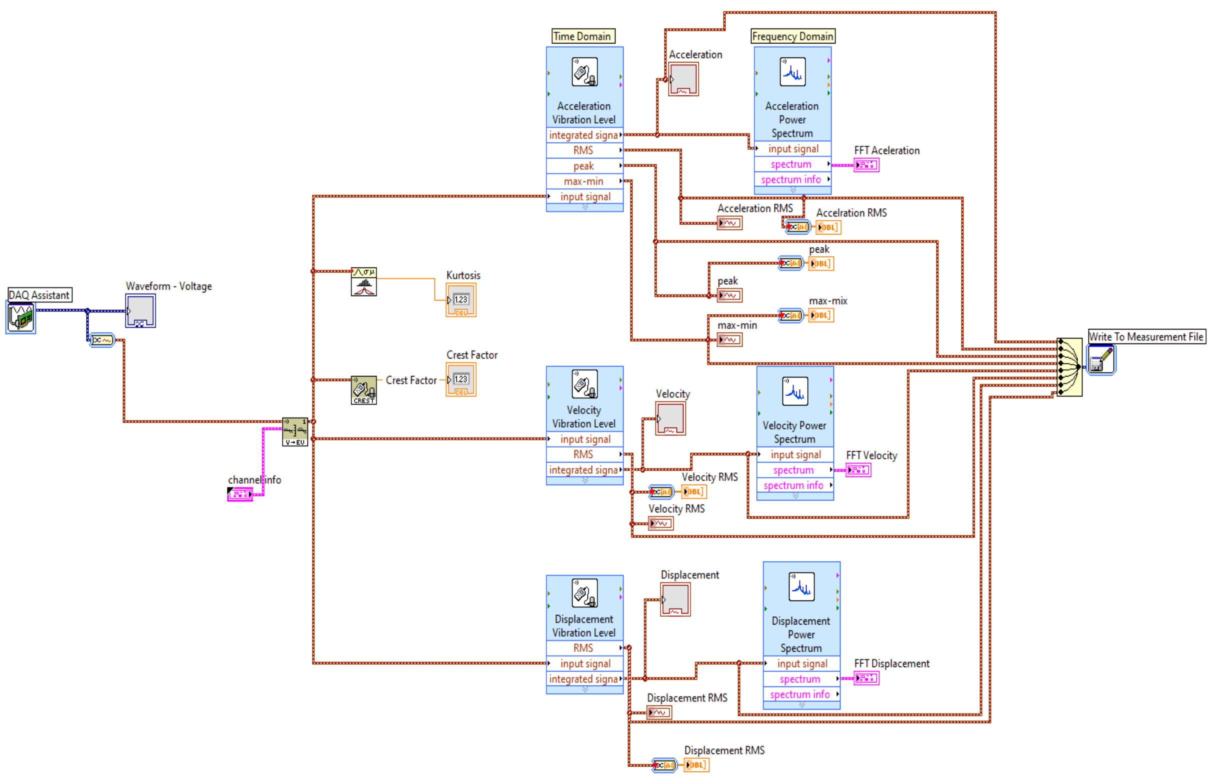

Figure 5.10: Snippet of LabVIEW

Vibration measurements were plotted in Acceleration, Velocity and Displacement. RMS and Peak values were considered for establishing severity levels.

Configuration for Acquisition:

- Acquisition Mode for Number of Samples Read – 30,000 samples
- Sampling Rate in Hertz – 3,000hz
- Sample/ Update Period in Seconds – 10s

5.3.1.1 Severity Test 1

Test 1 features results of fresh bearing with no damage:

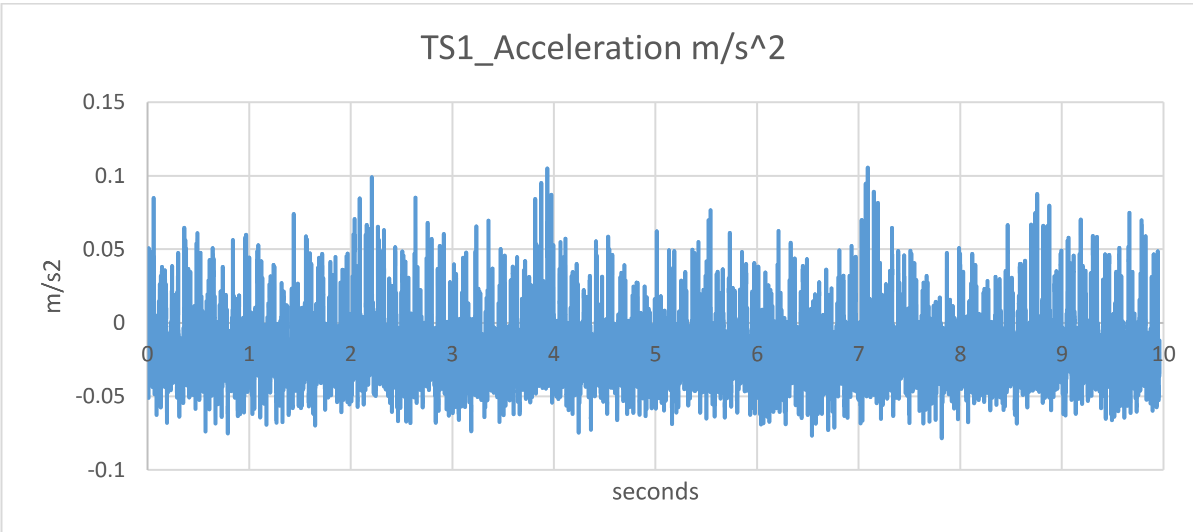

Figure 5.11: Acceleration levels for test sample 1

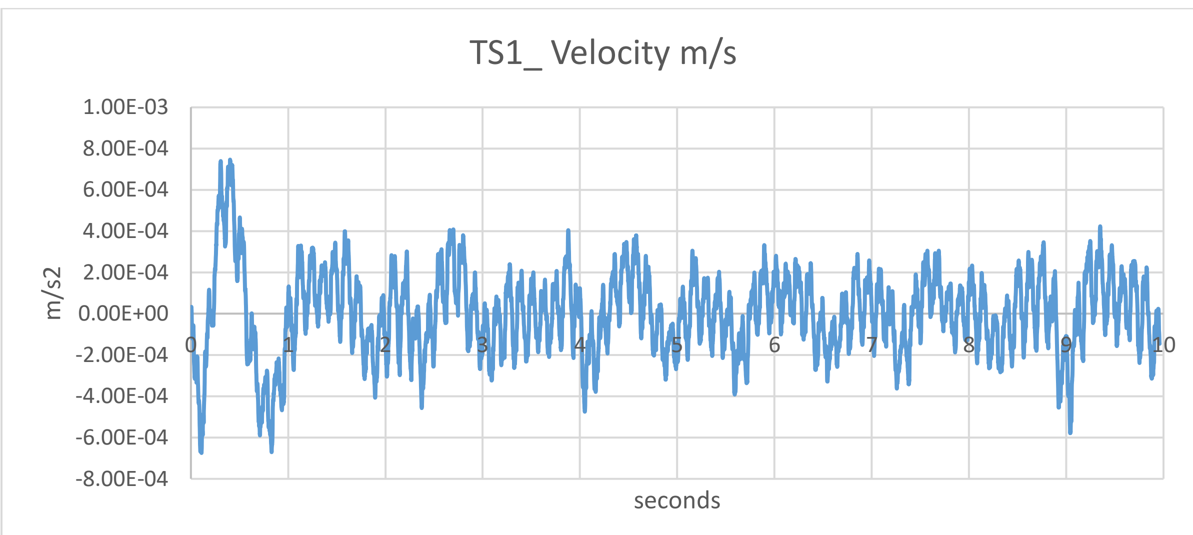

Figure 5.12: Velocity levels for test sample 1

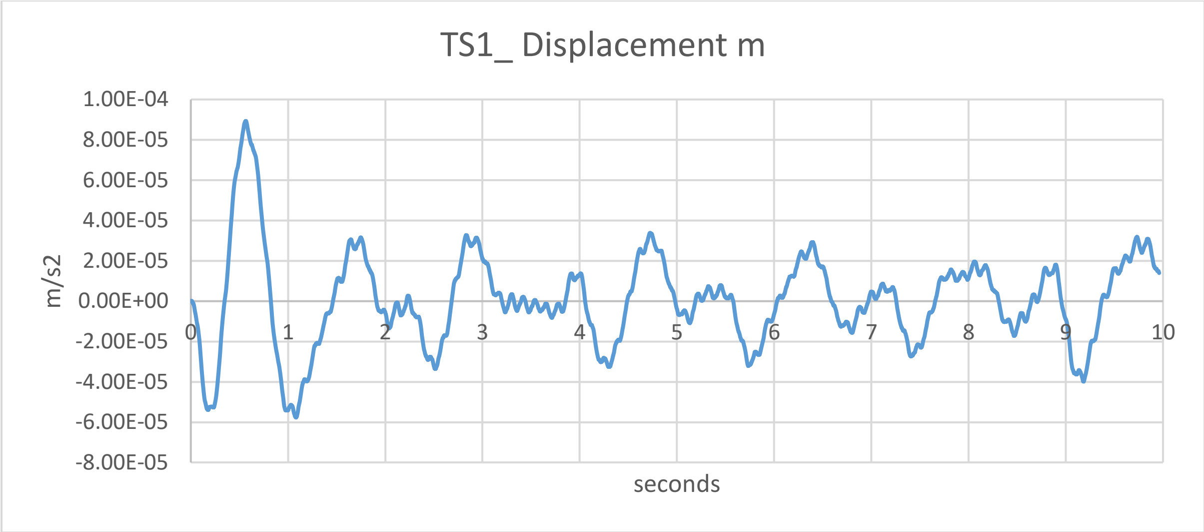

Figure 5.13: Velocity levels for test sample 1

Table 7: Performance Results from Test 1

RESULTS FOR TEST SAMPLE 1	
RMS - Acceleration	0.025861
Peak	0.105685
Peak Max-Min	0.18412
RMS - Velocity	0.000204
RMS - Displacement	2.32E-05

5.3.1.2 Severity Test 2

Test 2 features results of bearing with light damage:

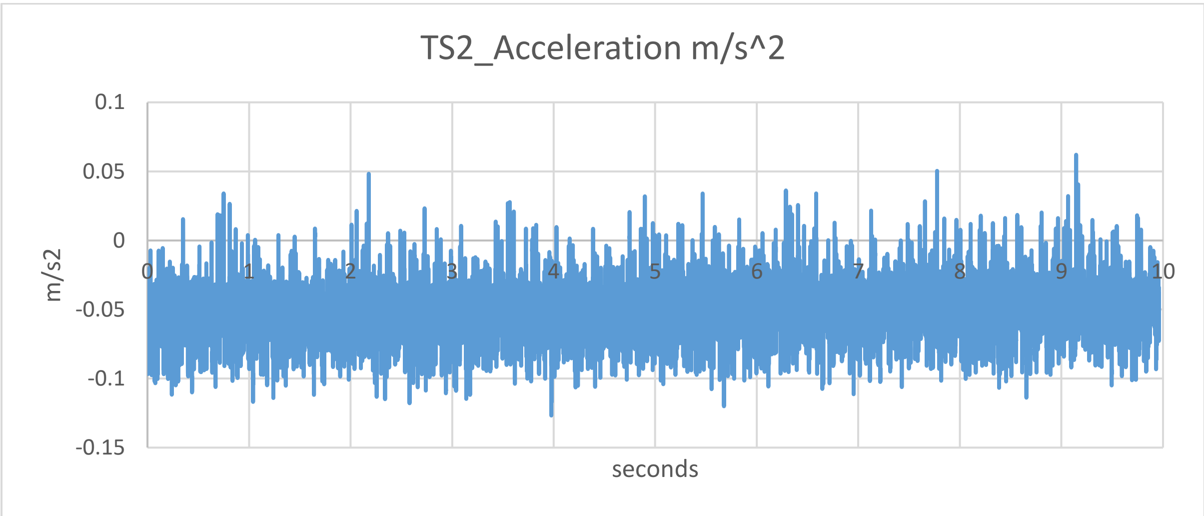

Figure 5.14: Acceleration levels for test sample 2

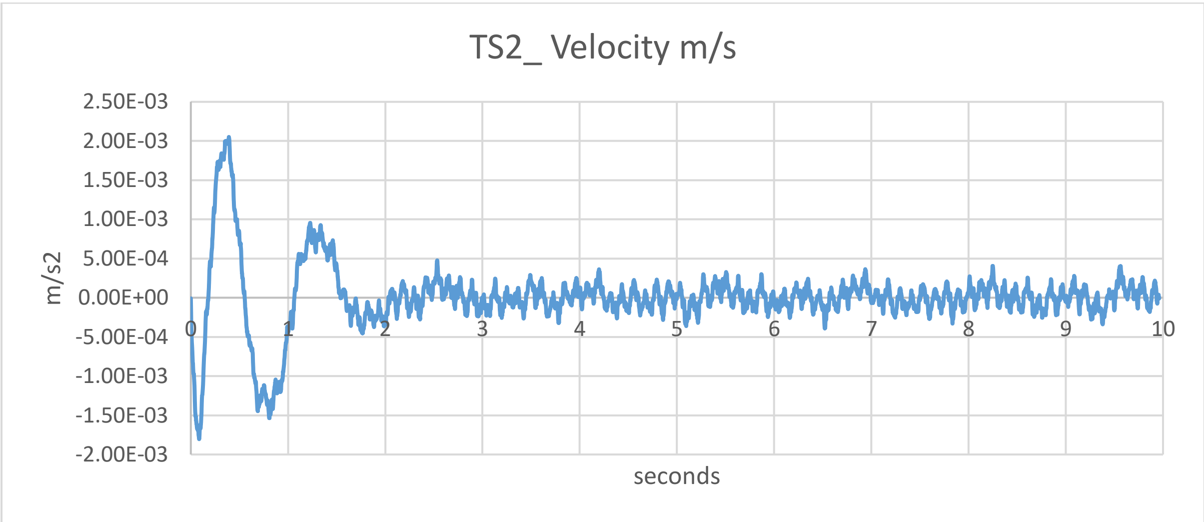

Figure 5.15: Velocity levels for test sample 2

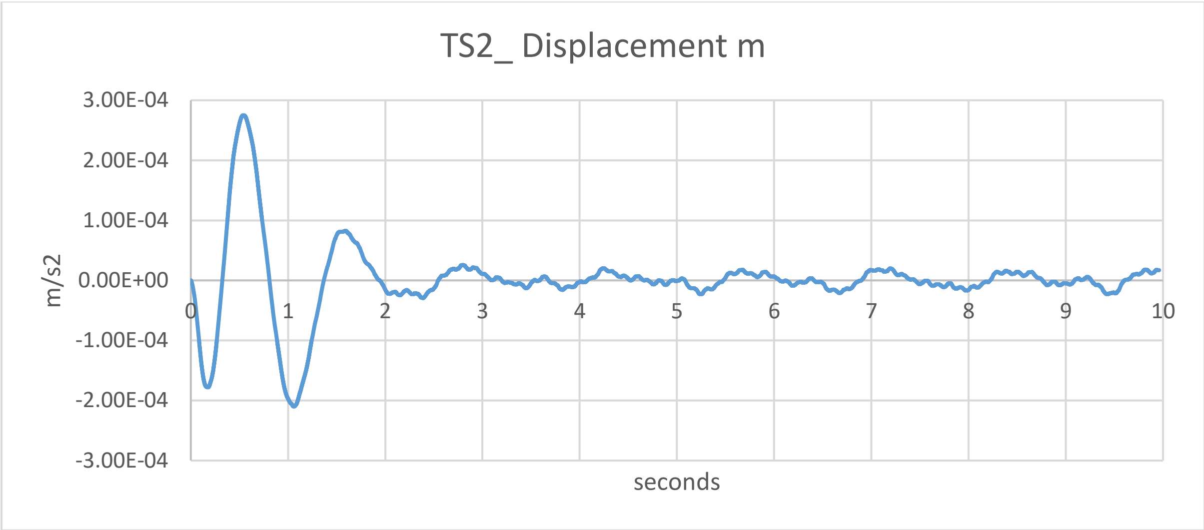

Figure 5.16: Displacement levels for test sample 2

Table 8: Performance Results from Test 2

RESULTS FOR TEST SAMPLE 2	
RMS - Acceleration	0.053514
Peak	0.126799
Peak Max-Min	0.188908
RMS - Velocity	0.000429
RMS - Displacement	6.06E-05

5.3.1.3 Severity Test 3

Test 3 features results of bearing with moderate damage:

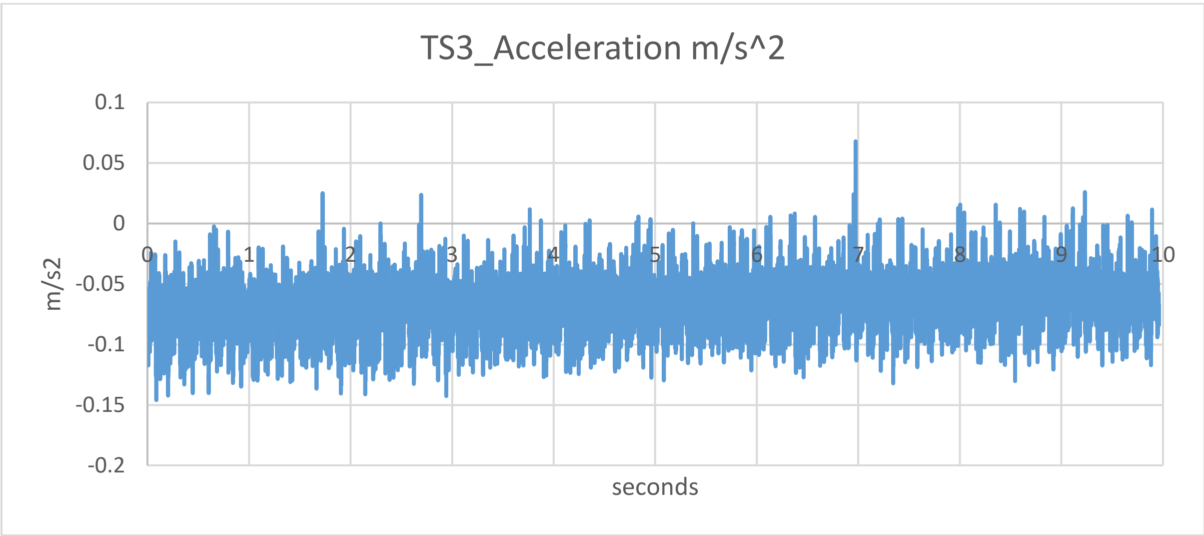

Figure 5.17: Acceleration levels for test sample 3

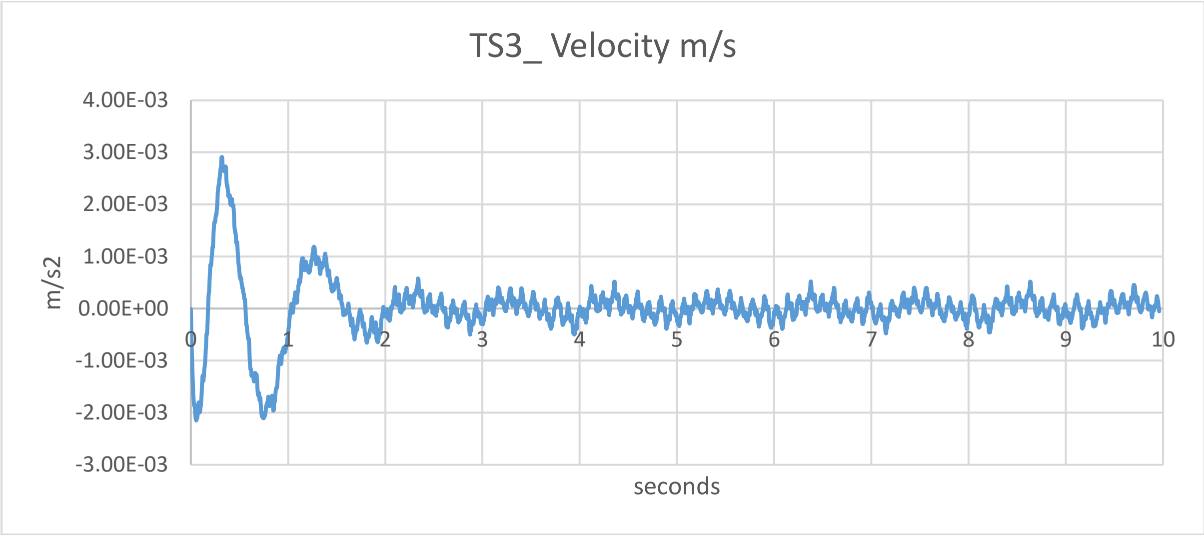

Figure 5.18: Velocity levels for test sample 3

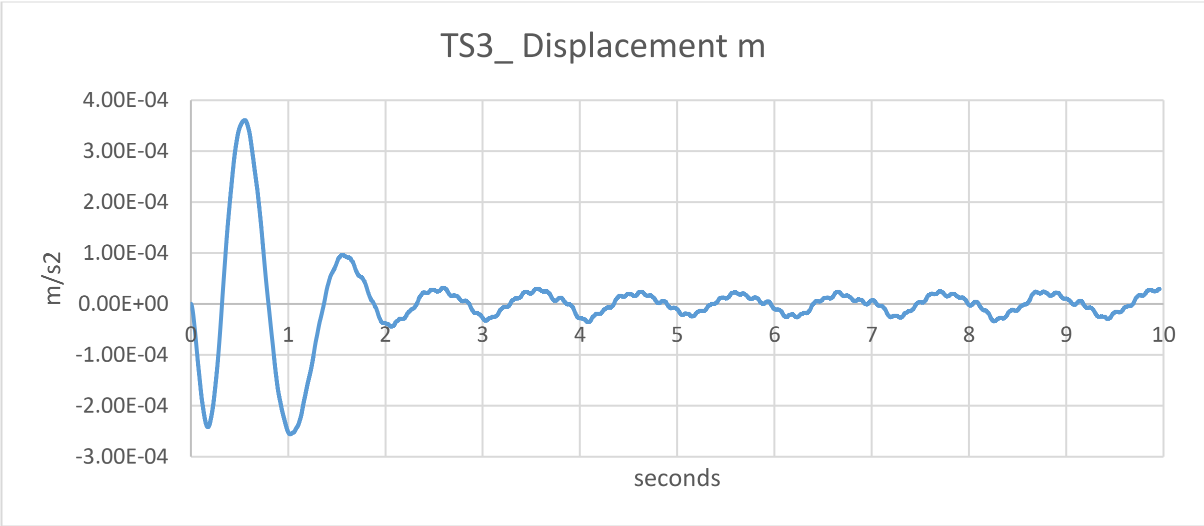

Figure 5.19: Displacement levels for test sample 3

Table 9: Performance Results from Test 3

RESULTS FOR TEST SAMPLE 3	
RMS - Acceleration	0.068702
Peak	0.145954
Peak Max-Min	0.213928
RMS - Velocity	0.000563
RMS - Displacement	7.89E-05

5.3.1.4 Severity Test 4

Test 4 features results of bearing with damage displaying high range:

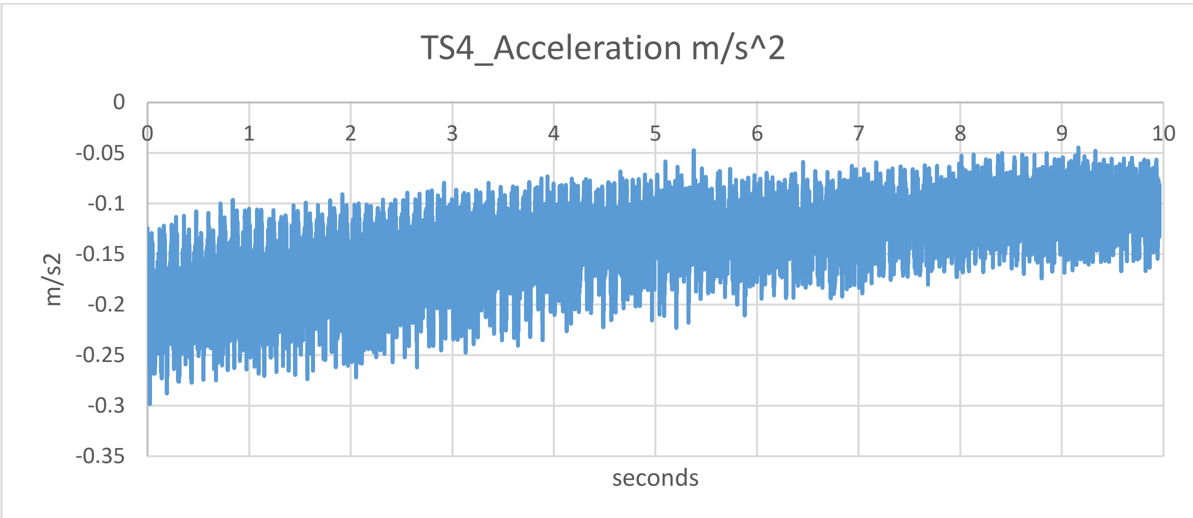

Figure 5.20: Acceleration levels for test sample 4

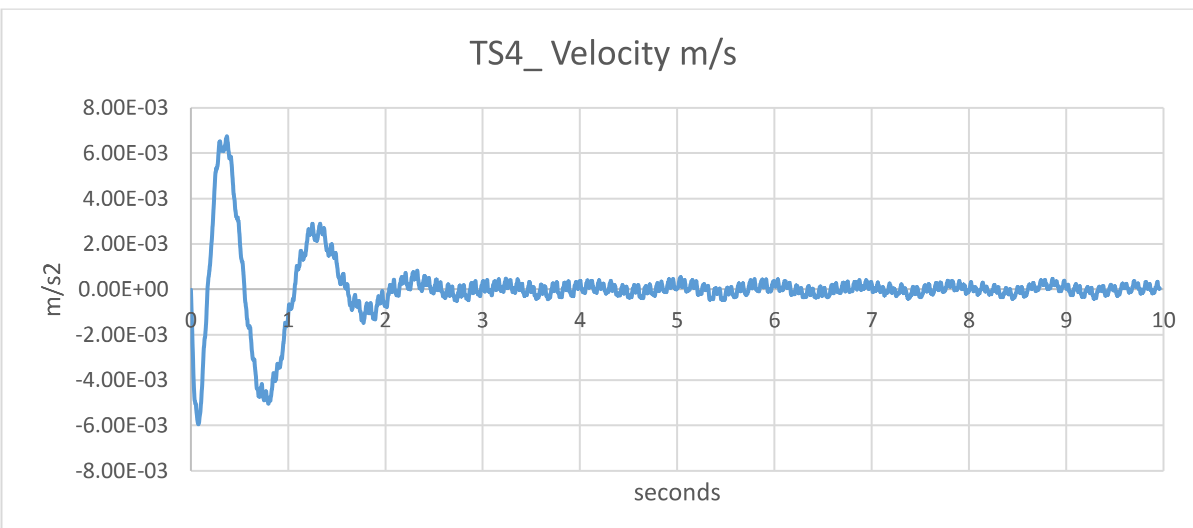

Figure 5.21: Velocity levels for test sample 5

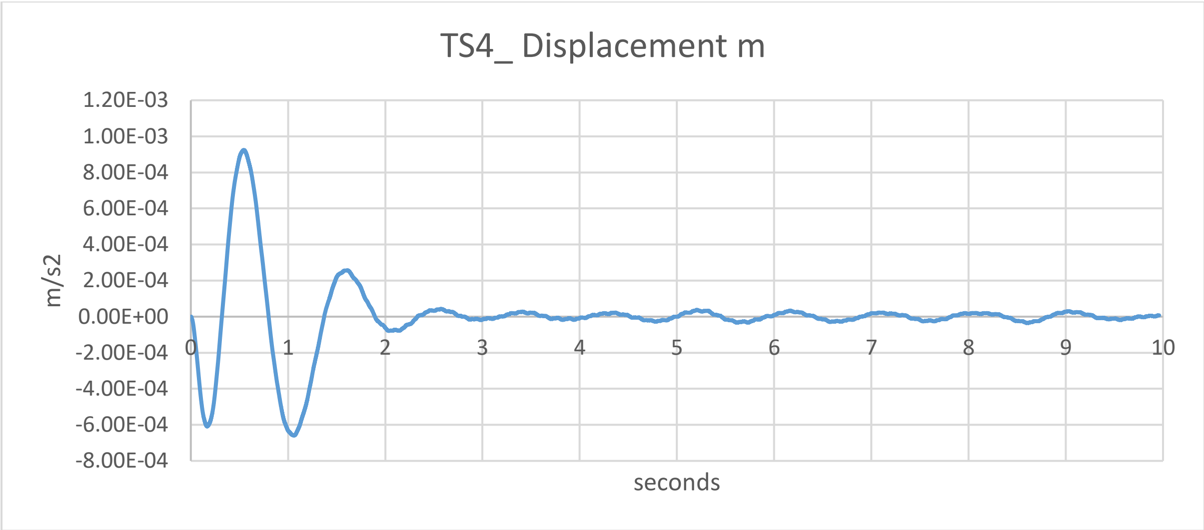

Figure 5.22: Displacement levels for test sample 4

Table 10: Performance Results from Test 4

RESULTS FOR TEST SAMPLE 4	
RMS - Acceleration	0.13873
Peak	0.298289
Peak Max-Min	0.253733
RMS - Velocity	0.001383
RMS - Displacement	0.000199

5.3.2 Summary: Bearing Severity test

From the gathered test results obtained using the setup, a base line of severity levels was clearly established through the opted method of vibration analysis. Use of RMS and Peak signals allowed to illustrate a clearer separation between levels of severity from collected data. For the integrated monitoring system using IoT with the XDK sensor linked with the cloud platform, similar severity levels were used.

5.4 Testing of the Monitoring System Using IoT

Preceding chapter explained the methodology for an IoT based monitoring system that could be used to enable monitoring and diagnosis of autonomous vehicle components using the onboard sensors of the XDK110 device integrated with cloud monitoring platform Akenza.io. This section of the testing chapter presents the results obtained from using the detailed methodology.

To evaluate the IoT monitoring system setup using the Akenza.io platform and the XDK sensor, a list was established for areas to cover as the points to test.

5.4.1 Sensor connectivity Test

The connectivity between the sensor and the Akenza.io platform has been evaluated and verified. The sensor was properly connected to the network, establishing a reliable connection with the platform. The Figures 5.23 – 5.25 below illustrate the outcomes.

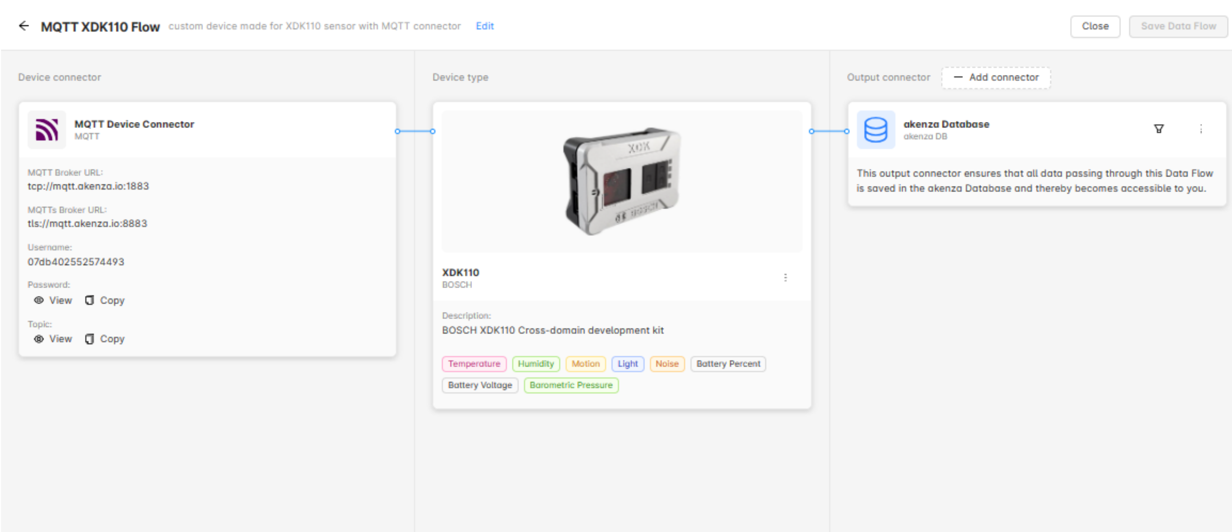

Figure 5.23: Direct link set up of XDK on Akenza.io trialled

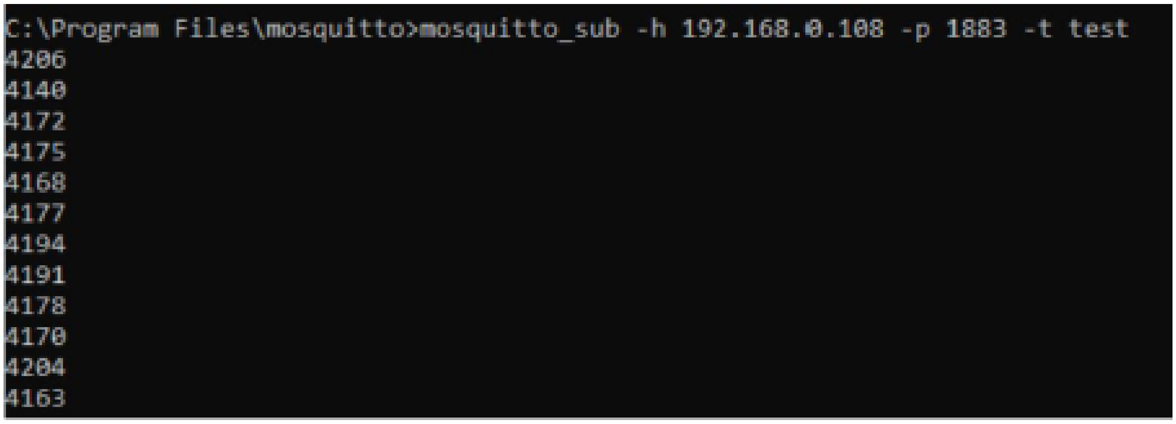

Figure 5.24: Mosquitto Broker connectivity test

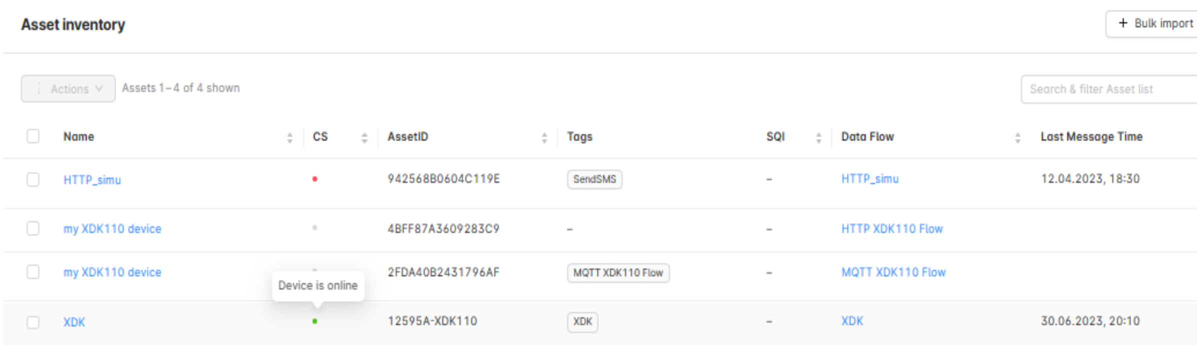

Figure 5.25: XDK connectivity test to Akenza.io – successful connection indicator showing status

5.4.2 Data transmission Test

Data transmission from the sensor to Akenza.io was confirmed, ensuring that sensor readings were accurately transmitted and received, as shown in Figures 5.26, 5.27.

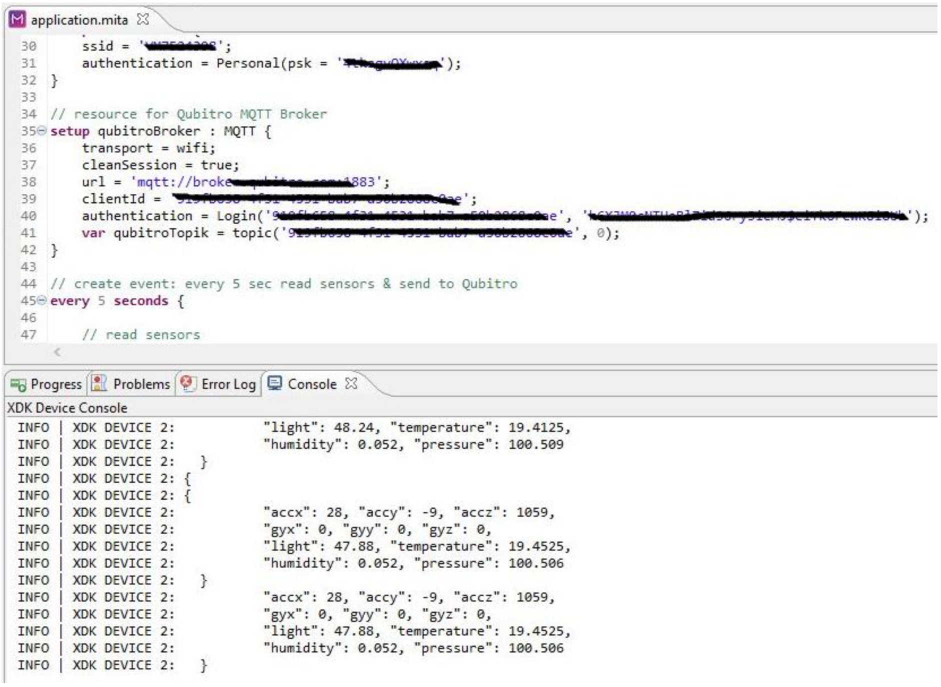

Figure 5.26: XDK workbench data transmission test

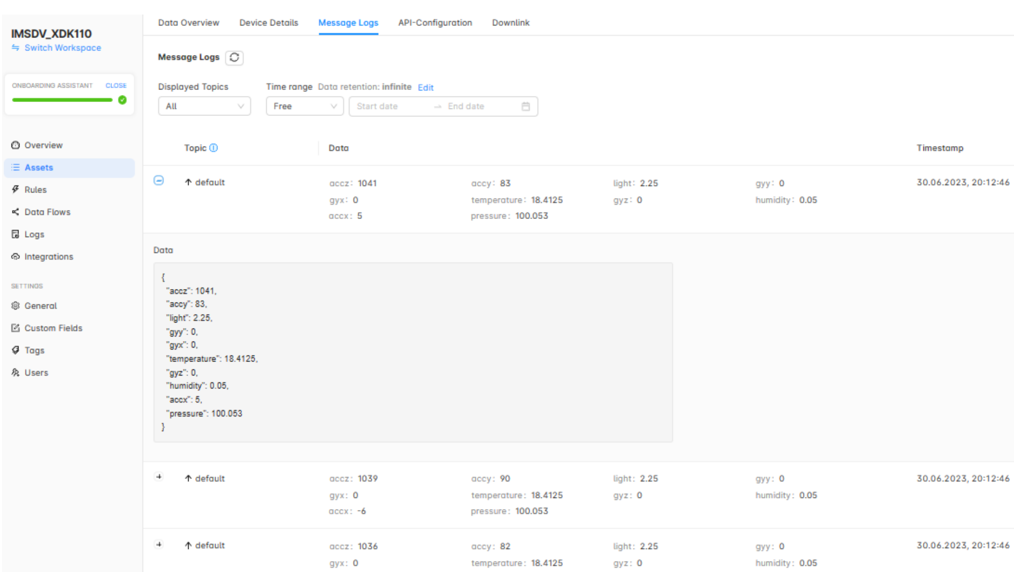

Figure 5.27: Akenza.io data transmission test. Data is received on Akenza.io

5.4.3 Data Visualisation

The platform's data visualization capabilities were tested and found to be effective. The sensor data was correctly displayed and visualized on the Akenza.io dashboard or interface, allowing for real-time monitoring of the data points (Figure 5.28). The visualisation elements were updated promptly, providing a correct representation of the sensor readings.

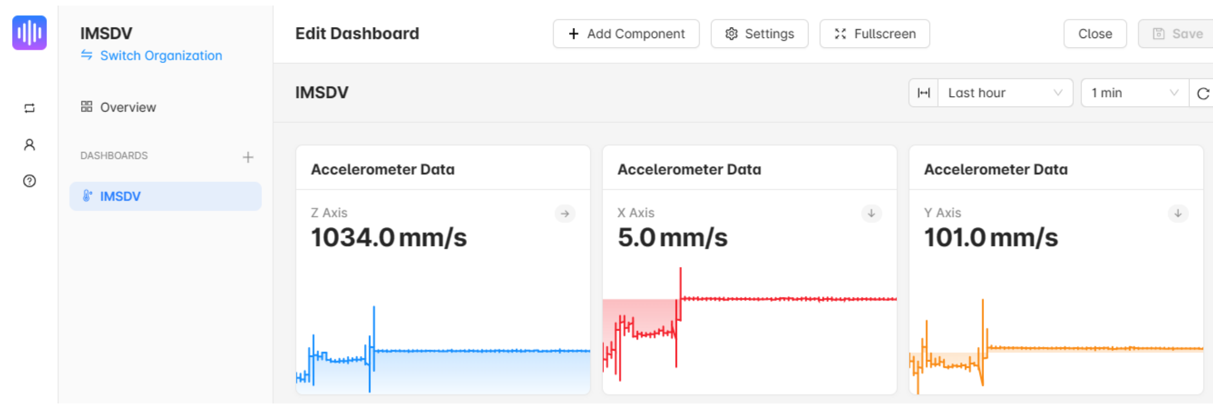

Figure 5.28: Snippet of Akenza.io's dashboard

5.4.4 Alert and Notification

Alerts and notifications were set up based on specific conditions, such as threshold values or events, shown in Figure 5.29. These alerts were thoroughly tested, and it was confirmed that they were triggered correctly when the defined conditions were met. Notifications were successfully delivered through the designated channels, such as email, SMS, or mobile app notifications.

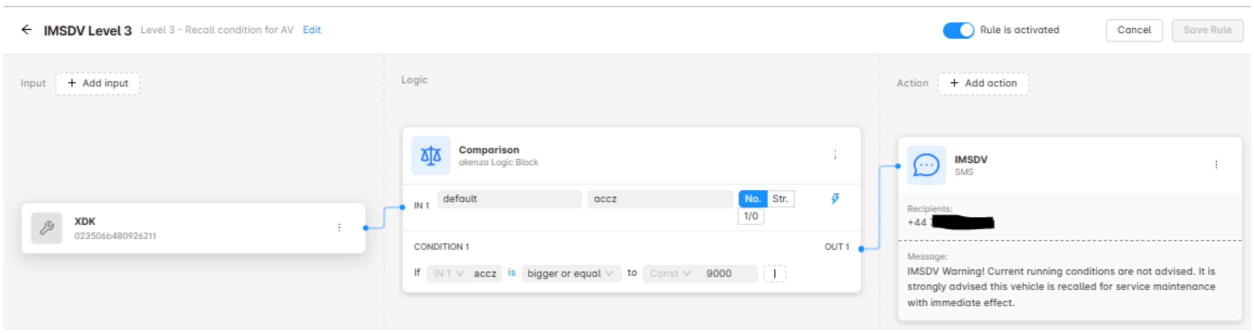

Figure 5.29: Rule base engine utilised to test alerts

5.6 Developed Monitoring Sub-System Tests Using the Developed PMP

Overall, the IoT monitoring platform using Akenza.io and a sensor has been trailed, tested, and achieved through the desired objectives, providing a reliable and effective solution for monitoring, and managing IoT devices and data. The akenza platform is consequently utilised to enable its dashboard viewing properties which can be accessible from anywhere in the world using the correct credentials.

For the application of diagnostics where the device is attached to the PMP under investigation and data from the accelerometer and other relevant sensors the developed system proves to be sufficient. Validation of a system was carried out by testing the developed system together. The developed IoT based monitoring system was validated using the developed driverless pod.

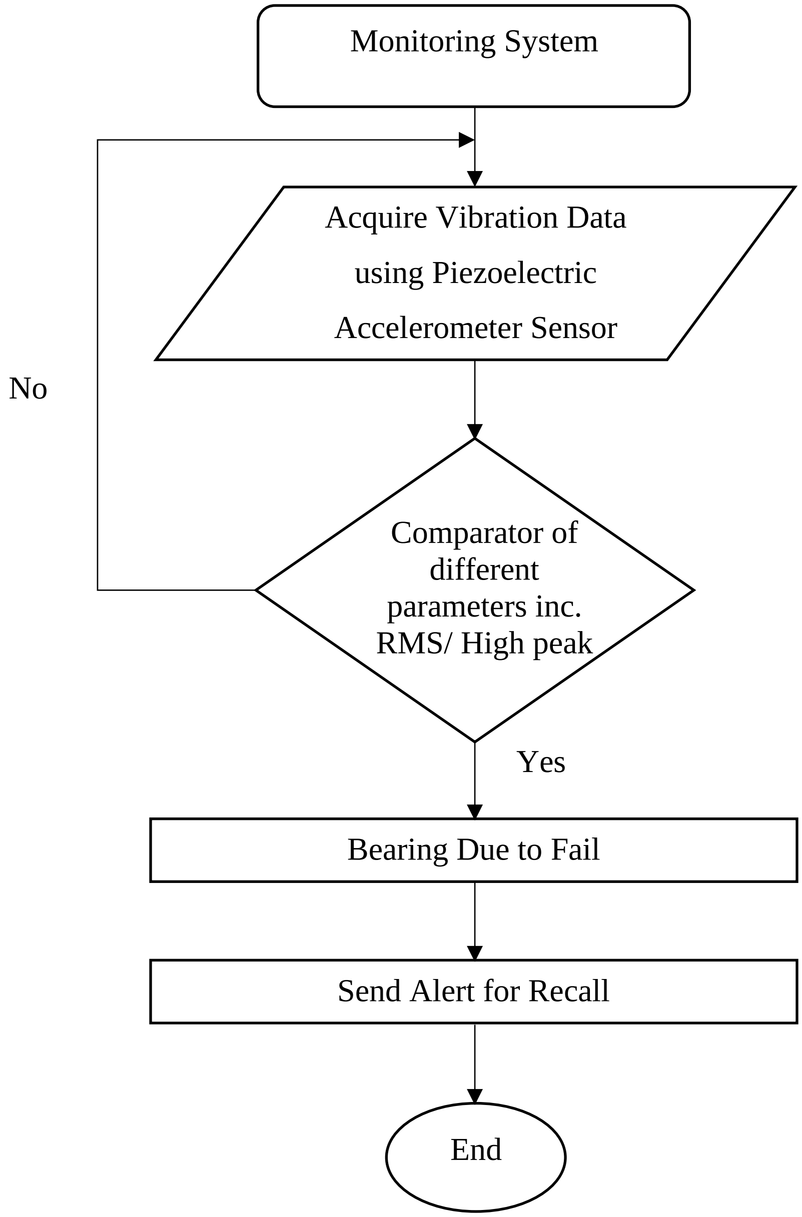

Figure 5.30: Details the running order of the system

CHAPTER 6

DISCUSSION AND CONCLUSION

6.1. Original Contributions

This study delved deeply into various sensory and actuation systems utilised in unmanned systems and active condition monitoring. It provides a thorough grasp of their applications and functions, which is embodied in a newly developed test apparatus. This apparatus not only signifies the depth of understanding gained but also serves as a practical application of the identified principles. In essence, this research extends the theoretical knowledge base and offers a tangible tool for future explorations and applications in unmanned systems and condition monitoring.

The designed and developed purposeful test apparatus, namely the innovative Personal Mobility Pod (PMP), specifically designed to meet the criteria of SAE's Level 5 Automation Category. This autonomous vehicle integrates various systems operating on the Sense-Plan-Act paradigm. The PMP functions as a dependable platform, facilitating experiments and assessments of the performance of driverless vehicle components.

This research addresses critical issues concerning the steering systems of autonomous vehicles by introducing a novel Monitoring System that utilises Internet of Things (IoT) technology. The development of this system represents a substantial original contribution, focusing on the mitigation of steering component failures, particularly those related to wheel bearing functionality, within the context of SAE Level 5 automated vehicles. The monitoring system implemented in this study enhances the performance and functionality of the driverless car's steering system, leading to improved reliability, maintainability, and safety in autonomous vehicles.

The developed systems were thoroughly validated in both laboratory and field settings, employing the personal mobility pod. Rigorous testing and evaluation processes were conducted to assess the systems' performance, reliability, and effectiveness. The outcomes of these assessments offer valuable insights for refining the systems and contribute to their real-world implementation.

6.2. Discussion

The advancement of driverless vehicle technology has gained significant attention in recent years. With the ultimate aim of providing autonomy in the transportation industry. Car manufacturing companies are actively engaged in research and development have been aiming to achieve the requirements of level five automation, as defined by the Society of Automotive Engineering (SAE) automotive automation standard. The objectives regarding this include safety, efficiency, accessibility, and environmental impacts. As level five automation aims to improve commuter satisfaction and vehicle performance by introducing fully autonomous vehicles. Despite the progress made, there are still critical issues that need to be addressed, particularly in the areas of on-road safety and integration as highlighted in The UK Department of Transport's report titled 'The Pathway to Driverless Cars'.

While the potential benefits of fully autonomous vehicles are promising, it is crucial to overcome the challenges associated with ensuring on-road safety and seamless integration of these vehicles within existing transportation systems. By addressing these areas of interest, advancements in driverless vehicle research can pave the way for a future where road accidents are minimised, and the potential of autonomous transportation is fully achieved.

This research has made significant contributions to the field of driverless vehicle technology. Throughout its study, a low-cost driverless single seat Personal Mobility Platform (PMP) was developed, featuring a robust system architecture and integrated components. The primary objectives were to enhance reliability, maintainability, and safety of high-level driverless vehicles.

The design and development of the PMP covered the establishment of connections between various systems, including Google Maps, online planners, trajectory tracking, and low-level controllers. A Pure Pursuit technique was used in this study partly to understand tracking systems and points out the potential for tuning using intelligent control systems like Fuzzy controllers or Neural Network controllers to achieve further system stability. The flexible architecture of the PMP also allows for seamless integration with other sub-systems.

Furthermore, the research presented the implementation of a component level health monitoring system using IoT. This sub-system targeted the health of steering system components to enhance maintainability and reliability for driverless vehicles, contributing to system integration at level 5 of SAE automation.

The developed IoT monitoring platform using Akenza.io and BOSCH XDK sensor, provide a reliable and effective solution for monitoring component health of driverless vehicles and creating an alerting system as part of this intelligent management system research. The successful validation of the developed monitoring systems demonstrated their efficiency in laboratory and real-world testing, including the developed Personal Mobility Pod.

The development of the PMP played a key role in the study for not only understating the area of research but also to establish key focus areas for further development with regards to reliability, safety, integration on road focusing level 5 autonomy. The PMP was used through the various stages of testing and integrated with the developed monitoring sub-system.

By addressing the ongoing development of an Intelligent Management System for Driverless Vehicles (IMSDV), this study aimed to bridge existing theoretical and technical gaps. Critical reviews of influential literature in the field were conducted, highlighting areas that require further attention and advancement.

Some of the limitations to be considered from the study are the applicability of the findings are constrained to the specific system. Hence, scalability is to be considered with further study.

Overall, the outcomes of this research contribute to the advancement of driverless vehicle technology by providing valuable insights, practical solutions, and future research directions. The developed PMP, integration possibilities, intelligent control techniques, and IoT-based monitoring system lay a foundation for improving reliability, safety, and performance in driverless vehicles.

6.3. Further Work

Further develop the developed Pod using AI to stabilise the system. Path & Behavioural Planning could be the focus point to determines optimal route considering vehicle state, traffic, and environment and decides vehicle actions in various scenarios for improved safety and efficiency.

In the area of the monitoring systems, intelligent methods could be used to implement active CM. Future researchers could explore and develop more advanced algorithms for the detection of component-level failures in driverless vehicles. This could involve the use of machine learning or artificial intelligence techniques to improve the accuracy and efficiency of fault detection.

Additionally, advancements accompanying IoT would lead towards a comprehensive system. This presents opportunities for extended research and development in Cybersecurity for IoT in Autonomous Vehicles.

6.4. Final Thoughts

The concluding chapter detailed and reviewed the work carried out during the research. The main highlights from the chapter cover the original contributions containing the developed Personal Mobility Pod; developed sub-system that is an IoT based monitoring system which focuses on level 5 of driverless vehicles. The system features driverless vehicle steering system component monitoring.

The research conducted in this field plays a crucial role in driving forward the technology of driverless vehicles. It offers significant contributions in terms of valuable insights, practical solutions, and guidance for future research endeavours.

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APPENDIX A

PUBLICATIONS

1. J. T. Philip, O. H. Rashed, A. Onsy and M. R. Varley, "Development of a Driverless Personal Mobility Pod," 2018 24th International Conference on Automation and Computing (ICAC)
2. J. T. Philip, A. Onsy and M. R. Varley, "An Intelligent Maintenance System for Driverless Vehicles" 2017 30th International Conference on Condition monitoring and diagnostic engineering management (COMADEM)

An Intelligent Maintenance System for Driverless Vehicles

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ABSTRACT

The UK Department of Transport states that most road accidents are caused by human error. Several car manufacturing companies are now involved in research that aims to address this issue through the development of commercial driverless vehicles employing intelligent systems. Driverless vehicle research has been principally concerned with satisfying the requirements of level five of the Society of Automotive Engineering (SAE, USA) J3016 automotive automation standard; a standard that will improve commuter satisfaction and vehicle performance. However, many outstanding issues still need to be addressed, such as on-road safety and integration. Significant efforts are being made to advance current technology in order to create cost effective and robust driverless technology, which is expected to increase in the coming years. Additionally, an Intelligent Management System for Driverless Vehicles (IMSDV) is becoming a necessity as it is an intricate combination of Advanced Driver Assistive Systems (ADAS) management with an added intelligence algorithm that consists of various decision-making parameters, depending on a priority-based hierarchy. This resulted in research being conducted which focused on driverless vehicles in order to create a platform for testing, by developing a 'Driverless Pod' with intelligent systems suited for the advance of a complete IMSDV.

The paper introduces a new 'Driverless Pod' that has been developed and evaluated as an experimental test bench used to validate an IMSDV. The Pod incorporates several subsystems including different sensors, actuators and controllers, all of which are similar to those used in commercial driverless vehicles. Current development integrates both hardware and software. Further publications will detail two monitoring subsystems for the driverless vehicle steering system and vehicle wheel/tyre condition. A new and intelligent algorithm for driverless vehicle management that addresses health, safety and maintenance issues in relation to driverless vehicles will then be developed. These developments will be validated in three stages: laboratory testing, workshop testing and on the Driverless Pod.

Keywords: Multi-Disciplinary; Advanced Driver Assistance Systems (ADAS); Intelligent Management for Driverless Vehicle Systems (IMSDV).

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1. INTRODUCTION

Since the conception of Intelligent Transportation Systems (ITS) in the 1980s, many transport researchers have progressed to work on the development of incident management models and integrated systems for real-time operations [1]. Several attempts have been made to develop a successive fully autonomous vehicle and many milestones have been reached. The challenges presented by the Defence Advanced Research Projects Agency (DARPA) in 2004 were perhaps the major spur behind the research for autonomous driving and autonomous vehicles, making it to be currently among the most intensively researched and publicly followed technologies in the transportation domain [2], which is an achievement. The challenges were introduced in order to emphasise the development of fully-autonomous ground vehicles. The agency cordially invited major companies and research organisations, and over 50 robotic and non-robotic vehicles drove simultaneously, but only six of these vehicles successfully completed the race. While the DARPA Challenge remains the major demonstration of autonomous vehicle technology to date, it excluded many capabilities and requirements critical for actual city driving, thus, completing an off-road course within a time limit which remained a challenge [3].

Principal automotive companies (Ford, GM, Nissan, Volvo, etc.) and technology companies (Google, Induct etc.) have already demonstrated autonomous driving through working prototypes and pilots. The automotive industry is aware of the potential market emerging from autonomous driving. Relative companies are competing to prepare themselves for future revenue due to increased potential and other beneficial factors. Individual consumer benefits as well as societal benefits are a leading factor in the immensely gained attention of the research.

Current statistics concerning the number of accidents on the roads are worrying. Cars are a primary mode of transport and it is estimated that there are over 800 million cars on the road worldwide [4]. Reports produced by the UK Department for Transport state that 90 percent of UK road accidents are due to human error which include: speeding (32 percent of accidents), alcohol (21 percent) and distraction (17 percent). The average driver in England spends 235 hours driving every year, representing the equivalent of six working weeks. Additionally, according to the World Health Organisation, road traffic injuries account for almost 1.3 million deaths a year across the globe. Autonomous driving could help prevent these accidents by eliminating the role of human error in driving [5].

Several Advanced Driver Assistance Systems (ADAS) such as active lane keep assist, adaptive cruise control and self-parking are already currently available on the market have been combined as a major thriving aspect for the development of driverless vehicles. The replacement of a human by technology requires the performance of critical sensory functions using various technologies simultaneously. Many of these facilities currently exist in the latest technology, facilitating 'Level 3' SAE J3016 automotive automation standard, therefore requiring a high level of training in order to be viable for consumer use [6]. Several areas require mastery: vehicle location, prediction and decision algorithms, real-time accuracy and other factors; because technology must perform better than human eyes, ears, memory and coordination. This requires a high level of advancement. The UK has diagnosed the key areas which need consideration: safety and integration (Greenwich), vehicles on roads (Milton Keynes & Coventry), legal and insurance (Bristol).

The persistent transformation through the stages of autonomous driving is consistent with the latest technology, although mastery is not yet achieved in all areas. It is practically necessary to monitor the complete vehicle condition through an Intelligent Management System for Driverless Vehicles in order to contribute to health and safety research and the integration and vehicles on roads for driverless vehicles. The aim of this study is to find key areas which need substantial attention to health and safety.

To validate the IMSDV, a 'Single Seat Driverless Pod' has been developed. Current development integrates both hardware and software which are similar to those used in commercial driverless vehicles. Preliminary test results for the Driverless Pod have been included and indicate that the Pod is suitable for gathering real data that can be used in the final validation stage. Further publications will discuss the development of two monitoring subsystems addressing health and safety concerns for IMSDV.

2. DESIGN AND IMPLEMENTATION OF A NEW 'DRIVERLESS POD'

The aim of the research is to develop an Intelligent Management System for Driverless Vehicles.

The research investigates new possibilities of contributing to the largely researched field of driverless vehicles, incorporating both design methods and computational systems that would allow the development of an Intelligent Management System for Driverless Vehicles (IMSDV) with the aid of a 'Driverless Pod' regarding current technological developments. The rationale behind the development of the 'Pod' is not to replicate the advances of a driverless vehicle, but to use as a test apparatus for gathering real data in order to develop an IMSDV.

A methodological proposal has been established in order to achieve the aim of the research. The design structure for the project research was considered prior to the commencement of the initial stages which include: study the background and existing systems, analyse current issues and areas which require further improvements, design and develop a driverless pod to validate the management system, and developed driverless pod will be used to test/ validate.

The proposed test apparatus (Driverless Pod) needed considerable attention to its structure as it involves combinations of multidisciplinary systems including, electrical, mechanical, control and other factors. Considering these subsystems which create the Pod, some specifications were considered:

- Dimensions: the structure of the Pod needs to be within the test bench architecture for ease of usage and for testing within a lab environment
- Pre-existing structure or build from first principles: rather than creating a structure/chassis from first principles, a pre-existing system that could be ambiguously fitted with driverless capabilities would be ideal
- Sensors: it should be possible to mount numerous sensors around the Pod; real-time data through sensory feedback and automated actuation
- Monitor various parameters such as movement through sensory fusion, actuators, and data processors

Many different possibilities were considered. After numerous considerations, concepts of building the mechanical structure from first principles were eliminated and the focus was towards electrically-powered karts because of their many advanced features which are suitable for the research. After assessing many options, a used mobility scooter was purchased and modified.

The Landlex Broadway mobility scooter was selected for the research of driverless vehicle systems. This remains an ideal platform, providing a robust chassis, multi-terrain tyres and user-friendly console with automatic breaking. Additionally, the ability to revert to human control of the vehicle if the software or the power fails is achieved by switching from automatic to manual mode. This pre-existing feature was greatly appreciated when selecting this scooter.

Additional modifications to the pre-existing structure were undertaken in order to fit the requirements of a 'Driverless Pod'. The Pod's steering was a major aspect to be considered during the redevelopment. Considering the weight of the scooter, no DC motor would operate efficiently. Various actuators were attempted and tested using numerous mounting strategies. Following the testing of various actuators, torque force was a recurring issue on each occasion. Therefore, replicating an actual car, an electric power steering system was fixed with the reasoning of high load and torque capabilities. A Vauxhall Corsa C, electric power steering (EPS) was modified to fit the Pod's chassis. Additionally, numerous mounting methods were used. The design of the mounting bracket and all subsequent parts have been manufactured to fit the Pod.

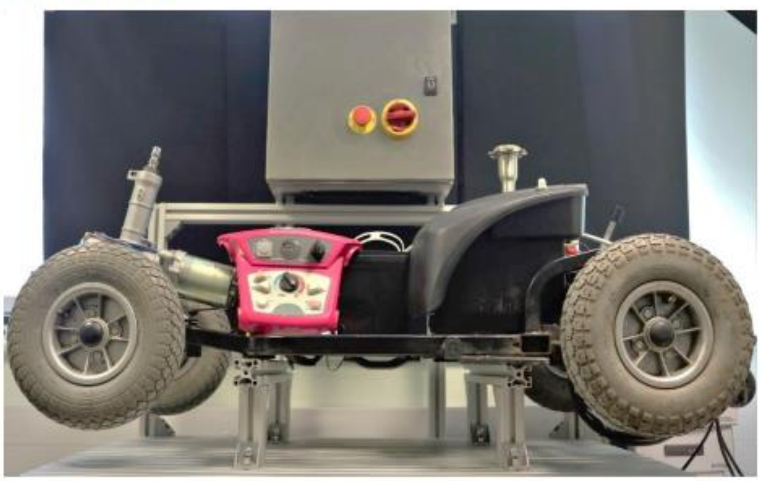

Figure 1: Landlex RS Broadway Mobility Scooter was purchased and modified to suit the requirements of a suitable test apparatus. The Pod incorporates multiple sensors, actuation and controller systems available in current driverless vehicles.

Patenting for 'Autonomous vehicle arrangement and method for controlling an autonomous vehicle' [7] states that it includes a receiving unit for travel order(s) and route planning with an array of sensors for detecting position, condition features, collision avoidance and a unit for controlling the vehicle actuator systems based on feedback generated by the vehicle control system. The array of sensors should include at least one range sensor at the front and rear of the vehicle, ultrasonic and/or microwave radar sensors arranged around the side of the vehicle, and at least one camera located in each of the front and rear areas of the vehicle.

The developed Pod was implemented with multi-sensors and actuators interfaced with an NI myRIO FPGA control module. The NI myRIO enables a completely powerful hardware tool which delivers the performance of a complex real-world system. NI myRIO features the Xilinx Zynq-7010 all-programmable system on a chip, which includes a dual core The ARM Cortex-A9 processor, and an Artix-7 FPGA controller processes the functionalities of the 'Driverless Pod'. The current suite of sensors includes: video camera, infrared, ultrasonic, LiDAR, potentiometer, rotary encoder, EPS actuator, servo motors and relays. The myRIO module was programmed using a LabVIEW (Laboratory Virtual Instrument Engineering Workbench) interface to the controller to navigate the forward/ backward/left/right movements of the Pod remotely by using wireless communication.

In order to test the functionality, a pre-programmed sequence was created, implanting structured loops and case structures consisting of various moves and turns, each loop occupying specified time delays. Therefore, real-time sensory feedback was used to stop the pod from crashing and avoiding objects. Figure 3 illustrates an overview of the development of the 'Driverless Pod' which includes the multiple sensors, actuators and controller diagram.

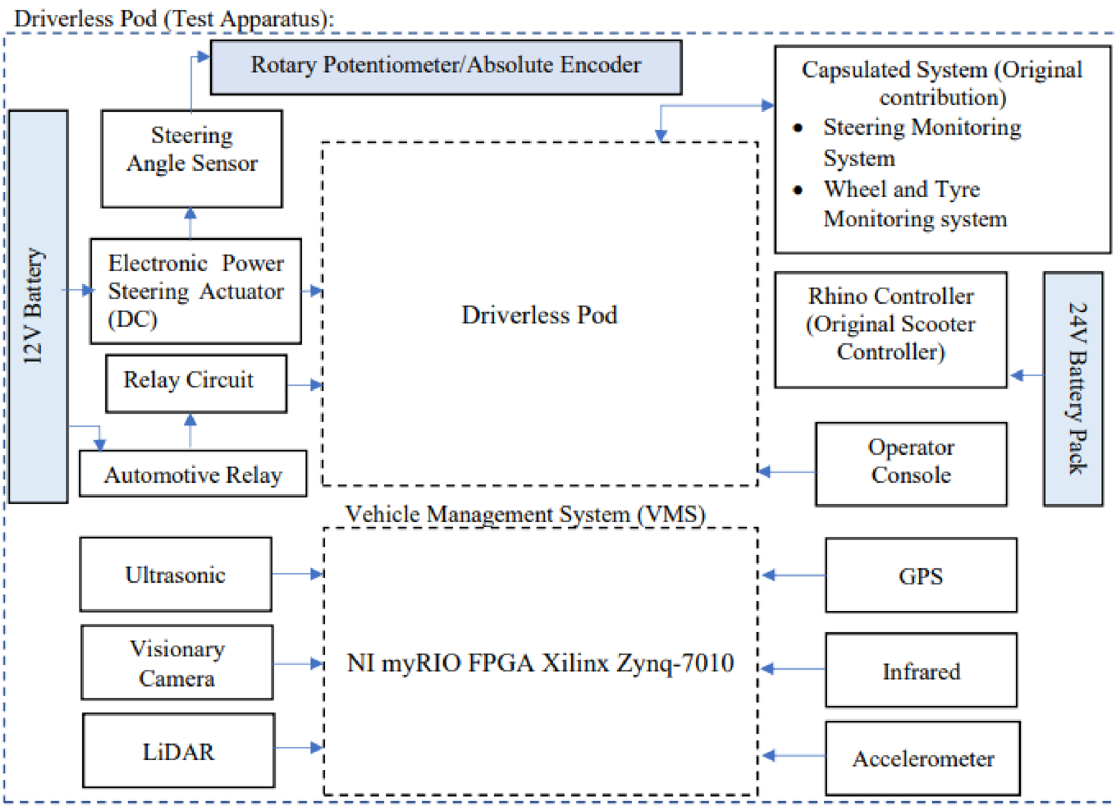

Figure 2: Driverless Pod Block Diagram.

3. TESTING AND EVALUATION

To evaluate the developed 'Driverless Pod's' performance under different conditions and to verify the analytical results, it was subjected to test procedures. These include a two-stage procedure which tests and validates the operation of each subsystem individually and also the developed Pod to confirm its suitability for use in constructing an IMSDV.

3.1 Evaluation of sensory actuation system

The developed sensory actuation system consists of two main actuators, the main driving motor and the steering motor. Each motor has been assigned with subsequent sensors which acquire different parameters relating to distance, speed and angle. Therefore, the implemented sensors and actuators have been individually tested and validated. Initial results have been acquired using the LabVIEW platform and subsequently documented.

3.1.1 Infrared Range Finder

The Sharp 2Y0A21 IR Ranger Finder was used to identify the range between the obstacles and the Pod. To calibrate the sensor accurately, multiple measurements were logged and compared. By mounting the sensor to a vertical surface, with a known range, an object was placed in front of the sensor and moved respectively to a known range on each occasion in order to identify the resulting output, Vo.

The measurable range for the sensor was 10 to 80 cm, therefore, it could be noted that at the specified range, a typical analogue voltage output was 2.30 to 0.4 V with respect to 38.3 ± 9.6 ms measurement time, 5 ms update lag.

$$R = K_s \frac{1}{V_o} + K_o$$

R = Range, K_s = Calibration Coefficient Scale, V_o = Voltage Output, K_o = Calibration Offset

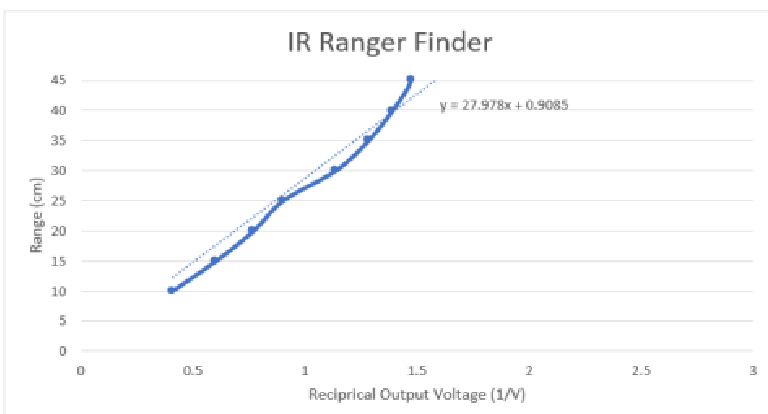

Figure 4: The graph shows the voltage in reciprocal form versus range (cm). A linear region is identified and extracted with a liner trend-line after calibration.

It can be concluded from this test that the scale factor Ks = 27.978 cm-V and offset, Ko = 0.91 cm. At close ranges, the sensor has improved sensitivity as opposed to objects further away. Also, the sensor must be at least 10 cm from the target for accurate measurements within the range.

3.1.2 Main Driving Motor

The motor was controlled wirelessly and the NI myRIO FPGA module could acquire, display and log data. The logged data could be plotted in order to analyse the trend-line. This would be utilised while testing and validating the IMSDV, using the Pod (test apparatus) through wireless connectivity. The Pod was wirelessly controlled using the FPGA controller, interfaced with the original mobility scooter controller, in order to test and evaluate forward/reverse movements using a developed code through LabVIEW. The actuator was deployed by using digital I/O with additional relay circuitry.

3.1.3 Steering Angle Sensor

The Pod's steering is achieved by using Electric Power Steering (EPS) together with an angle sensor. A rotary potentiometer has been used for preliminary testing and the relationship between the acquired voltage and the position angles was noted. Therefore, the sensitivity equation was generated in order to identify the variation between central position/left/right angles.

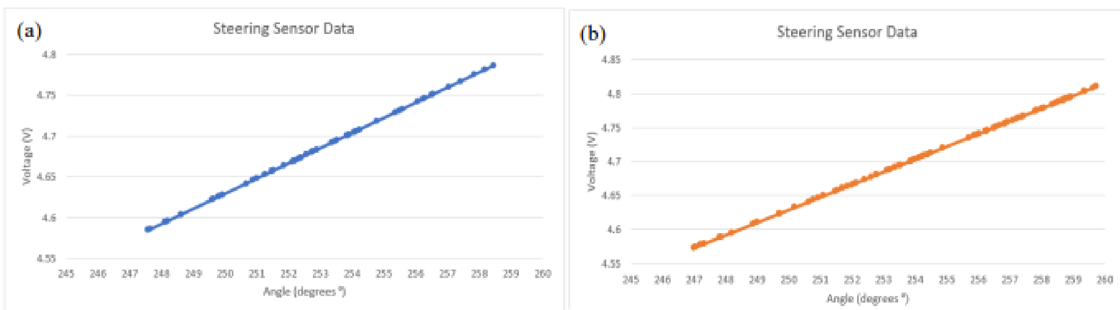

Figure 5: Graphs (a – left turn, b – right turn) illustrate the relation between Voltage Output and Steering Sensor angle from a test run of the Pod. This relation was acquired using the above equations. The test run of the Pod consisted of controlling the steering system wirelessly through LabVIEW FPGA controller.

3.2 Wireless Control

Wireless connectivity was achieved using the NI myRIO FPGA module via a laptop. This allowed remote access to the Pod via the subsequent circuitry. A relay board interfaced with the controller with an additional battery source was used for the forward/backward/left/right movements. Additional sensors have been interfaced directly to the FPGA.

Following validation of the developed Pod's installation and the controlling of the Pod remotely, a pre-programmed sequence was created, positioning structured loops and case structures consisting of various moves and turns creating a sequence, each loop occupying specified time delays. Therefore, real-time sensory feedback was used to prevent the Pod from crashing and to avoid objects.

3.3 Discussion

The research investigates new possibilities of contributing to the largely researched field of driverless vehicles; incorporating both design methods and computational systems that would permit the development of an Intelligent Management System for Driverless Vehicles. The paper includes the development of a 'Single Seat Driverless Pod' to be used in the actual system validation. Succeeding work will include new monitoring systems with a further focus on health and safety; this is an area which needs to be addressed.

According to SAE the steering system in an autonomous driverless vehicle is one of the current development tracks [6]. Vehicle steering is considered to be at level 2 of the SAE J3016 automotive automation standard, so that it incorporates human interaction as part of the decision. Current fully automated power assisted or semi-assisted steering systems utilise feedback signals by using angular position sensors to enhance the driving experience.

Defective wheel bearings are an additional cause of an uncomfortable drive. The monitoring of the life of wheel bearings could be used to develop advanced maintenance strategies for driverless vehicles using a wireless monitoring system. Wheel bearing defects will create excessive vibration and such signals can be monitored by using piezo electric elements, and by providing warning systems. This is built on the study of 'A New Acoustic Emission Wireless Monitoring System; An Experimental Validation of Bearing Condition Monitoring' [8].

Tyre pressure has a significant effect on vehicle performance and therefore, tyre life, correct tyre pressure and temperature should always be revised. The life of the tyre can be extended by monitoring tyres with pressure sensors, thereby ensuring that the pressure is always kept at the standard limits.

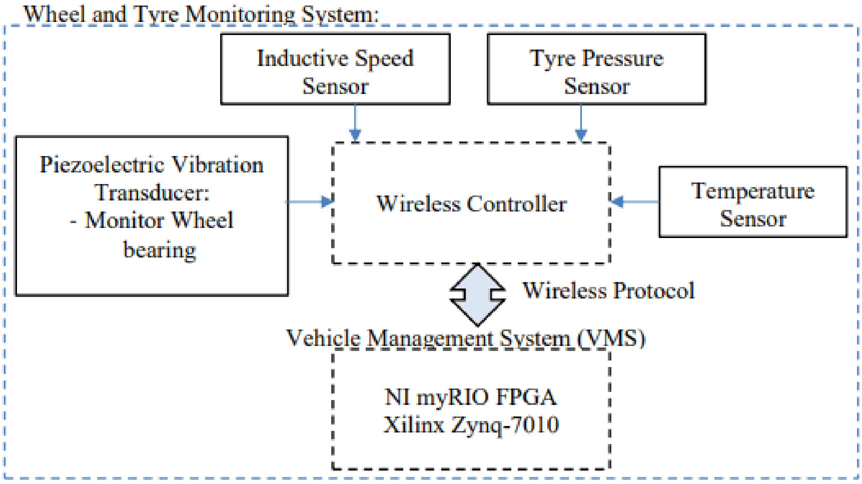

Figure 3: Sub System Block Diagram – Wheel and Tyre Monitoring System.

4 CONCLUSION

Driverless vehicle research has been principally concerned with satisfying the requirements of level 5 of the Society of Automotive Engineering (SAE, USA) J3016 automotive automation standard; a standard that will improve commuter satisfaction and vehicle performance. However, several outstanding issues still need to be addressed, such as on-road safety and integration. Therefore, this study addresses the ongoing development of an Intelligent Management System for Driverless Vehicles.

This paper documents the work achieved in the initial developments of the IMSDV. It presents critical reviews of influential literature on driverless technology that is associated with this field, in order to highlight the existing theoretical and technical gaps within the international research. Combination of both design and development aspects have been considered in this paper in order to develop an adequate test apparatus (Driverless Pod) that suits the requirements.

The authors have presented preliminary test results for the Driverless Pod including the use of multiple sensory actuation systems which indicate that the Pod is suitable for gathering data that can be utilised in the final validation stage of IMSDV. These developments will be validated in three stages: laboratory testing, workshop testing and on the Driverless Pod. The following publications will illustrate the integration of monitoring systems for driverless vehicles by utilising IMSDV.

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Development of a Driverless Personal Mobility Pod

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Abstract **— The paper describes design and development of a new 'Personal Mobility Pod' using low cost systems proposed for use in urban areas. Recent studies have shown increased use of personal mobility, suggesting the scope for further research. Adding to Mobility-on-Demand and vehicle share, such mobility pods could bridge the gap in driverless vehicle research and possibly be a solution to road traffic and congestion in urban areas. The proposed platform is a combination of sensory fusion with feedback managed by a main controller. The navigation system considers offline mapping and localisation with user interface, illustrating waypoints through Google Maps. A Pure Pursuit technique is used to track the vehicle along the given path. The scooters robust, reliable, safe design allows operation in various terrains. The developed platform is moreover proposed as a suitable test platform for driverless vehicle sub-system for testing and experimentation. The reliability of the pod has been tested and validated in two stages: laboratory testing and field testing.**

Keywords – Perosnal Mobility Pod (PMP); Motion Control; Trajectory Tracking; Mobility Scooter

I. Introduction

Self - driving vehicles were perceived in the past as a fantasy by futurists and visionaries. Though sufficient research has proved they are perhaps a solution to many mobility issues we face today: traffic congestion, air pollution, road fatalities and the changing demands of young and elderly [1].

Major car manufacturers (i.e. Tesla, Nissan) and industry leading technological companies (i.e. Google, Induct) have demonstrated various levels of self - driving capabilities through working prototypes. Researchers have predominantly been concerned with satisfying the requirements of Level 5 - the highest ranked - of the Society of Automotive Engineering (SAE, USA) J3016 automotive automation standard [2]; that will improve commuter satisfaction and vehicle performance. Researchers and manufactures are competing to be at the forefront of testing and development. Growth in industry, along with individual consumer and societal benefits are leading factors in the immensely gained attention for the research.

An area of progression in both testing/ development is in personal Mobility-on-Demand. A 'Personal Mobility Pod' (PMP) could bridge the gap in industry, which could be used in urban areas which could reduce road traffic and congestion. Where these vehicles are closely in alliance with mobility scooters focused for elderly users, the proposed PMP is an opportunity for all types of road users for urban environments for shorter commutes in multi terrain environments.

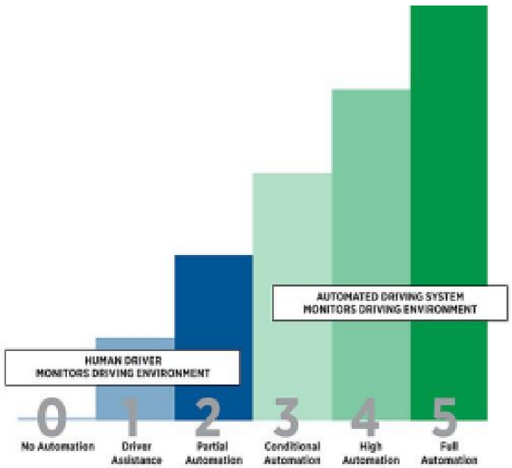


Figure 1. SAE J3016 Automotive Automation Standard [2]

The increased users of mobility scooters clearly indicate the scope for such vehicles. According to Research Institute for Consumer Affairs (RICA) from a UK based research, approximately 300-350 thousand mobility scooters are in use. The global forecast for mobility scooters market to grow at a CAGR of 5.23% during the period 2017-2021 according to Technavio analysts. Considering the demand for personal mobility scooters, this paper presents a 'Personal Mobility Pod' (PMP) for all types of users.

The main contributions of this paper are:

1. Design, development and implementation of a new 'Personal Mobility Pod' using low cost systems which is proposed for use in urban areas.
2. Use of sensory fusion with feedback and a navigation system that considers online/ offline mapping and localisation.
3. A suitable test platform for driverless vehicle systems. Experimentation in multi terrains.

This paper is organised as follows. In Section II, related work on self – driving pod for personal use will be studied. Section III will cover system architecture and focuses on the design implications. The implemented navigation arrangement involving mapping, localisation and the combined controls system is to be discussed in section IV. Experimentation methods will be explained in Section V and section VI and the paper is concluded in Section VII.

II. Related Works

Since the conception of Intelligent Transportation Systems (ITS) in the 1980s, many transport researchers have progressed to work on the development of incident management models and integrated systems for real-time operations [3]. The challenge presented by DARPA in 2004 was perhaps the major spur behind the research for driverless vehicles; making it currently among the most intensively researched and publicly followed technologies [2]. Major car companies and research organisations attended the event.

While the DARPA Challenge remains the major demonstration of autonomous vehicle technology to date, it excluded many capabilities and requirements critical for actual city driving, thus, completing an off-road course within a time limit remained the challenge [3].

It has been suggested, for a true multi-class fleet of autonomous vehicles, where each class of vehicle would be selected depending on the intended environment, would widen the possibility for all types of commuters whether it be young, elderly or a disabled individual.

Wheelchair systems has shown a significant development in the recent years, few number of studies focused on scooter type vehicles and its autonomous development are in high demand. Personal mobility devices have been an active area of research since 1980's. Notable developments include MIT's robotic wheel chair for indoor purposes, equipped with voice and brain control interfaces, with laser and odometry to identify its surrounding. The wheelchair also follows a human tour guide and learns metric and topological representations of its surroundings.

Tsukuba Real World Robot Challenge [4] held at Japan in 2007, focused on autonomous navigation in human environments. In crowded surroundings where humans are present will prove a greater challenge as the possibility of a collision increases. Developing a stable robot platform, with optimum mapping and localisation were the main goals. Tsukuba challenge presented various studies of personal autonomous scooter platforms.

A study of autonomous scooters demonstrated a robot platform featuring Mobility-on-Demand where the user can order an autonomous scooter online, and to set target location using a waypoint system would pick the user from their location and navigate them safely to the desired location. This system used high cost compact Gigabyte BRIX Pro computer and multiple LIDAR sensors in order to localize the vehicle within the surrounding obstacles. The planning system consist of three layers; mission planner, behavioural planner, and local planner. For path tracking, a pure pursuit algorithm and simple PID controller with feed forward compensation are used [5].

This study is focused on 'Personal Mobility Pod' (PMP) designed and developed for testing and implementation of driverless vehicle sub-systems using low cost methods. The navigation system implements mapping, localisation, obstacle avoidance and waypoint interface with google maps.

Table 1: Personal Mobility Pod Specifications

Max. Speed	8mph
Range	25 miles
Dimensions	130cm (L) x 63 cm (W) x 80 cm (H)
Max. Payload	170kg
Weight w/o Batteries & Seat	52kg
Net Weight	94kg

III. System Configuration & Architecture

The base platform for the personal mobility pod is Landlex Broadway RS. It has been modified and retro fitted where necessary to accommodate the various sensory actuation systems, power systems, computing units and other features used in the process of automating the Pod.

The original scooter chassis was preserved during conversion and kept as non-destructive as possible with minor cutting, drilling. Any modification and custom-built parts were specific to the scooter type, utilising existing mounting points. Similar method maybe used to recreate the described pod using other scooter platforms. Tri-wheeled scooters may also be used for recreational models with other hardware components.

This specific mobility scooter consisted of various running conditions and features: User Friendly Console, Light Sensors, Status indicator, Adjustable Speed Dial which complement the unit highly for its intended users. Additionally, the portability of the x2 12 V battery that it is powered by, robust chassis, multi terrain tyres and the straightforward design, with automatic breaking were the features that were most complementary when choosing a mobility scooter for the proposed PMP.

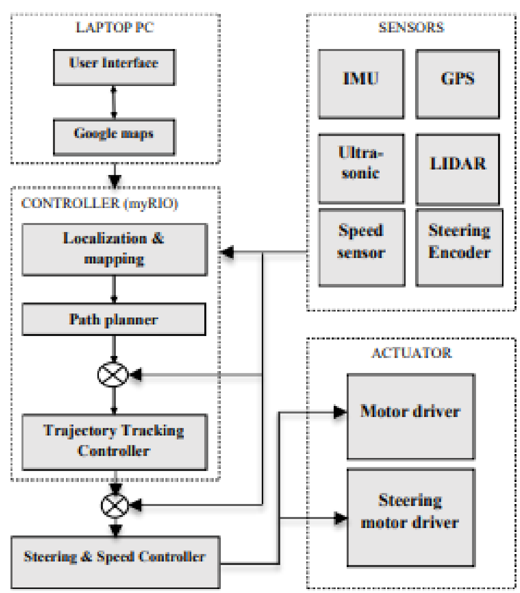


Figure 2: Configuration of PMP

A. System Architecture

As in the Figure 3, the personal mobility pod consist of multi systems including user interface, vision system, and obstacle detection and mapping system, planning and motion control system. However, the purposed research focuses on the user interface with vehicle and the motion control system. The main components of the autonomous scooter is:

- Arduino Mega2560: slave controller which control the actuators
- CYTON 30A 5-30V Single Brushed DC Motor Driver: the steering driver
- ADAFRUIT INDUSTRIES 746 GPS Module: it's a GPS receiver which get the position data from
- Adafruit 1946 FONA Mini Cellular GSM Breakout uFL Version
- Adafruit 2472 9-DOF Absolute Orientation Inertial Measurement Unit IMU Breakout
- Motor speed sensor
- Absolute encoder for the steering
- Laptop for interface and monitor the system

B. Electrical Power

The main electrical power for the PMP is produced by two 12V battery packs connected in series to make 24V. The main motor of the Pod as well as accompanying circuitry are powered by the 24V power supply. An additional 12V 34AH/ 20hr battery is used specifically for the steering motor and associated circuitry. Both power sources have been equipped with circuit breakers and fuses to provide protection to components.

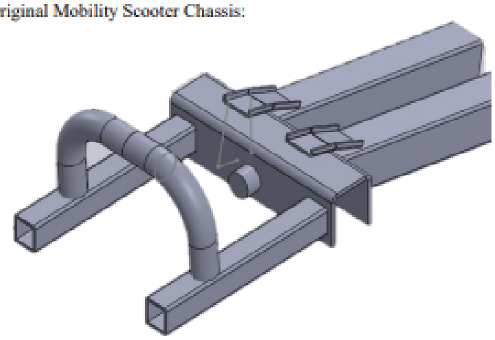
C. Actuation

The PMP has been designed to have two modes of driving: Fully Autonomous Mode equivalent to level 5 of the SAE [2] & Manual Mode where the driver has manual software control of steering and drive. Controllability of both the drive motor and steering actuator have to be accessible to operate in autonomous/ manual mode. Also, accessible from the computer commands via the on-board laptop.

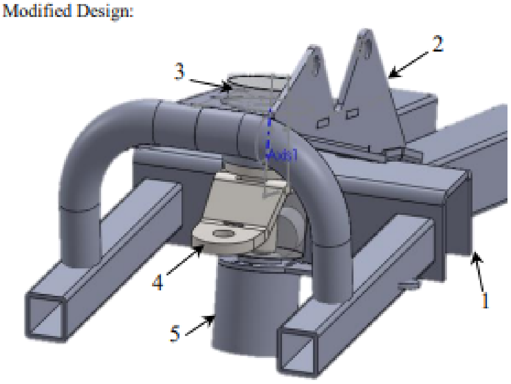
The steering is achieved using an Electric Power Steering (EPS) motor from a Vauxhall Corsa C. The motor has high torque, compact size, controllability with accompanying circuitry; characteristics which were desired. A steering encoder was linked adjacent to EPS to monitor angular movement with feedback. Each motor driver circuitry capable of handling up to 30A current have been implemented for control of both actuators through NI FPGA module.

Figure 3 illustrates CAD models of the modification made to accommodate the motor. This novel design was constructed to retrofit the actuator to the scooter chassis.

Original Mobility Scooter Chassis:



Modified Design:



1) Chassis
2) Mounting Bracket to Accommodate Steering Actuator
3) Link to Steering Actuator
4) Linkage from Actuator to Front Axle
5) Steering Encoder Mounted to Pod Chassis

Figure 3. CAD representation illustrating modifications made to original chassis (top) to accommodate new EPS actuator (bottom)

The pre-existing manual control tiller of the scooter was replaced by newly constructed mounting position for the actuator. The old tiller was removed completely disengaging any form of manual control over the PMP's steering as this would oppose a safety risk whilst in Autonomous Mode. A custom metal bracket to suite a display module for passenger interaction was custom-made. The display user interface would be used for manual controls of the PMP in manual mode.

The original scooter motor Landlex 9000F 92N was operated using a throttle potentiometer, which worked on an input range pre-programmed in the scooter's control system by RHINO as a proportional system between 0-5V; 0V being maximum reverse speed, 2.5V at standstill, 5V maximum forward speed. For controllability, FPGA module surpassed the system and would allow automating PMP. Though, due to minor fluctuation in voltage when battery starts to run low, the main motor won't operate (as a safety measure implemented by RHINO) and generate a fault status, having to require a troubleshoot to restart PMP operation. To eliminate uncertainty, the actuator was disengaged from pre-set RHINO throttle programme and controlled using DC motor driver circuitry.

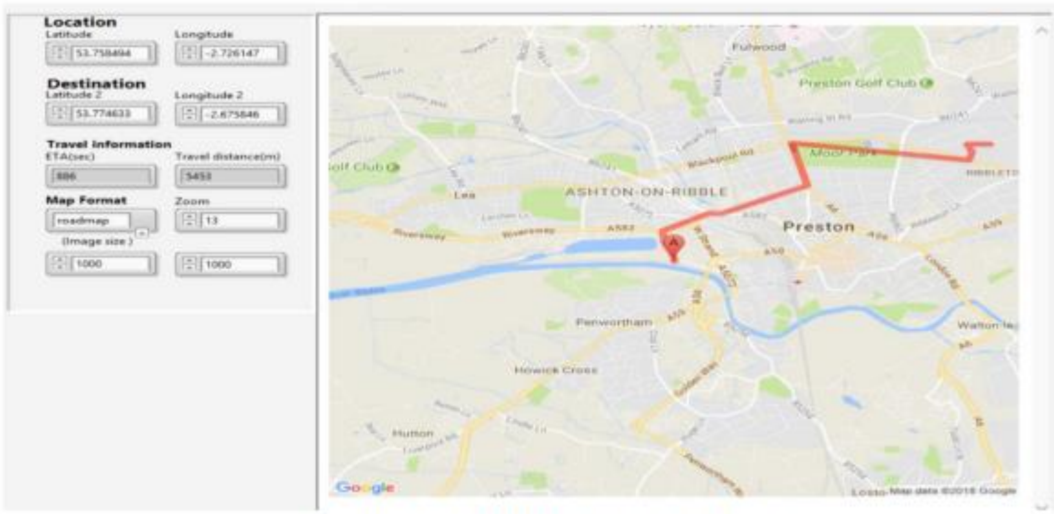


Figure 4. User Interface for PMP Integrated with Google Maps

D. Software Framework

National Instruments myRIO FPGA module acts as the main control/ management system for the PMP. NI myRIO-1900 is a reconfigurable I/O device which is a portable, multifunctional unit used in various multidisciplinary applications including robotic and mechatronic systems. It features the Xilinx Zynq-7010 all-programmable system on a chip, which includes a dual-core ARM Cortex-A9 processor and an Artix-7 FPGA. The dual-core ARM Cortex-A9 processor on NI myRIO runs the NI Linux Real-Time OS. Additionally, it provides the option to program the processor in either LabVIEW or C/C++.

The module has been used with LabVIEW software which is an object orientated language. The programme includes various sub VI's each including the required objects and libraries. For navigation, the robotics library was used to create the map and find the optimum path with search techniques. By using ActiveX object an interaction between the browser and LabVIEW was established to send and receive map data. Associated sensors were all programmed using myRIO communication library.

IV. Mapping and Navigation System

This section discusses localization and planning for the vehicle using GPS sensor and Google maps to define the desired route that the vehicle must follow. Different researches discussed how to make a real time data logging using low cost system which uses the controller to send and receive location's data through a server and monitor it using google maps or any different mapping tool [6]. In this stage, the user interface software will communicate with google maps using Google Maps APIs service [7]. This service uses HTTP request to calculate direction between given locations and return the data as an image to be displayed along with waypoints to the targeted location.

To track the vehicle on maps, The Google Static Maps API provides the user interface with updated map image according to the specified location by the GPS feedback and map parameters including zooming, format, map type, markers, and path visualization which the user can control. Also, the user can specify the target location and request the direction from Google maps Direction API to return the path waypoints and travel duration and distance in xml format. Afterwards, the waypoints are used to update the local mapper. This command is used by LABVIEW ActiveX object to interact with a browser to send HTTP commands and then receives the google maps results as in Figure 4. Additional features can be added to the navigation system and the GUI such as searching for an address or looking for the nearest hospital, or workshop. This features would be helpful in the future work to monitor the vehicle

V. Motion Control System

The purpose of the trajectory tracking controller is to provide the setting points for the steering and speed controllers, aiming to follow the pre-defined path which given from the planner considering the desired speed and orientation of the vehicle. According to De Luca et al. [9], there are three main tasks for the tracking controller, namely Point-to-point motion, path following, and trajectory tracking. Firstly, the controller try to reach the desired point from the initial position then try to follow the geometric path from the staring to the end point and finally try to reach the desired point with the determined velocity. There are different type of controllers developed to handle the tracking task based on the vehicle model.

There are different types of controllers developed to handle the tracking task based on the vehicle model. One of most popular type of controllers is the pure pursuit controller which determine the nearest point on the given path from the planner then create a look-ahead distance and calculate the steering angle to set the steering controller with. This method ensures the smooth steering and reduce the oscillations during movement.

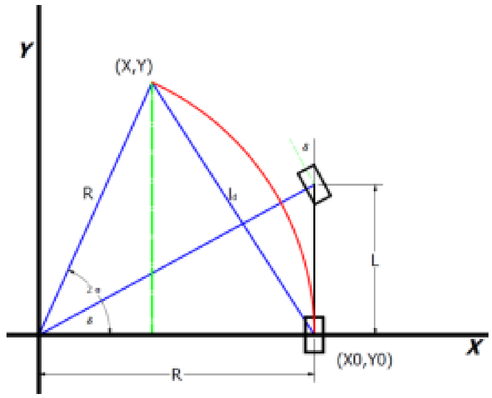


Figure 5: Bicycle representation of vehicle in geometrical model

A. Geometrical modeling

Generally, scooters which considered as car like robot vehicle can be described as a rigid body with concentrated mass in the centre of gravity and it's classified as a non-holonomic system [9]. Geometrical model considered as a simplest modelling technique. Based on Ackerman steering configuration, it only uses the dimension and position of the vehicle regardless its velocity and acceleration. The importance of this method is come from evaluating the path tracking performance and developing the pure pursuit controller [10, 11]. In this method, it is considered that the vehicle moves with low speed and has moderate steering angles. So, there are two main assumptions;

1) The four wheel scooter is simplified into a two wheel bicycle model by combining the two front wheels together and the two rear wheels together to form a two wheeled model neglecting the slibing effect.

2) The vehicle moves only on plane

As in the Figure 5, the geometrical relationship between steering angle and the curvature where the vehicle move along can be driven as:

$$\tan \boldsymbol{\delta} = \frac{L}{R} \qquad (1)$$

Where:
$\boldsymbol{\delta}$: steering angle
L: wheelbase length
R: radius of the curvature that the vehicle moves on

B. Pure Pursuit algorithm

In Pure Pursuit method, a circular curvature is calculated between starting and ending point according to the look-ahead distance. By applying the sines law in the geometry of the Figure 6, steering angle $\boldsymbol{\delta}$ can be calculated using the look-ahead distance l_d and the angle $\boldsymbol{\alpha}$ as derived from the below equations:

$$\frac{l_d}{\sin 2\alpha} = \frac{R}{\sin(\frac{\pi}{2}-\alpha)} \qquad (2)$$

$$\frac{l_d}{2\sin\alpha\cos\alpha} = \frac{R}{\cos\alpha} \qquad (3)$$

$$R = \frac{l_d}{2\sin\alpha} \qquad (4)$$

$$\gamma = \frac{2\sin\alpha}{l_d} \qquad (5)$$

Where: γ is the curvature between start and end points. By substituting in Eq.1, the steering angle will be as:

$$\delta = \tan^{-1}(\gamma . L) \qquad (6)$$

$$\delta = \tan^{-1}(\frac{2\,L\sin\alpha}{l_d}) \qquad (7)$$

From Eq.7, the Pure Pursuit controller is function of the look-ahead distance l_d in front of the vehicle. So, small look-ahead distance provides more accurate tracking while large distance provides more stable and smoother tracking. To tune the Pure Pursuit controller, the look-ahead distance is scaled with the longitudinal velocity of the vehicle.

$$l_d = K . v_x \qquad (8)$$

As in the Figure 6, the controller is calculating the steering angle using current position of the vehicle and goal point given by the planner which constrained by the speed provided that scales the look-ahead distance. The next step is to control steering and speed of the vehicle by a simple PID controller for tracking the desired steering angle and speed provided with tracking controller. This low-level controller is tuned by the steer angle and speed sensors feedback.

The main disadvantage of Pure Pursuit method is neglecting the dynamics effect which could cause an instability of the system obviously in the high speed. To overcome this effect, several approaches are used to enhance this system such as adapting the Pure Pursuit method with PID or Fuzzy systems.

VI. Expermentations

In this section, the implementation of the system will be discussed as well as some of the field results will be shown

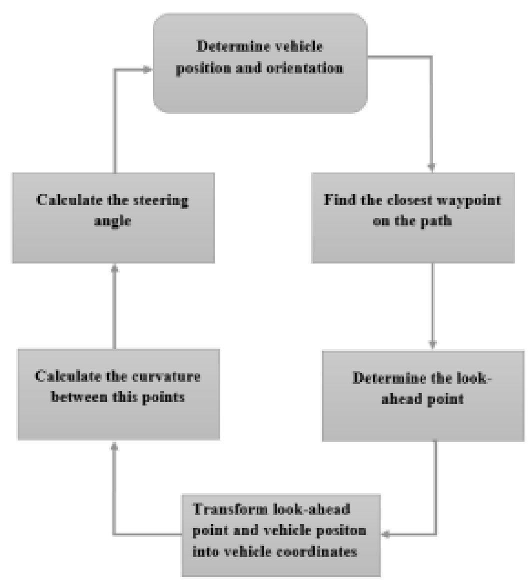


Figure 6: Pure Pursuit algorithm flowchart

as validation of the system. According to Safety regulations, the PMP cannot be tested on streets for the moment, so currently we are testing it on a prepared safety field.

A. User interface

Using the vehicle laptop, the user specifies the desired location on the LABVIEW GUI and start running the PMP. First, the program interacts with google maps API by sending the HTTP command and then receive the direction as waypoints to the desired location as in the Figure 7. Also, the interface informs the user with the calculated distance and estimated travel time. However, the user can't choose within alternative routes, but it will be considered in the future work. The user as well can monitor the vehicle position, velocity, heading angle and the surrounding environment.

B. Vehicle testing performance

After getting the google maps main point, the main planner transfers the waypoints into vehicle coordinates. This waypoint processed through the controller to give the steering and speed inputs to the slave controller. In laboratory, the steering was tested separately to ensure the response of the controller and it has a fast response as in the Figure 8. To verify the performance of the system, it was tested in a prepared ground field. A distributed objects were located randomly to test the obstacle avoidance algorithm, the vehicle successfully went through the field without hitting any object. This test was monitored and recorded to verify that the vehicle will pass through google maps waypoints and reach the target.

VII. Conclusion

In this work, a low cost driverless PMP was developed with its system architecture and components. This platform was designed to achieve high reliability and integrity with different systems as shown in the connection between individual systems such as google maps, on-line planner, trajectory tracking, and low-level controller. Although, the Pure Pursuit technique doesn't consider the dynamic effects, it could be tuned using intelligent control system such as Fuzzy controller or Neural Network controller to

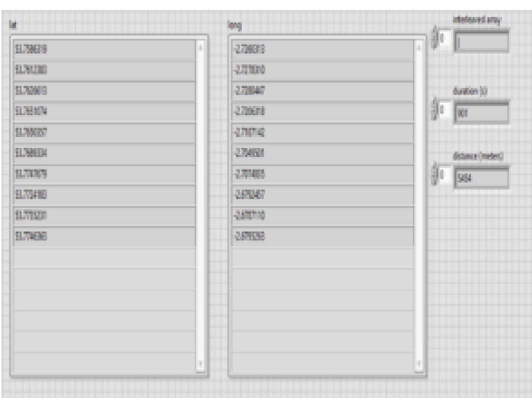


Figure 7: Google maps with path waypoints

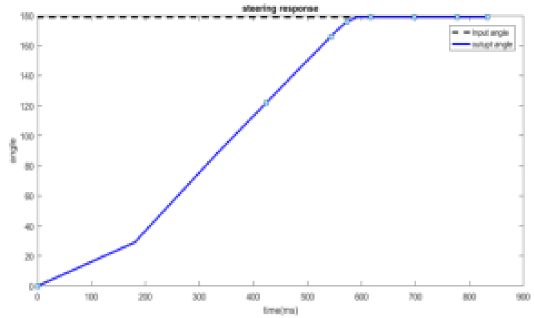


Figure 8: Steering response of the actuator with step input

achieve the system stability. This structure also has the ability to be integrated with other systems such as vision system and wireless charging system. In the future work, it's planned to integrate the PMP with vehicle monitoring system to monitor the vehicle mechanical and electrical systems such as wheels pressure and alignment, bearings vibration, battery charge, and power circuit current.

Acknowledgment

This work would not have been possible without the funding provided by the EU Erasmus + ICM Programme, and research resources and support provided by the University of Central Lancashire.

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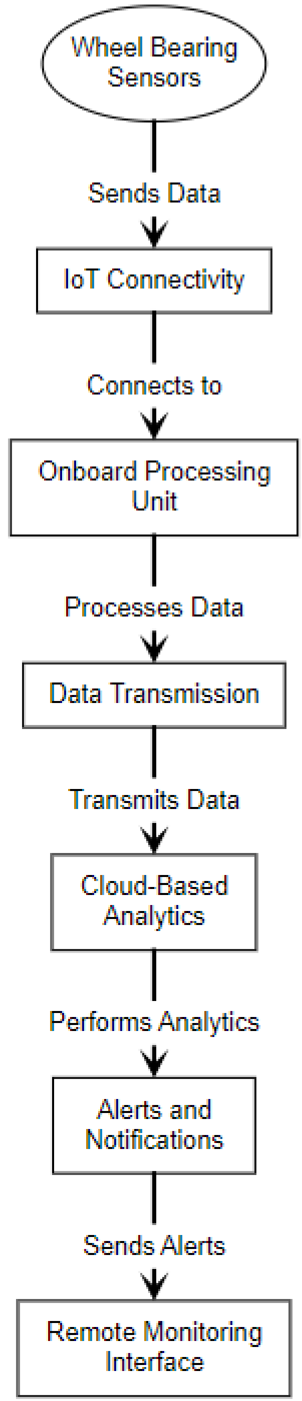
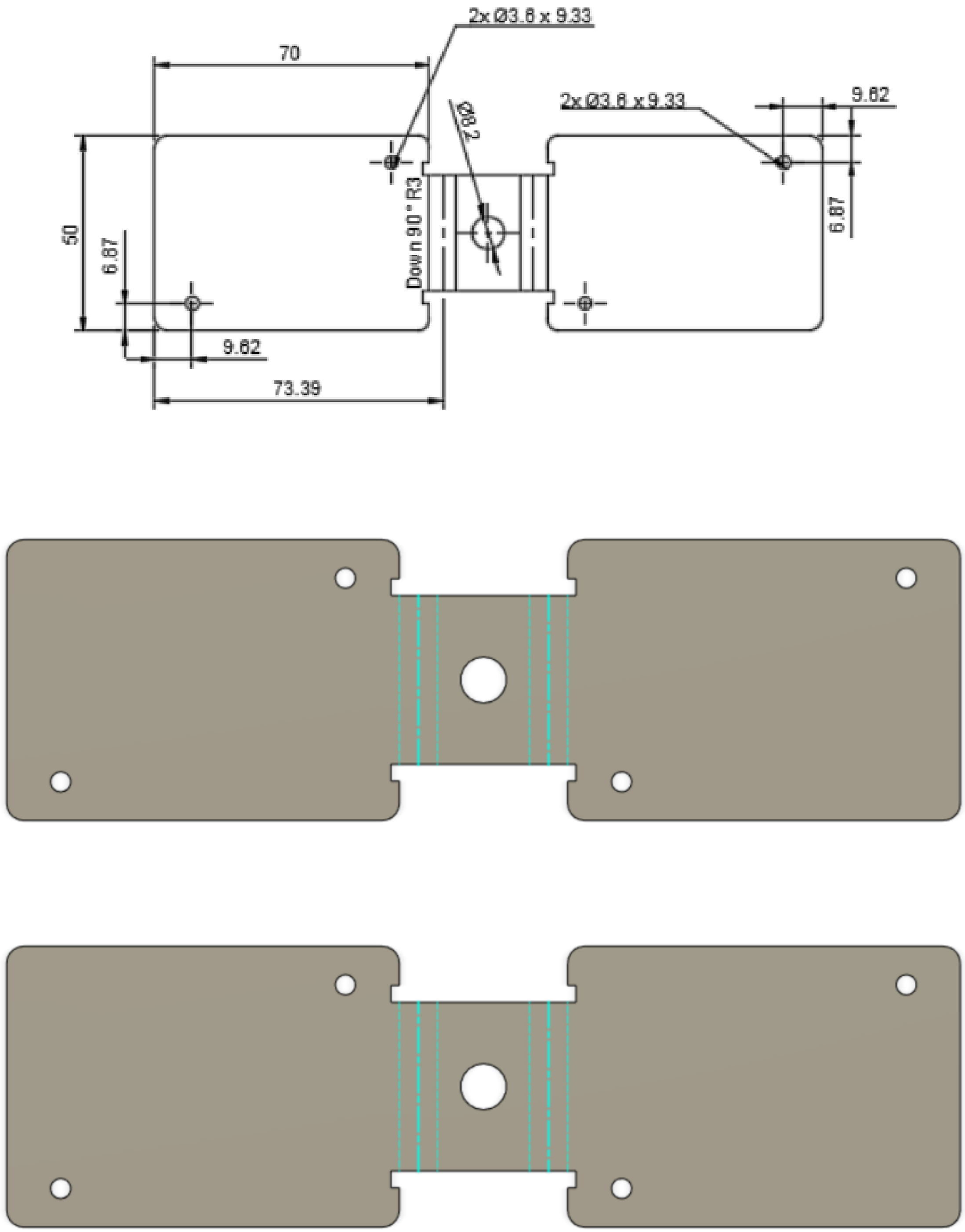
APPENDIX B

KEY ADDITIONAL DEVELOPMENTS

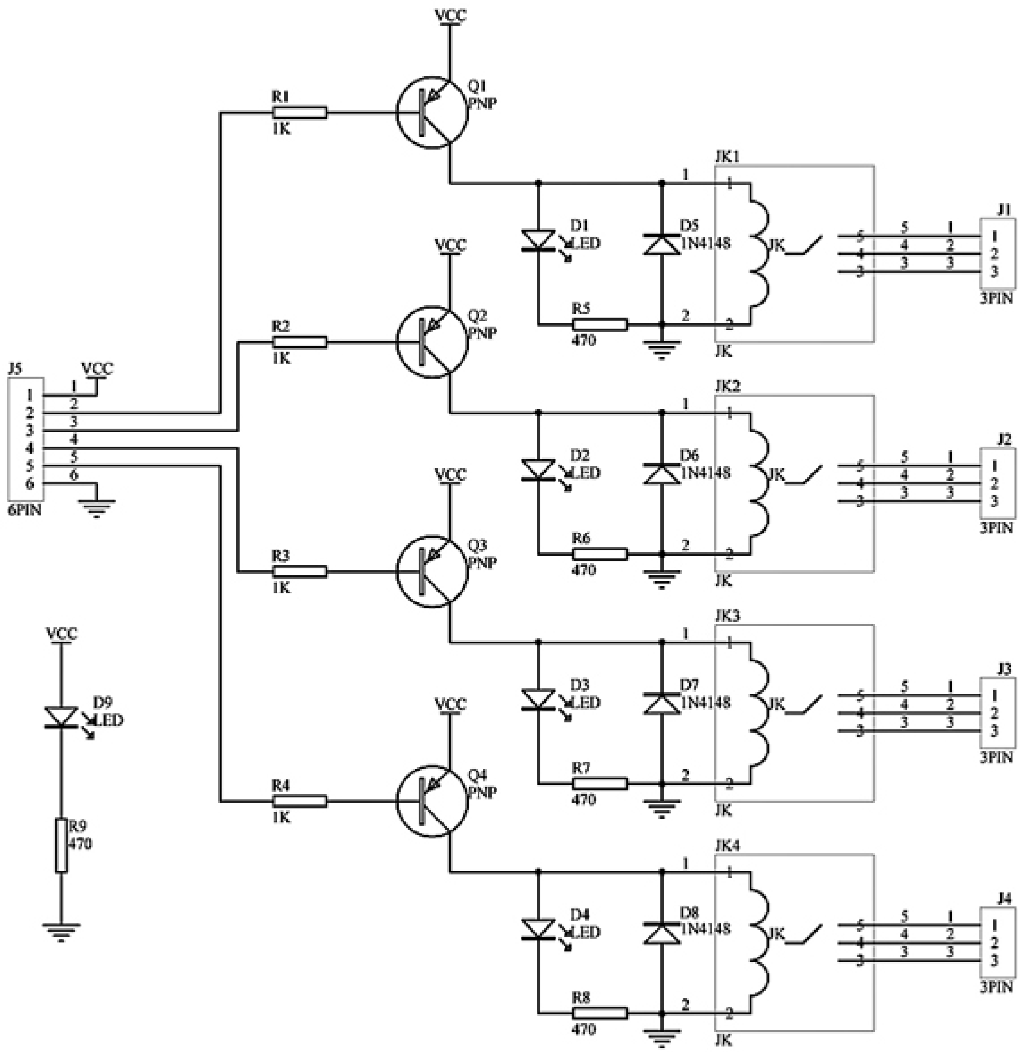
Overview of the developed monitoring sub-system tests using the developed PMP



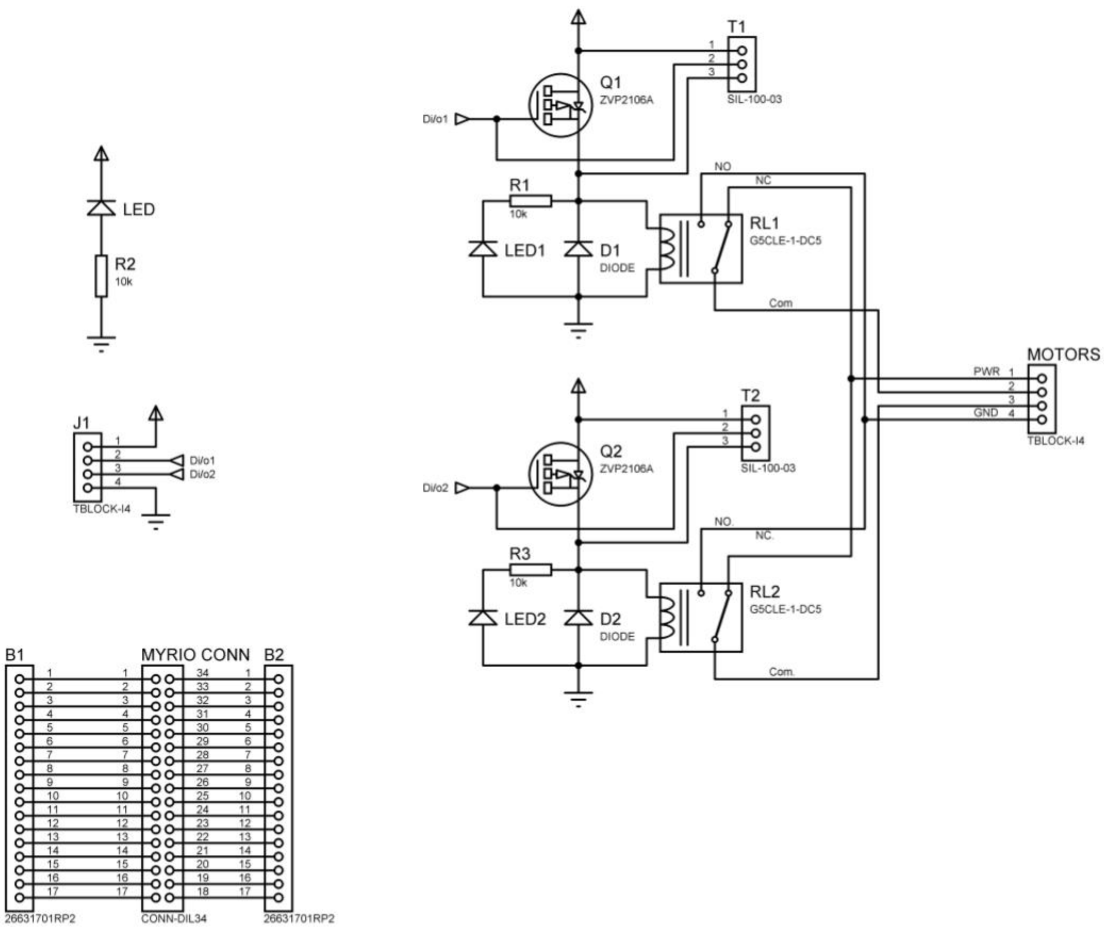
Design model for capsulated sub-system mounting for steering component monitoring



Circuit designs for PMP drive control



Circuit designs for PMP actuator control



PCB design for steering relay control