The University of Queensland

Inductive Position Sensing of Power Cables for Autonomous Vehicle Navigation

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Submitted for the degree of
Bachelor of Engineering (Honours) and Master of Engineering

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June 27, 2019.

To Noel, from whom I learned my passion for electronics.

Acknowledgments

I wish to acknowledge the assistance provided by Dr Konstanty Bialkowski for the academic aspects of this thesis. I am particularly grateful for the support and guidance provided by Dr Erik Isokangas, and would like to extend my gratitude to all the staff at Mining3. Finally, I wish to thank my parents for their unconditional support and encouragement throughout my studies.

Executive Summary

Mining3 has responded to rising fuel and labour prices [1], stricter ventilation requirements in underground mines [2] and the shift towards a "green" future [1] by proposing an all-electric, autonomously controlled hauling truck called the AEH, to replace conventional and comparitively inefficient [3] diesel trucks.
All existing solutions in the mining sector only address one of the aforementioned problems — from retrofitting autonomous control solutions [4], autonomous diesel-electric hybrids [5] and trolley-assist systems [6], no one technology provides a solution to all three of these issues.

Enter the AET — the goal is to reduce operations cost by utilising autonomous control and efficient electric drivetrains, while minimising capital cost by employing a dynamic wireless power transfer system (WPTS) which reduces the need for large battery storage on the haulers, saving cost and weight [7]. Aligning the hauler with the charging system accurately provides the maximum efficiency, and since mine sites are harsh, often GPS denied environments, an "on-wire navigation" system is proposed to guide the haulers along the WPTS — this is the design project.
The objectives are to build an operational prototype of the AET and necessary systems to follow the WPTS cable, and requirements are that no additional parts be put on the WPTS in order to navigate. Since the AEH is to be used in mining environments, conventional line-following techniques are not feasible, and thus active magnetic sensing is the focus.

Inductive metal detection is proposed to follow the cables of the WPTS from a literature review of several different sensing methods. In particular, an inductance to digital converter IC was selected for ease of use and its 28-bit resolution. Location and detection algorithms were developed and tested on a piece of test track until a suitable combination was found. From this, a PD controller was developed and added to the platform vehicle, where it was then tested by allowing it to navigate a second test track. This track was a $3m$ straight section followed by a $3m$ radius left hand arc. The AEH followed the test track in its entirety, and the on-board odometry was used to track the vehicle position. It was found that the average position error on the straight section was $4cm$, and $6cm$ on the arc. Although it appeared the AEH hit its software steering limit and could not turn quite sharp enough at the end of the arc, resulting in approximately a $20cm$ error.

The AEH project met the initial design goals and was therefore determined to be successful. Future work is proposed to optimise certain parts of the AEH, as the on-wire navigation project to date was intended as a proof of concept.

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1. Introduction

1.1 Context

Resource extraction companies aim to boost profitability and efficiency in their operations by reducing costs [17], such as the capital, fuel and labour involved in hauling raw materials within the site [18]. Conventionally, large diesel fueled trucks with electric drivetrains such as the Komatsu 930E and CAT AD60 (for underground mining) in Fig. 1.1 are used to transport this material [19]. However, with shifting public opinion on fossil fuels and global resource markets changing, diesel engines in haul trucks are "failing to address major issues facing the industry" [20], including:

1. Increasing diesel and maintenance costs [1];
2. Tunnel design in underground mines reaching geotechnical limits [20];
3. Greater environmental awareness to mining operations [1]; and
4. Stricter ventilation requirements in underground mines [2].

Figure 1.1: Komatsu 930E (Left) and CAT AD60 (right) [8][9]

Eliminating the diesel engine from haul trucks is a major contributing factor to solving the above problems, but there are further technologies which could be implemented to continue reducing operation costs.

- Caterpillar's MineStar Command System — an autonomous navigation package retrofitted to existing vehicles [4]; and
- Trolley assist technology — using pantographs installed on key parts of haul routes to extract "maximum use of the capacity of the electric motors" [21].

However, these systems still rely on diesel internal combustion engines, and thus don't address the core of the problem. It is widely accepted that electric vehicles are more efficient at converting stored energy to mechanical [3], and are also faster on inclines, and capable of climbing steeper inclines [6] which is a major benefit for open pit mines. Naturally, all-electric haulers are a topic of investigation for cost reduction in mines by addressing issues 1 and 2 from above.

Issues 3 and 4 are eliminated by electric haulers, as they improve safety in the case of underground mines, in so called "gassy" environments[1] by reducing emissions and ignition sources. Goldcorp's *Borden* mine will be Canada's first all-electric underground gold mine [2], reducing carcinogenic diesel exhaust [22] and allowing costs to be reduced in diesel and ventilation requirements [23]. The main drawback of electric vehicles is their capital cost — those in Golcorp's mine are said to be 25 – 30% more expensive initially, but can halve energy costs [23]. There is a "simple" solution; according to [24], "dynamic [wireless] charging can help lower the price of EVs by reducing the size of the battery pack."

The on-line electric vehicle (OLEV) is a transit bus at the Korean Advanced Institute of Science and Technology (KAIST). OLEV was retrofitted with electric motors, a small amount of battery storage and an accompanying wireless charging system [25]. The OLEV's battery is only about 20% the capacity of existing electric vehicles and is intended to be used for about 10km of travel [25]. The reduction in battery storage is enticing for the project as it severely cuts down on the capital cost of the vehicle. Another indirect benefit of a wireless power transfer system (WPTS) is that there is no ignition risk, which is an important fact for underground mines [21].

Combining electric haulers, wireless charging and autonomous control would provide a major leap forward in mining efficiency, production and safety. This is the proposed Autonomous Electric Hauler (AEH) project. The specific projects undertaken address key problems in the overlapping technologies of the AEH. The focus of this thesis will be the so called, "on-wire navigation system", which is employed to keep the AEH on the WPTS and to provide a guided navigation method for the vehicle.

1.2 Purpose

The purpose of the overall AEH project is a refined proof of concept of an autonomous, electric powered, wirelessly charged mining hauler. Within this, there

[1] A by-product of underground coal mining is the release of the coal-seam gas, methane [21].

are several gaps in the previously existing technology which need to be addressed.

The overarching aim of this thesis is to ensure the AEH can wirelessly sense, and subsequently follow a model charging cable, with the specific purpose of:

1. Directing the AEH on the correct haul route, in the right direction; and
2. Keeping the AEH in an optimal charging position above the WPTS.

Keeping the AEH aligned above the WPTS is crucial, and is considered by [7] as one of the main hurdles faced by wireless charging systems.

1.3 Scope

The scope of the on-wire navigation project is defined in the following sections, detailing what a successful project will produce. Not considered in the scope of the project is learning any software packages, although these will be critical for project completion. In addition, although assessment for ENGG7290 is required, it is *not* considered in the scope but *is* considered in the project plan[2].

1.3.1 Objectives

Completion of the following goals corresponds to a successful project:

1. Design and build a platform vehicle on which to overlay the on-wire navigation system;
2. Design and produce a suite of sensors and accompanying hardware to detect metallic structures;
3. Implement a method to locate the WPTS in relation to the AEH; and
4. Verify the prototype by integrating sensors with the control system, using sensor data to navigate the AEH along a test WPTS.

1.3.2 Requirements

The main requirement for the final on-wire navigation system is it must sense the bare WPTS directly, with the intention of minimising the cost of the WPTS.

A simplified diagram of the project is presented in Fig. 1.2. Additional relevant requirements for the AEH project as a whole are:

- The AEH must have a *wireless* charging system;

[2] Assessment items are not classified as deliverables.

- The WPTS should be relocatable and easily deployed (e.g. from a truck); and
- All technology created must be safe/applicable for use in mines, meaning:
  - No use of GPS as mines are often in GPS denied environments;
  - No optical sensing as lenses/receivers will get dirty;
  - No reliance on the WPTS being powered; and
  - Is a contactless system due to the near certainty of uneven, rocky ground.

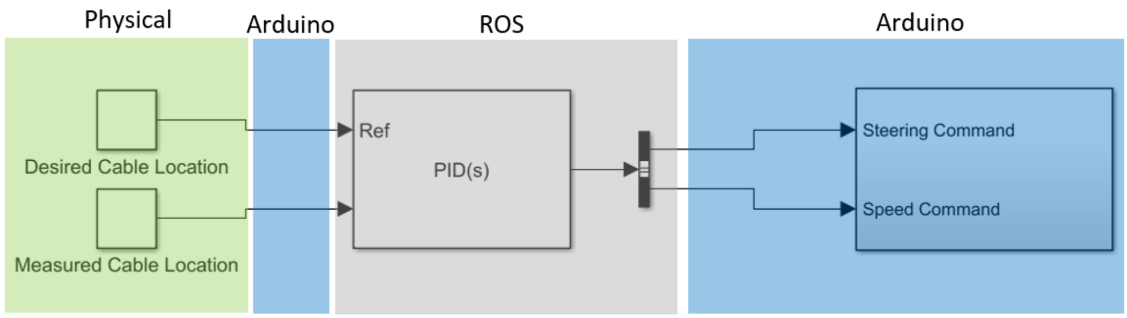


Figure 1.2: Basic Overview of Software Requirements — PID Control as Example

1.3.3 Deliverables

The two deliverables for the project are a working prototype of the AEH and the sensing software and hardware which control the platform vehicle, which are detailed as:

Hardware

- Remote control hardware to drive motors, steering and accessories;
- Sensors for steering angle and ground speed;
- Controllers (microcontrollers and computers) to interface with and run ROS; and
- Sensors mounted on the vehicle to sense and locate the cable for navigation.

Software

The software element of the project will be written specifically for use with ROS and to comply to the goals outlined in Section 1.3.1. Parts may be written in embedded languages, while others may be written in higher level languages such as Matlab or Python. In addition to the code, it is expected that at a bare minimum the code will be commented conforming to Google's Style Guides [26].

2. Technical Background

This chapter will review the necessary background concepts relevant to the AEH on-wire navigation project and requirements, which can be simplified to a cycle of sense, locate and actuate. This section is a precursor to the literature review, which examines prior art and relevant technologies. The background information commences with a review of wireless sensing techniques.

2.1 Active vs Passive Metal Detection

Commercial cable location for burried utilities detection (for example pipes and mains electric cables) is often done by sensing the electromagnetic field radiating from the target, known as passive magnetic field (PMF) detection [27]. This method can be thought of as purely magnetic field detection caused by electrical currents flowing in the cable. This is dissimilar from active detection, which is used when the target object cannot be energised to produce a magnetic field. PMF contradicts the requirements for the AEH, but active sensing does not. There are several methods of active metal detection, but most rely on the phenomenon of eddy current flow in conductive targets.

2.2 Inductive Metal Detection

The premise behind the AEH's on-wire navigation is to follow a passive metal structure. Most metal detectors rely on the principle of electromagnetic induction to sense conductive targets near their sensing surface [28].

AC Current flowing in a coil will produce a changing magnetic field (B-Field), which will be referred to as the "primary" field. Conductors exposed to primary B-fields will produce circulating eddy currents, which themselves generate opposing, "secondary" B-fields [29]. This causes destructive interference with the primary, and various methods are employed to detect this change, such as that shown in Fig. 2.1.

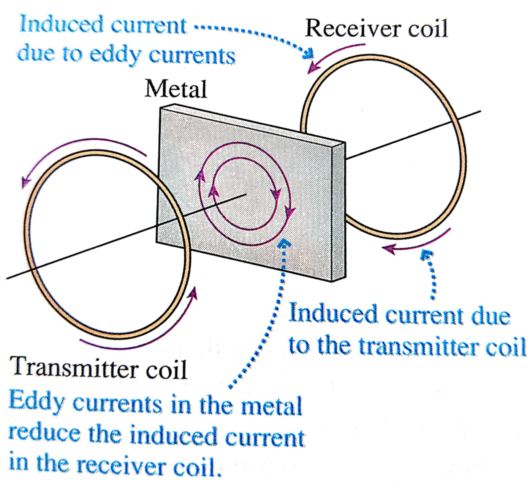


Figure 2.1: 2 Coil Metal Detector Operation Principle — from [10]

For efficiency reasons, the primary fields are often driven by an oscillator, or "LC Tank" [29]; these topologies of circuit have the natural frequency:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{2.1}$$

The inductance, L, will change when a conductive object is moved closer to the coil [29]. Part of the primary field's energy is stored in the conductive target, which has the net effect of increasing the inductance, and decreasing f_0. The change in inductance caused by the target in this situation is dependent on the circulation and density of eddy currents within it.

2.2.1 Eddy Current and Skin Depth

The skin depth represents how deep electric current penetrates into a conductor when it flows, or in the case of magnetic fields — how deep the field penetrates the conductor [14]. Eddy currents flow paralell to the coil windings, and flow density is determined by the skin depth, δ, where

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}} \tag{2.2}$$

ρ is the resistivity of the material (Ω/m), f is the frequency of the current, and μ is the magnetic permeability of the material. The deeper the magnetic field can penetrate a target, the more eddy currents will flow, and so too then secondary magnetic fields. That being said, eddy currents will have the highest density at the surface [14], as illustrated by Fig. 2.2, so it follows that exposing the maximum possible surface area will also contribute to increasing the metal detector response.

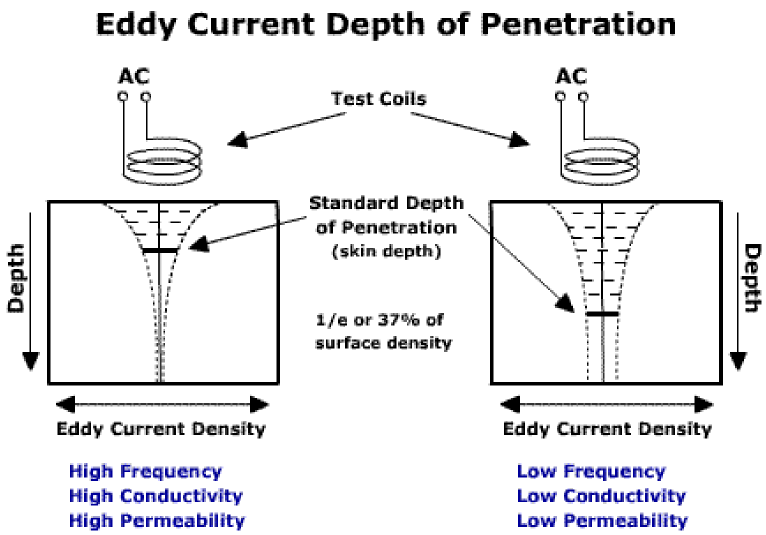


Figure 2.2: Eddy Current Density — from [11]

The following factors are considered variables when seeking to maximise the response from the coil:

- Frequency of the magnetic field, f;
- Amount of primary current, I (and therefore primary B-field);
- Conductivity of the material, $\sigma = \frac{1}{\rho}$;
- Exposure area of the target to the magnetic field, A; and
- Magnetic Permeability of the conductive target, μ.

Three of the five variables are directly linked to the WPTS design itself as opposed to the detector. Therefore the selection of the WPTS cable will be a major factor in the effectiveness of the on-wire navigation system.

2.2.2 Magnetic Field Behaviour

The primary field strength, d meters along the axis of a coil located in the XY plane will be [14]:

$$B_z(d) = \frac{N\mu_0 I}{2}\frac{R^2}{(R^2+d^2)^{3/2}} = \frac{\mu_0 M}{2\pi(R^2+d^2)^{3/2}} \tag{2.3}$$

In Eq. (2.3), $M = NI\pi R^2$. This is the magnetic moment (M), which relates the number of turns (N), current (I) and radius (R) of the coil. For distances $d \gg R$, the relationship follows the familiar inverse cube law:

$$B_z(d) \approx \frac{\mu_0 M}{2\pi d^3} \tag{2.4}$$

These equations show that for a small d, if N and I remain constant, increasing R decreases the z-axis B-field strength. However it is also observed that for this arrangement, as d increases, the B-field "decreases less rapidly" [14]. There must be a balance of coil size and expected distance, but in summary, as put by [14], "Smaller coils provide better sensitivity at closer ranges, but do not allow to go as deep [further]."

2.3 Wheeled Robot Movement

The AEH is intended to be a replacement for traditional mine haul trucks, the majority of which are wheel based. Planning and predicting motion of an autonomous vehicle is critical for vehicle positioning, path planning and navigation – this is the study of kinematics. For low speed operation, a four-wheel car-like vehicle can be represented by the so-called "bicycle kinematics" model [12], shown as the dark grey region in Fig. 2.3. Key points of this model are:

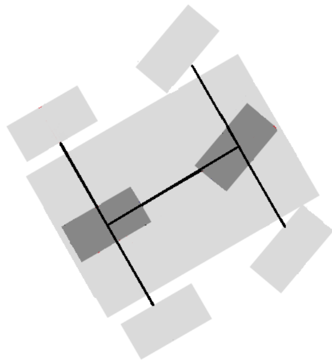


Figure 2.3: Bicycle Kinematics Robot Model

- The vehicle cannot turn unless it has velocity, $|v| > 0$;
- The kinematics of the vehicle is described from a fixed world frame, $\{\mathbf{O}\}$;
- It is assumed the wheels do not slip; and
- The vehicle turns about an instantaneous centre of rotation (ICR).

The only two controls to the robot are v and γ, which are velocity and steering angle respectfully. Practically, these variables will also need to be controlled on the AEH so accuracy can be maintained throughout the robot. Feedback controllers are a viable and relatively simple option to manage these variables. Given this, the model can be adapted to an "Ackermann Steering" model from which vehicle motion can be predicted and controlled.

2.4 Ackermann Kinematics

Kinematics describe a how a robot is constrained to move given its joints [12]. This process is well documented in textbooks such as [12] for so called "Ackermann Steering" vehicles like the one shown in Fig. 2.4. Most noteworthy from Fig. 2.4 is that the final position of the vehicle is given at the point which bisects the "rear axle", $\{\mathbf{V}\} = (x, y, \theta)$. The heading of the vehicle is θ (anticlockwise from positive x axis) and the steering angle is γ. The wheelbase of the vehicle is L and the velocity v. The equations describing the robot's movement with respect to velocity then follow:

$$\dot{x} = v\cos(\theta)$$
$$\dot{y} = v\sin(\theta)$$
$$\dot{\theta} = \frac{v}{L}\tan(\gamma)$$

These equations form the forward kinematics of an Ackermann Steering Vehicle; the position of the vehicle can be found by integrating the above equations with respect

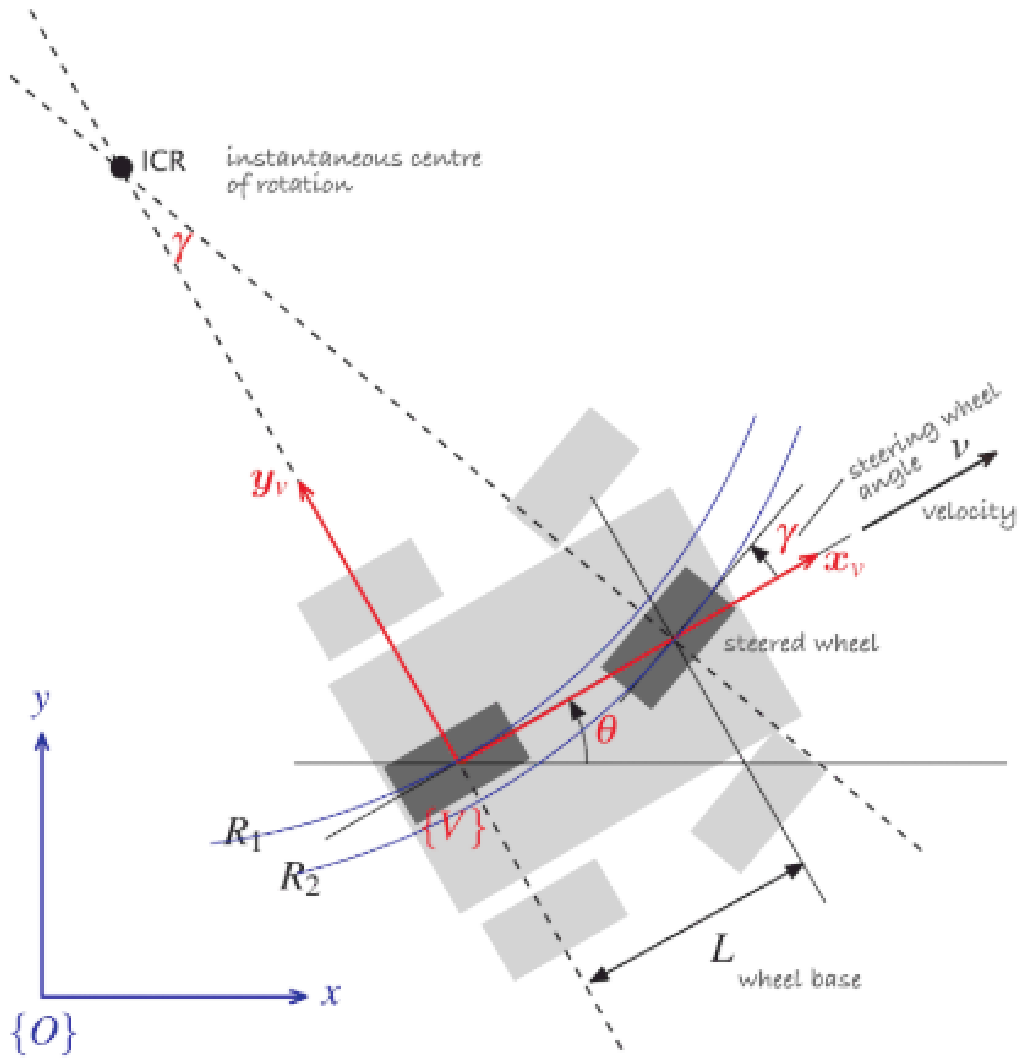


Figure 2.4: Ackermann Steering Robot

to time, which will be done by sampling on the prototype AEH. At this point, the vehicle position can be calculated, and therefore adjustments to γ and v can be made to navigate the robot.

2.5 Navigation Control Strategy

The Ackermann steering model is non-holonomic [12], and therefore a direct relationship between the variables of $\{\mathbf{V}\}$ cannot be found. Thus, the methods for navigation are closed-loop control, and Kalman Filtering (state estimation). [12] provides a Matlab controller model for moving an Ackermann vehicle to a point, along a path and to a pose. At least the first of these models is required, but more ideally is moving the vehicle to a pose (the reasoning for which is discussed in Section 4.4), that is (x^*, y^*, θ^*) and is shown in Fig. 2.5.

The kinematic model to this point is the following, where γ has been replaced with

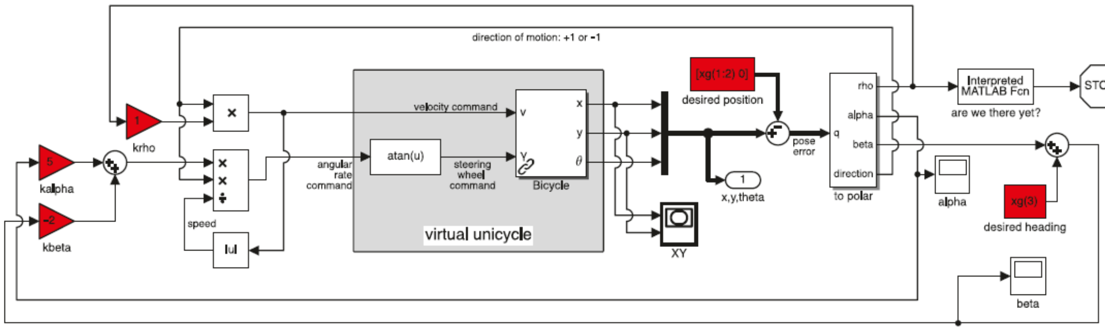


Figure 2.5: Corke's "Move to Pose" Model [12]

ω, the turning rate:

$$\gamma = \arctan\left(\frac{\omega L}{v} den\right)$$

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \cos(\theta) & 0 \\ \sin(\theta) & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} v \\ \omega \end{pmatrix}$$

Rewriting in polar coordinates as in [12] gives the following for the distance to the goal, see Fig. 2.6.

$$\rho = \sqrt{(G_x - V_x)^2 + (G_y - V_y)^2}$$

$$\alpha = \arctan\left(\frac{G_y - V_y}{G_x - V_x}\right) - \theta$$

$$\beta = -\theta - \alpha$$

$$\begin{pmatrix} \dot{\rho} \\ \dot{\alpha} \\ \dot{\beta} \end{pmatrix} = \begin{pmatrix} -\cos(\alpha) & 0 \\ \frac{\sin(\alpha)}{\rho} & -1 \\ -\frac{\sin(\alpha)}{\rho} & 0 \end{pmatrix} \begin{pmatrix} v \\ \omega \end{pmatrix}$$

The assumption for the AEH is that the goal frame, $\{\mathbf{G}\}$, will always be in front of the vehicle; that is:

$$\alpha \in \left(-\frac{\pi}{2}, \quad \frac{pi}{2} \right]$$

From [12], the linear control law can be applied in the below equations, where:

- $k_\rho \rho$ and $k_\alpha \alpha$ drive the robot linearly toward $\{\mathbf{G}\}$; and
- $k_\beta \beta$ rotates the aforementioned line such that $\beta \to 0$.

$$\begin{pmatrix} \dot{\rho} \\ \dot{\alpha} \\ \dot{\beta} \end{pmatrix} = \begin{pmatrix} -k_\rho \cos(\alpha) \\ k_\rho \sin(\alpha) - k_\alpha \alpha - k_\beta \beta \\ -k_\rho \sin(\alpha) \end{pmatrix}$$

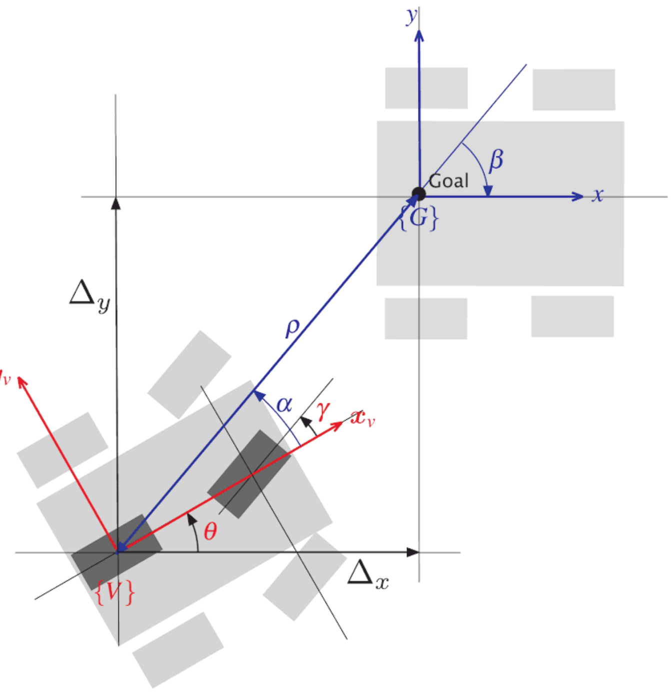


Figure 2.6: Coil Positioning Kinematics

This is the controller which is implemented in Fig. 2.5, and is one candidate for navigating the AEH on the WPTS. Alternatively, Kalman filtering has proven to be a useful tool in autonomous vehicle navigation.

2.5.1 Kalman Filtering

Kalman filters are often used in control and localisation of autonomous vehicles, such as UAVs [30] and cars [32], so clearly have uses in the AEH navigation. ROS provides an extended Kalman Filter tool, whereby sensors can be registered and filtering is applied automatically [31]. While this is useful for determining vehicle odometry, a customised Kalman filter would be required to fuse sensor bar location data as the library is limited to position and orientation and their derivatives [31]. The Kalman Filtering done in [32] could be adapted for the AEH, as lane keep assist is not dissimilar to navigating along a cable.

2.6 Feedback Controller Theory

Several types of controllers are likely to be used on the AEH, each with their own advantages and disadvantages. The responses of some combinations of these are shown in Fig. 2.7, and in general, the key advantages of these controllers are [33]:

- PID
  - Fastest rise time;

  - No oscillations;
  - No steady state error.

- PD
  - No overshoot;
  - D component decreases settling time;
  - Increased rise time compared to P-only.

And some disadvantages are:

- PID
  - Overshoot of setpoint;
  - Can become unstable.

- PD
  - Amplification of process noise;
  - No effect on steady state error.

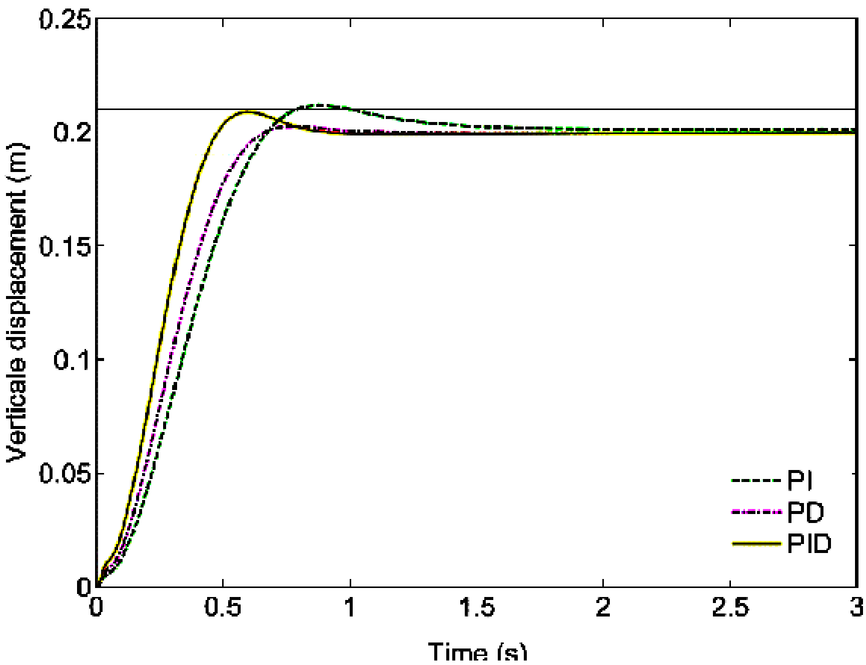


Figure 2.7: Controller Responses — from [13]

These differences are important for the different systems within the AEH, as some aspects of the hauler will be sensitive particularly to overshoot.

3. Literature Review

This chapter discusses any relevant prior work to components of the on-wire navigation system. Due to the constraints on the system as outlined in Section 1.3.2, traditional line following techniques such as optical and PMF sensing are not applicable. Therefore, active magnetic sensing is the main method considered. The prior art will discuss any relevant research on any aspect of the sense, locate and actuate cycle.

3.1 Radar Metal Sensing

In civil applications, before digging occurs, surveyors use several methods to locate and trace burried utilities such as pipes and power cables, including ground penetrating radar (GPR). This technology is based on the target object having different permittivity to its surroundings, which reflect transmitted microwaves back to the receiver for signal processing [34]. This is a valid option for the on-wire navigation system, though commercial GPR systems tend to be expensive and require carefully trained operators. Therefore for the scope of this project, GPR is not viable, but for future work it may prove useful. Instead, focus will be placed on less expensive methods of metal detection.

3.2 Active Magnetic Sensing

Metal detectors which actively sense the metal in the target already exist, and are discussed in the following subsections. The on-wire navigation problem is not dissimilar to electromagnetic landmine detection as the targets cannot be seen, powered or contacted [35]. Electromagnetic landmine sensors such as that in [36] widely employ the use of pulse-induction (PI) metal detectors.

3.2.1 Pulse Induction Metal Detectors

An example of an active duty PI metal detector is the HSTAMIDS is a U.S. Military multi-sensor landmine detector [36] which uses sensor fusion of GPR, PI metal detector and infrared (IR) data. Sensor fusion is left as a discussion in a later section, but the use of PI metal detectors in applications such as landmine detection and prospecting indicates they are a viable candidate for the AEH's sensor system. The operation of a PI metal detector is as follows [37]:

1. Slowly ramp up coil current.

2. Turn off current very rapidly, creating a large back emf.

3. Wait for a short time (μseconds) to exclude the "switch off transient".

4. Examine the voltage in the coil.

The expected time domain response of a PI metal detector is shown in Fig. 3.1. PI

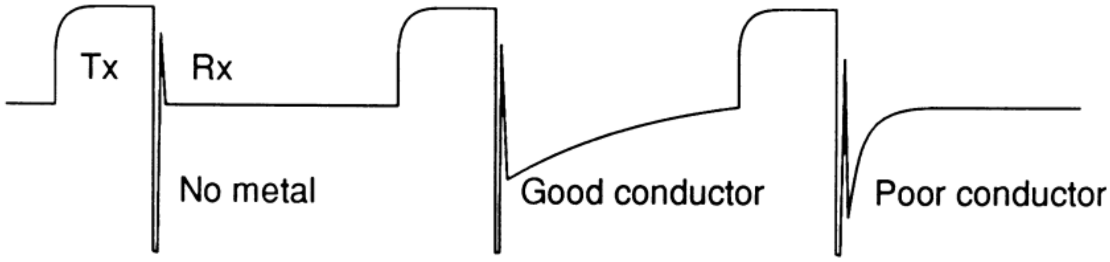


Figure 3.1: PI Metal Detector Time Domain Operation — from [14]

metal detectors are an example of single coil, DSP-based metal detectors. The use of this technology in the AEH project is only limited by the complexity of building the unit, requiring advanced DSP hardware and powerful analog circuitry to drive the coils [37]. Open-source or evaluation units are not common, and most examples of prior art are used in very specific circumstances. However, conventional metal detectors such as that which is described in Section 2.2 use two coils, and are in general significantly simpler in operation.

3.2.2 Two-Coil Metal Detector

The metal detector described in Section 2.2 utilises two coils in a transmitter/receiver configuration. This type of technology is packaged into simple inductive proximity sensors [50] which are found on various automation equipment. They tend to be close range detection only [28], but they do adhere to the AEH design requirements. The main drawback of these proximity sensors is that they are often digital output, and mostly come pre-packaged in sealed cases. Very-low frequency (VLF) metal detectors also rely on two coils, and operate with the same principle, using larger coils. Commercial examples of VLF metal detectors are readily found, and will be investigated for use on the AEH.

3.2.3 Inductive-to-Digital Converters

Another way of sensing the presence of metal is by measuring f_0 of a test coil in an LC tank. There are several ICs which exploit this, including:

- Texas Instruments' LDC family [29];
- IDT's ZMID520x family [38]; and
- Microsemi's LX330 family [39].

A comparison of these units and others follows in Section 4, but the focus will be on the LDC, as it is the most general use of the aforementioned sensors. A coil and capacitor forming an LC tank are driven by the IC, which can be programmed with values to drive at the resonant frequency, or can automatically detect it [29]. When conductive objects come into proximity of the coil, the inductance decreases due to some of the flux leaking into the metal, and the chip can detect the change in f_0 with up to 28-bits of resolution. The LDC especially seems to be a valid candidate for the on-wire navigation sensor which will ultimately make up one part of the on-wire navigation sensor array .

3.3 Electromagnetic Sensor Arrays

Vehicle based metal detector arrays that are employed for scanning broad areas are not uncommon, and there are several European manufacturers which produce such devices [14]. This section will discuss the use of an electromagnetic sensor array on the AEH. According to [14], "development of arrays (for vehicles) is rather recent," so the AEH will not have specific prior art from which to base the design.

3.3.1 Operation

A method described in [40] of multiple buried metallic object detection using a PI electromagnetic sensor coil array of 5×5 square receiver and transmitter coils 25cm, and 35cm respectively. [40] also states the sensor array can be run in either of the following modes, which when generalised to an $N \times M$ array given the following number of data points:

- Monostatic
  - All sensors transmit and receive simultaneously.
  - $N \times M$ data points.
- Bistatic
  - Sensors transmit sequentially, but all coils receive.
  - $(N \times M)^2$ data points.

The monostatic and bistatic modes of operation are of particular interest to the AEH project for the drastic increase in data points and therefore information on the cable's location. This technique could be applied to any sensor array, including one inductive based sensors.

3.3.2 Data Processing

In [15] and [16], a coil setup of three receiver coils is used as shown in Fig. 3.2.

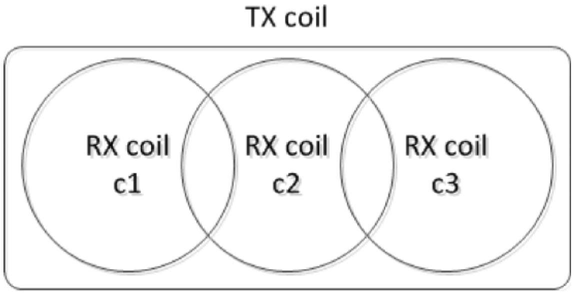


Figure 3.2: Sensor Array Used in [15],[16]

This array puts the frequency response of the measurement through the model in [41] to calculate the electromagnetic response of a target, including its rotation and location (given magnetisation polarisability). The main advantage of this method for the AEH project, according to [15] are that sensor inaccuracy can be overcome. In [42], [15], [43] and [16], "target model dictionaries" to match the EM response data are utilised. This technique can significantly increase the error if the target is a poor match, but as the general shape of the WPTS will be known, it is unlikely that this issue will arise.

3.3.3 Mounting

In the case of vehicle mounted metal detectors, front mounted arrays seem to be the most common, as supported by [14], [40] and [27]. It is also suggested in [14] that mounting the array on a suspension system can keep the coils oriented parallel with the ground and at a constant height, which is beneficial for repeatable detection of burried metal object, however may not be necessary for the AEH.

3.4 Navigation

Vehicle autonomous navigation is a relatively emerging field, and the back-end processing of these systems is relevant to the on-wire navigation project [32]. The system from [32] also uses the sense, locate and actuate methodology, but also puts an emphasis on tracking the vehicle on the road.

3.5 Sensor Fusion

"No single sensing technology is adequate for the detection of [land]mines" [36]. This is the philosophy of the HSTAMIDS — a U.S. Military multi-sensor landmine detector which fuses GPR, PI electromagnetic and IR sensors [36]. The main downside of sensor fusion in the case of the on-wire navigation system is that the sensors are effectively measuring identical parameters, which may cause issues with interference, or could add complexity for no real gain in resolution and accuracy of the measurements. Nevertheless, sensor fusion is considered as an optimisation goal.

4. Project Methodology

The on-wire navigation project is comprised of a sense, locate and actuate cycle. To meet the requirement of a working prototype the first goal was to enable the autonomous operation of the vehicle. This would lead into the design, building and testing of the on-wire navigation system.

4.1 AEH Platform Build

The AEH platform vehicle is an Ackermann steering robot, and thus the velocity, v and steering angle γ are the top level control inputs; Fig. 4.1 details how these inputs were processed and ultimately transformed into movement. To enable practical operation of the vehicle, power distribution, battery protection systems, and the ROS drivers were also required.

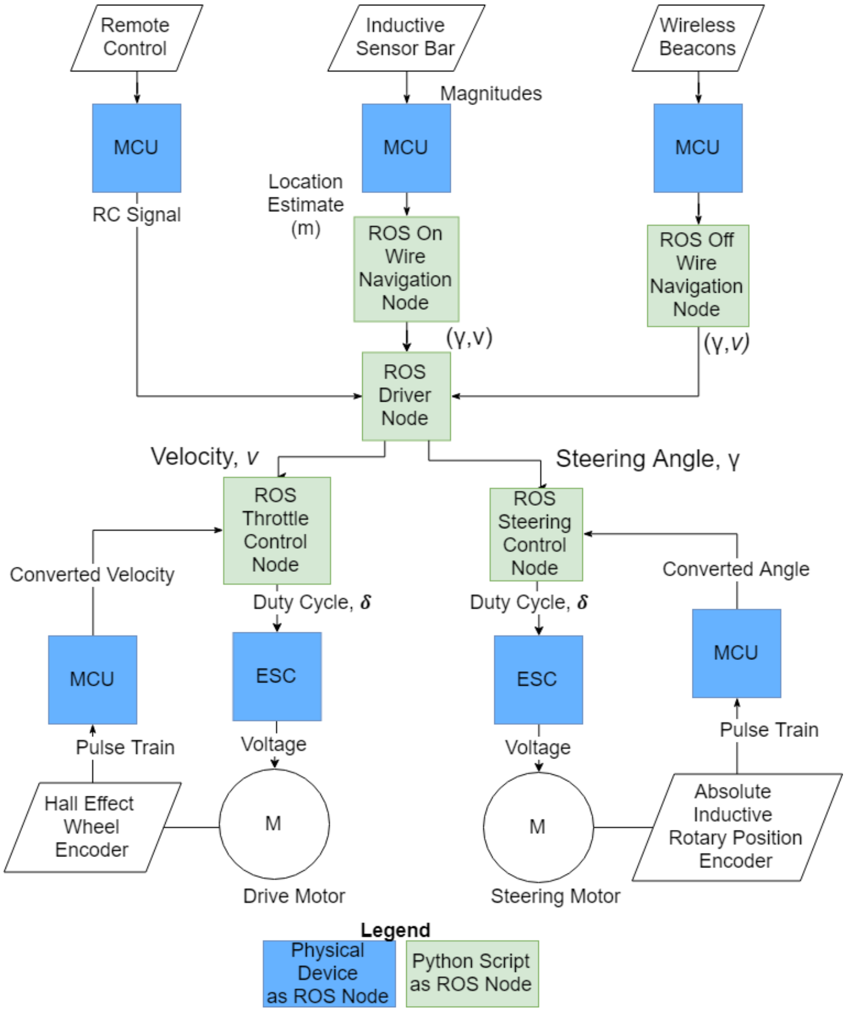


Figure 4.1: AEH Overall System and Signal Flow

The chassis, suspension and final drive of the AEH was adapted from a mobility scooter, as this vehicle allows for an appropriate scale whilst remaining within safe working limits for student projects, such as extra-low voltage [44].

4.1.1 Power Distribution and Battery Protection

Power management of the AEH is paramount to its operation, as lithium polymer (LiPo) batteries are being used. Thus, a safety system to be built into the AEH's power distribution network was proposed; the schematics for which are shown in Figures 4.2 and 4.3. Highlights of these designs are:

- Three stage redundant battery short protection:
  - HRC Fuse to stop LiPo arcing through fuse (Fig. 4.2);
  - Circuit Breaker (Fig. 4.2); and
  - Individual device fuses (Fig. 4.3).
- Hardware E-stop using solid state relay; and
- Use of non-reversible, anti-spark connectors.

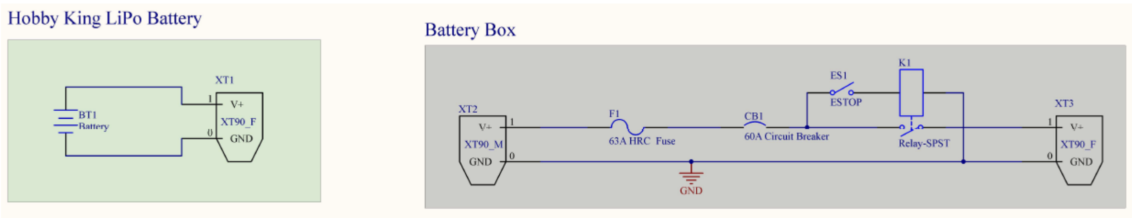


Figure 4.2: Battery Compartment Schematic

Fig. 4.3 also shows the rough power and signal flow of the main control box, which houses the motor and tipper drivers.

4.1.2 ROS Driver

The AEH is ultimately run by ROS middleware, parsing messages between microcontrollers and Python scripts which are run from a host PC. Arduinos were selected due to their ease of use, especially due to the `rosserial_arduino` ROS package, which is supported for all Arduino variants [45]. Each microcontroller is a ROS node as per Fig. 4.1, and the three main python nodes responsible for the vehicle platform are:

- `steering_control.py`
  - Control the steering angle to the setpoint;

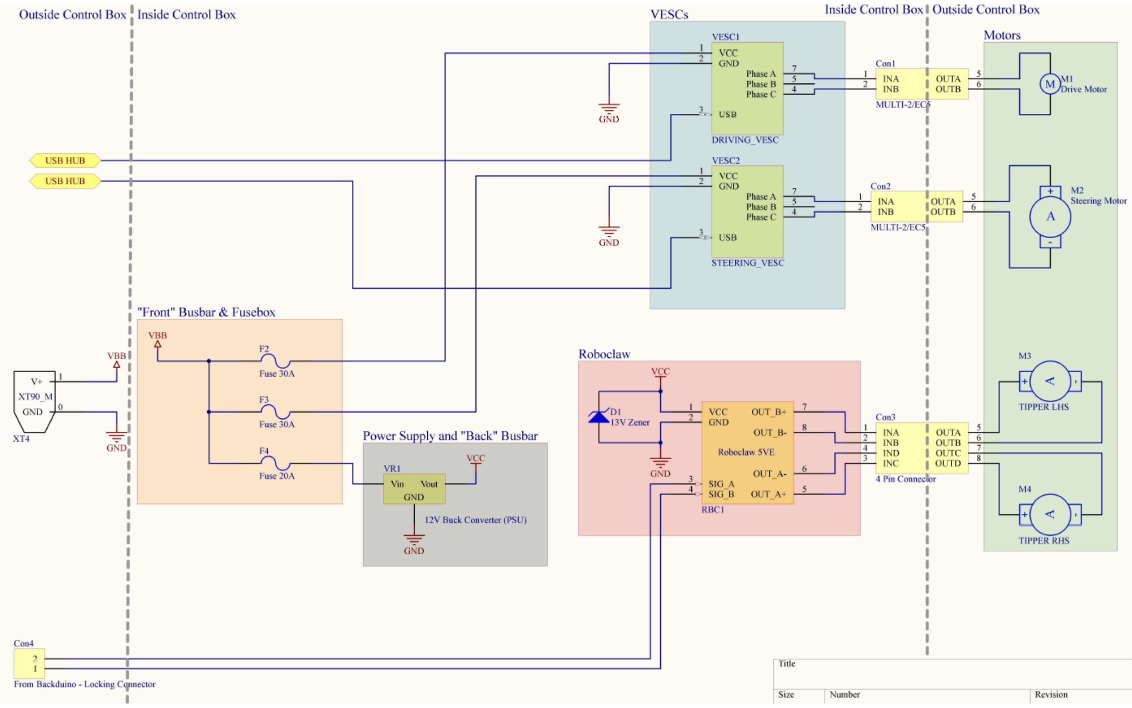


Figure 4.3: Main Compartment Schematic

- Manage soft and hard steering limits; and
- Convert raw steering angle senso datar.

- `throttle_control.py`
  - Control the AEH speed to the desired setpoint; and
  - Convert wheel encoder data to velocity.

- `driver.py`
  - Allow modular connection of ROS Nodes;
  - Management of safety lockouts and soft E-stops; and
  - Serve as control-state FSM.

The "control-state" FSM determines which γ and v are used, as shown in Fig. 4.4. The "on wire" input is a flag described in Section 4.3. The switch values comes from the RC controller, which was used to enable and disable autonomous operation. Following from the control FSM, the driveline components (steering and drive motors) were also adopted for autonomous control.

4.1.3 Steering and Throttle System

The steering and throttle system are implemented by PID controllers in ROS, which use the Python `simple-pid` library [46]. Vedder ESCs [47] (VESC) were selected as

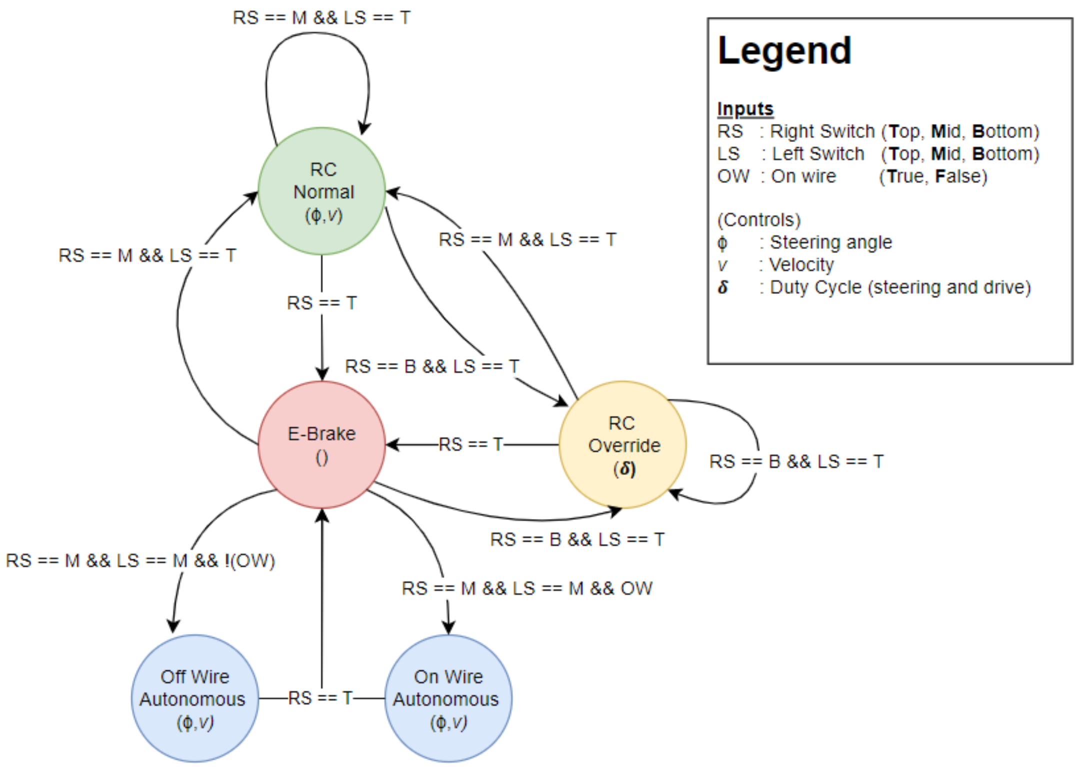


Figure 4.4: ROS Control-State Finite State Machine

the motor drivers due to:

- Pre-existing ROS driver code[48];
- Ability to work with a variety of motor types;
- Motor configuration PC tool (VESCTool) is written for Linux; and
- Portfolio of successful projects of similar scale to the AEH [47].

With the steering, drive motor, basic ROS integration and power system completed, work on the navigation began.

4.2 Sensing Methodology

The sensing target was one of the first desicions to be made regarding the on-wire navigation system. Many variations of cable were tested for their response, keeping in mind Eq. (2.3). Ultimately, a steel armoured section of conduit was selected, which is dimensionally close to that of a 3-core + Earth 1kV cable [49], which could run the WPTS. Next, the final options for electromagnetic sensors, as well as their respective advantages and disadvantages are discussed, and are shown in Table 4.2. This list was narrowed down from all the possible researched options, and the criteria for selection are presented after the table.

Table 4.1: Inductive Sensor Comparison

Sensor	**Advantages**	**Disadvantages**
Inductance to Digital Converter (LDC)[29]	Evaluation board option, reducing prototyping time.	Limited coil current driving capability: 1.5mA max. [29]
	Minimal constraints on coil geometry.	Susceptible to stray capacitances.
	28-bit frequency measuring resolution.	
	4-channel capability from single IC.	
Industrial Inductive Pickup [50]	Robust casing, ease of mounting unit.	Digital output.
	Well documented notes on EMI reduction mounting techniques.	Cannot adjust parameters such as coil drive current.
	Self correcting for environmental factors (up to 10%). [50]	Commercial product — protected IP and unit is fully sealed.
PI Metal Detector [37]	Well established technology in landmine detection field.	Limited open-source design availability.
	Multiple detection techniques possible.	Possibility of extended troubleshooting/prototyping phase.
	Full control over all parameters.	
ZMID Linear Inductive Position Sensor [38]	Output of sensor is location of metal target.	Complex and restricted coil design.
	Coil geometry must adhere to strict geometric properties.	Possibility of extended troubleshooting/prototyping phase.
		Very limited range (approx. 1mm on evaluation board).

When considering the options for the optimal sensor, the goal of the on-wire navigation system must be key: *detect the cable wirelessly, considering mine conditions, and follow it*. Therefore, range of sensing and resolution are prioritised in that order, with additional accolades given for customisation ability of the sensor. Furthermore, since the on-wire navigation project comprises multiple aspects, options which offer ease of use were favoured. Therefore, in consideration of the available options in Table 4.2, the inductance to digital converter (LDC) appeared to be best suited in all criteria, and was selected as the focus point for the sensing hardware. The LDC coils were eventually formed into a “sensor bar” which was mounted to the front of the vehicle.

The coils for the LDC were designed with Eq. (2.3) in mind; specifically that the coils should aim to sense roughly their diameter in axial distance [14]. Also, according to Eq. (2.3), the maximum possible current should also be driven in the coil, which is a technical limitation with the LDC1614, which can only drive maximum $1.5mA$ [29]. It was decided to test some coils of varying diameter, and $\O 70mm$ appeared to be sufficiently large to detect the cable at a reasonable distance. Coils had 25 turns, though due to shortages in litz wire used in the construction (to minimise skin effect), some of the coils had as much as five fewer turns. This resulted in coil inductances varying from $50\mu H$ to $85\mu H$. The impacts of this are discussed in following sections.

The mounting height of the sensor bar was determined experimentally by using an early version of the locating code to test at various heights of the bar. The geometry of the WPTS meant the cable should be followed not directly under the AEH, but rather slightly offset to one side; this can be seen as the straight section in Fig. 4.7. Eight total coils were positioned such that sensitive area was between $0.08m$ and $0.295m$ from either side of the centre of the AEH. The most sensitive coils were placed at the navigation setpoint of $0.15m$ to the right of the centre of the vehicle.

4.3 Detection and Localisation Methodology

The LDC modules calculate the oscillation frequency of the coils, which are returned as 28-bit values [29] of scaled frequency. From this, the signal characteristic of interest was the noise-laden low frequency component. Initial testing of the LDC determined that the response from a metal target only increased by up to 0.2%. This lead to the pre-processing of the data (Fig. 4.5) before detection and localisation algorithms were applied.

The LDCs are initially calibrated to the environment, which is performed by storing measurements with no metal present. This calibration and subsequent pre-processing allowed all coils to be analysed at a similar numerical scale — serving to aid in the rapid development of the system at the expense of computationally

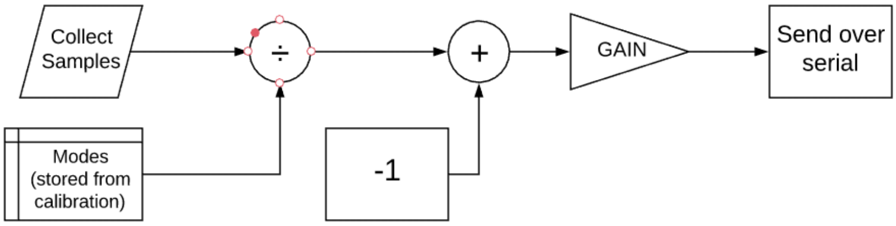


Figure 4.5: Preprocessing of Raw Data on Microcontroller

inefficient code. The response from the coils increased in magnitude when metal was present; therefore the higher the response magnitude of a coil, the more likely the cable in underneath that coil.

At each timestep, the response from each coil, was further processed to determine the location. Before this could occur, each channel of the LDC was added to a low pass filter with a cutoff of 2Hz (determined from analysis of FFT data of the signals) before continuing to estimate the location. To automate this process, the algorithm depicted in Fig. 4.6 was eventually refined using experimental results. To test the algorithms, the AEH was manually driven along the test track in Fig. 4.7, with the desired outcome of recreating the track's geometry shown in Fig. 4.8 from the collected sensor bar data.

There were also edge cases which were caught by the location algorithm, for example if the cable was detected to be heading out of the sensing range (i.e. past $\pm 0.295m$). The various additions to the location algorithm, as well as the tuning of the filter cutoffs and other processing were also determined with the same test track experiment.

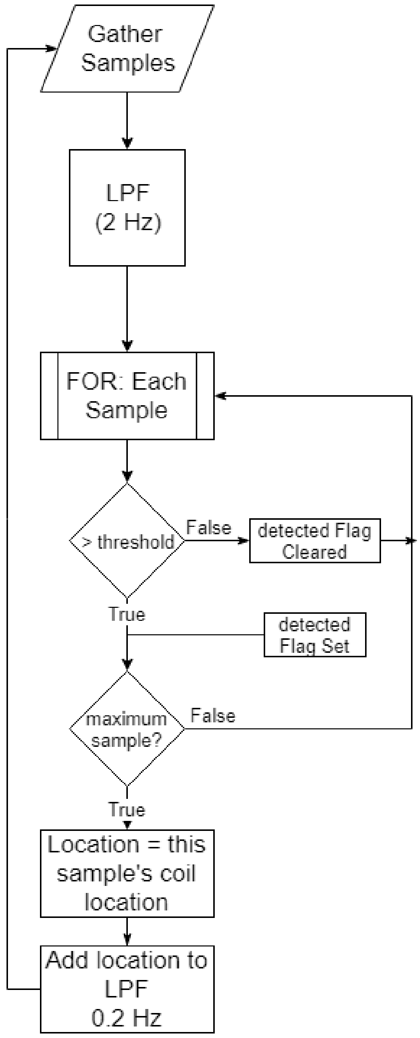


Figure 4.6: Basic Location Detection Algorithm

When detection and location algorithm was verified, work then began on the navigation system.

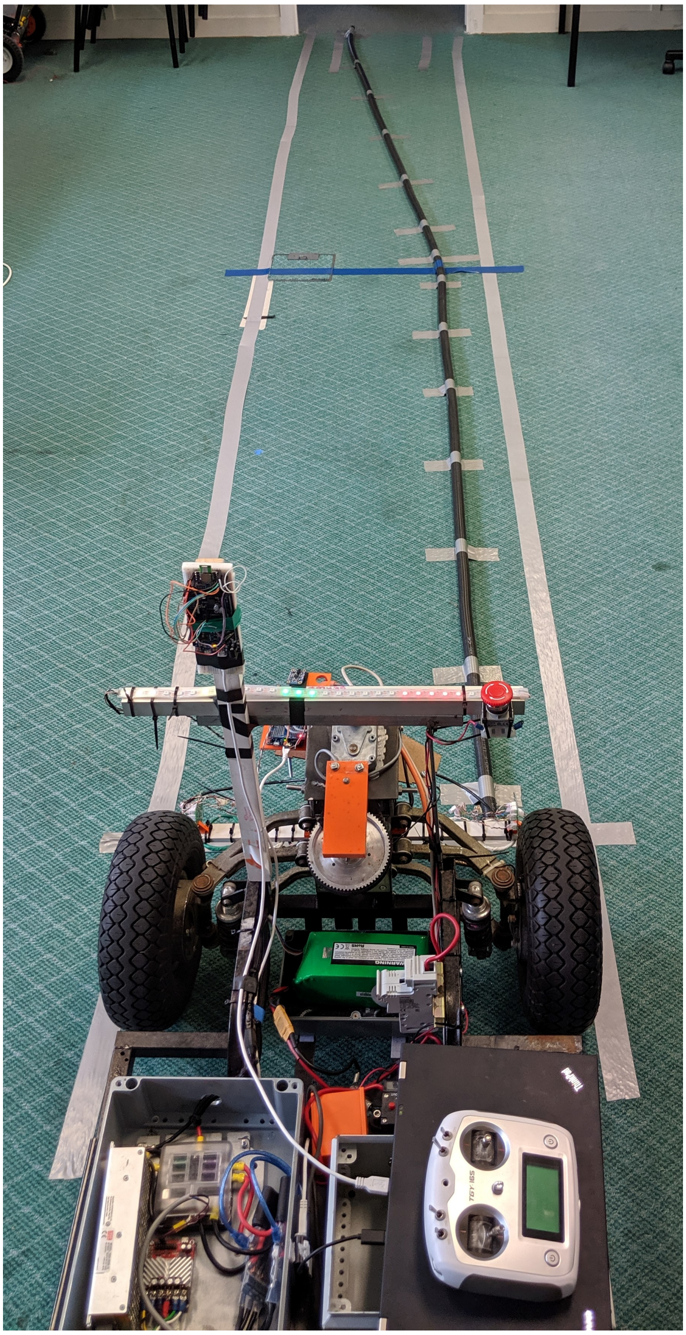


Figure 4.7: Test Track

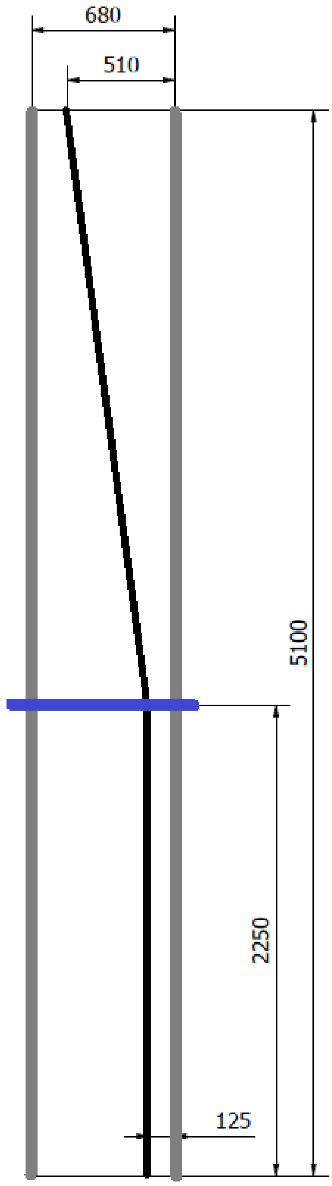


Figure 4.8: Test Track Geometry

4.4 Navigation Methodology

The goal of the navigation system is sense the cable and subsequently position the AEH in such a way that the coils of the WPTS are above each other with minimal offset. The cable is sensed at the front of the AEH, whereas the secondary coil is underneath the body. Therefore, the kinematics described in Section 2.4 are not specific enough, and were adapted to include the coil point $\{\mathbf{C}\}$ and sensing point $\{\mathbf{S}\}$ relative to the simple kinematic output $\{\mathbf{V}\}$ in Fig. 4.9.

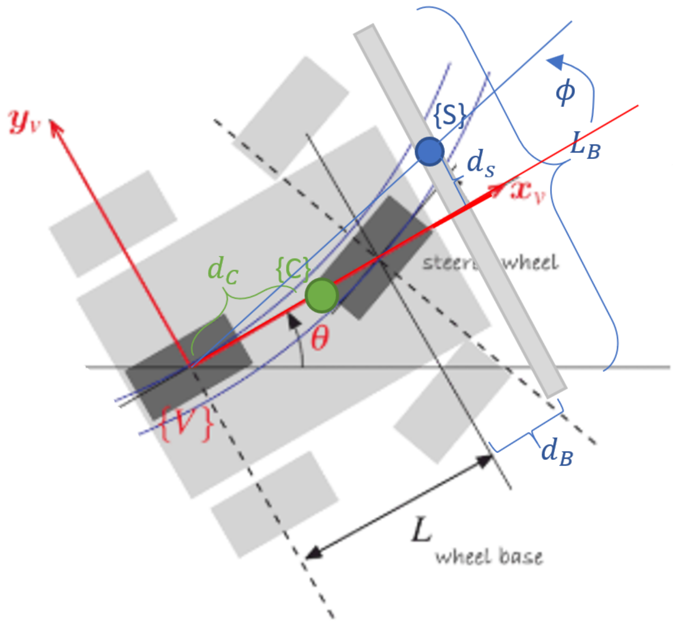


Figure 4.9: Coil Positioning Kinematics

First, the coil coordinates[1]:

$$\{\mathbf{C}\} = \begin{pmatrix} x_c \\ y_c \end{pmatrix} = \begin{pmatrix} x + ||\mathbf{VC}|| \cos(\theta) \\ y + ||\mathbf{VC}|| \sin(\theta) \end{pmatrix} \tag{4.1}$$

And the position of the sensor location coordinate:

$$||\mathbf{VS}|| = \sqrt{(L + d_B)^2 + (d_S)^2} \text{ and } \phi = \arctan\left(\frac{d_s}{L + d_B}\right) \text{ so}$$

$$\{\mathbf{S}\} = \begin{pmatrix} x_S \\ y_S \end{pmatrix} = \begin{pmatrix} x + ||\mathbf{VS}|| \cos(\theta + \phi) \\ y + ||\mathbf{VS}|| \sin(\theta + \phi) \end{pmatrix} \tag{4.2}$$

The above equations position critical features of the AEH relative to the kinematic output, $\{\mathbf{V}\}$. Each sample, the new goal pose from Fig. 2.6 was calculated using Eq. (4.2) and Eq. (4.1) so that $\{\mathbf{G}\}$ will put $\{\mathbf{C}\}$ in the most ideal spot.

$$\{\mathbf{G}\} = \begin{pmatrix} x^* \\ y^* \\ \theta^* \end{pmatrix}$$

The information for the desired heading, θ^* comes from the distance between sensed locations at each timestep. As shown in Fig. 4.10, with θ the current heading.

$$\theta^* = \theta + \arctan\left(\frac{d_S - d_{SG}}{v \times (t_2 - t_1)}\right)$$

This information was used in conjuction with a PD controller and the sensed location

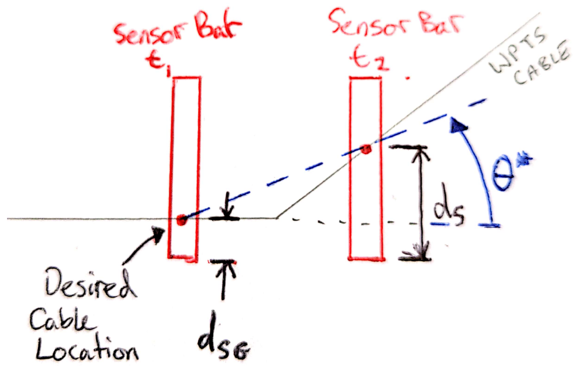


Figure 4.10: Determination of Navigation Heading

data keep the vehicle on the cable. PD feedback control was selected mainly for the lack of overshoot caused by the integral component, or lack thereof. Overshoot of the navigation controller could cause the sensor bar, with its limited sensing elements to momentarily overshoot the cable and thus lose track of it. To test this, a second test track, shown in Fig. 4.11 was constructed. This track would also serve to test the effectiveness of the system in its entirety. In addition, the ROS `robot_localization`

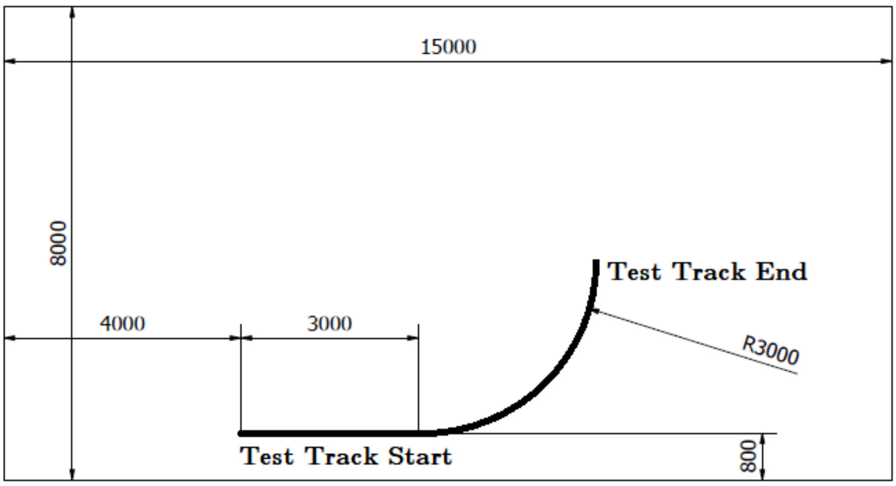


Figure 4.11: Navigation Test Track

package was used to implement an extended Kalman Filter for the AEH. Sensor fusion of the on-board IMU and self-telemetry data, as well as external beacons from the off-wire navigation project provide an accurate map of the location of the AEH, which will be used to numerically analyse the functionality of the on-wire navigation system.

5. Results

This chapter discusses the results of the AEH project, from the platform vehicle characteristics through to the performance of the on-wire navigation system in guiding the AEH on a piece of test track.

5.1 AEH Platform

An overview of the AEH's subsystems is shown in Fig. 5.1, including the completed on-wire navigation sensor bar. The capabilities of this vehicle were deemed sufficient for further testing of the on-wire navigation system and other technologies. The on and off wire navigation hardware are able to be physically removed from the vehicle, as well as disconnected from ROS with no human intervention all while the vehicle remains otherwise functional.

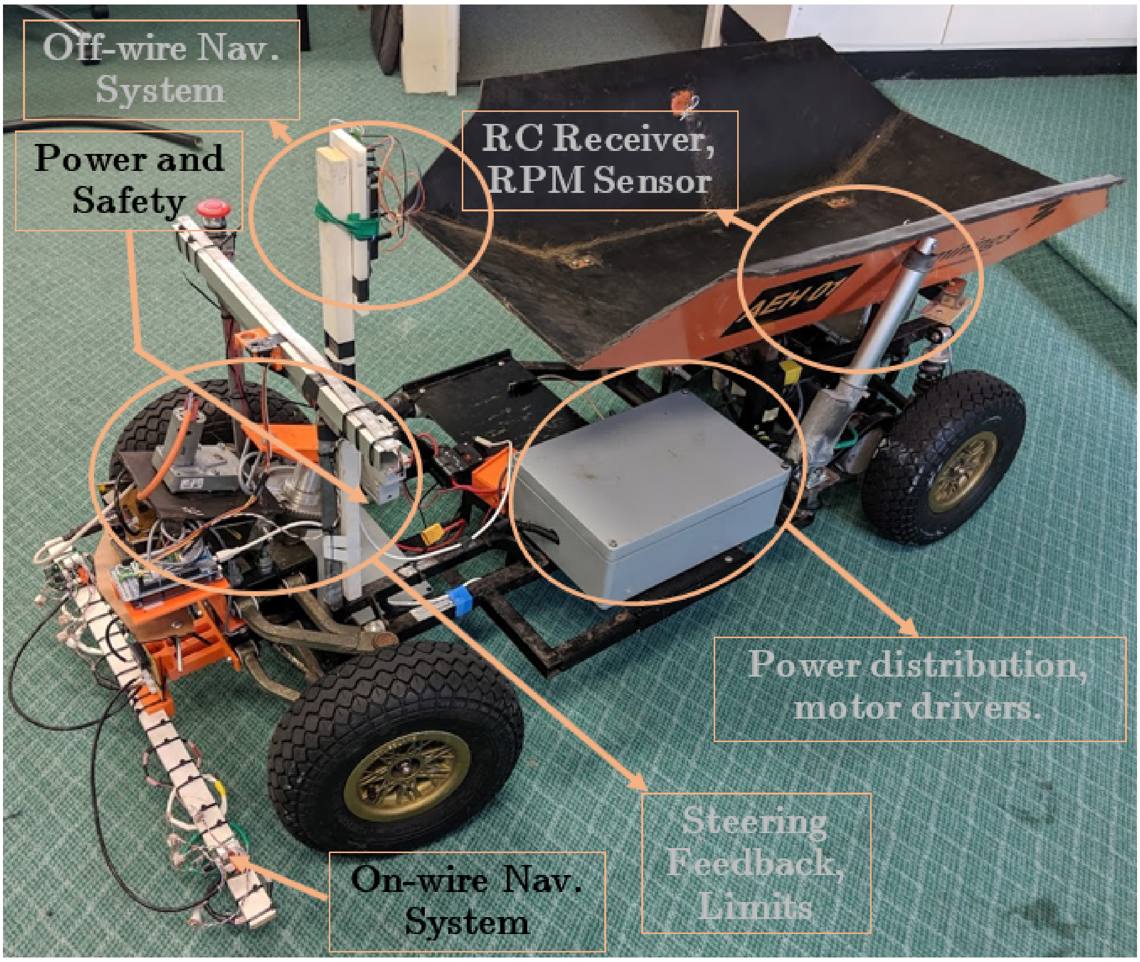


Figure 5.1: AEH Subsystem Summary

5.2 Driveline

The driveline of the AEH is comprised of the steering and motor components, the power distribution network and battery safety system. Components were installed as per Section 4, and the AEH platform are shown in Figures 5.2 and 5.3.

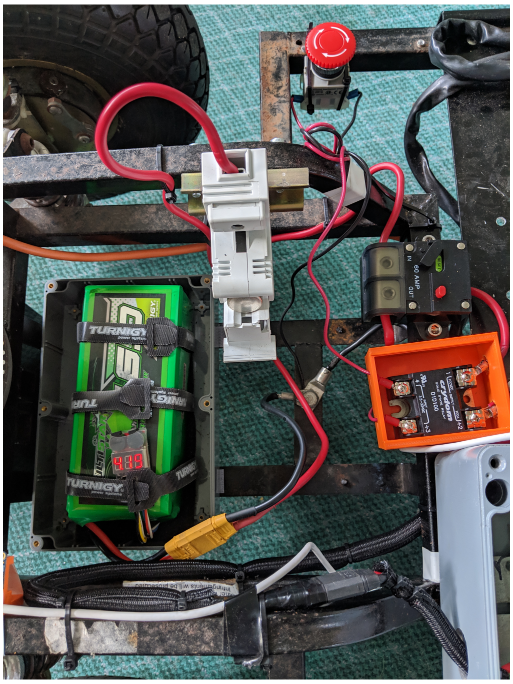


Figure 5.2: AEH Power and Safety

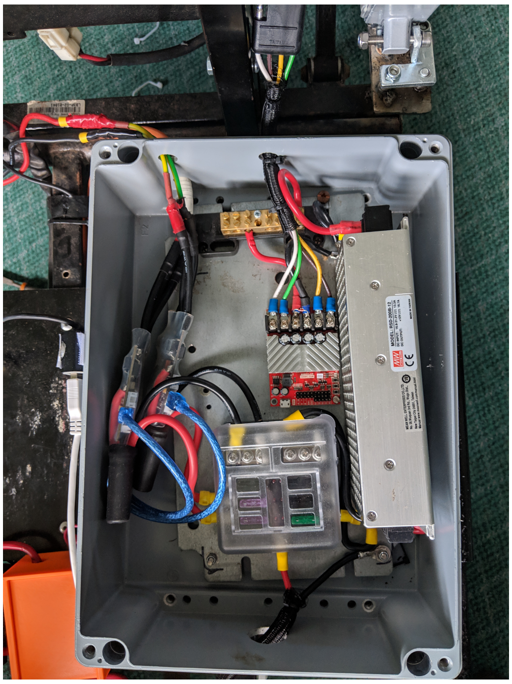


Figure 5.3: AEH Motor Drivers and Power Distribution

The steering and drive motor profiles have been tuned, then were integrated with ROS such that a remote control is able to control the AEH completely. The steering motor has a custom PID controller, tuned manually, which gives the response shown in Fig. 5.4. There is approximately a 0.25s phase delay between the desired actuation

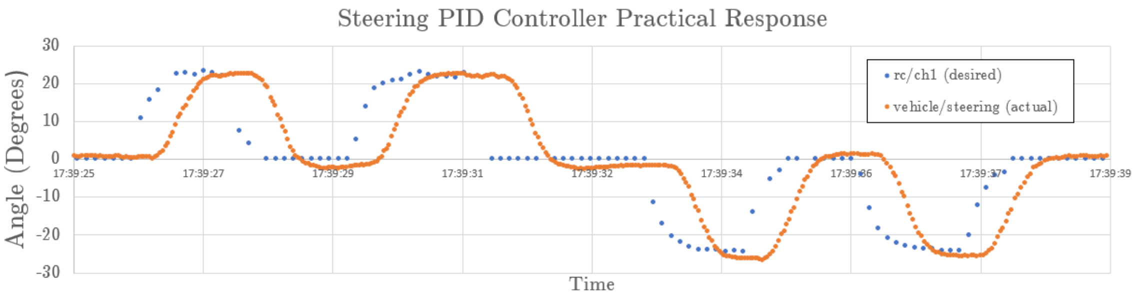


Figure 5.4: Steering Controller Step Response

(blue) and the reported steering angle (orange). This is considered acceptable for a "step" response, especially when no oscillation nor overshoot are present in the response. It can also be seen that the gradients of the desired and actual responses are similar, implying that computation delay within ROS is to blame for the phase delay.

The throttle controller was written in a similar way, and Fig. 5.5 shows the controller attempting to maintain the velocity setpoint along a piece of test track. While there

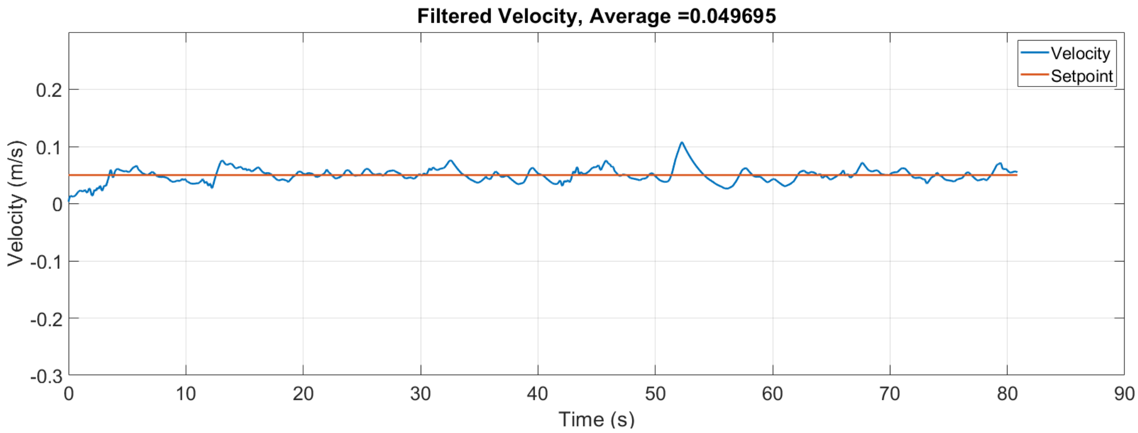


Figure 5.5: Throttle Controller Test — Setpoint $0.05m.s^{-1}$

is some variance from the setpoint, at this scale it is acceptable. The response in Fig. 5.5 validates that the throttle controller is functioning correctly, and with both system inputs γ and v now verified as working, the sensing system could now be implemented on the AEH.

5.3 Sensing Outcomes

The LDC1614 evaluation board has been used as a preliminary way to implement inductive metal sensing using Ø$70mm$ circular coils wound with 40 strand litz wire. A single coil placed $80mm$ above the cable gave the response shown in Fig. 5.6.

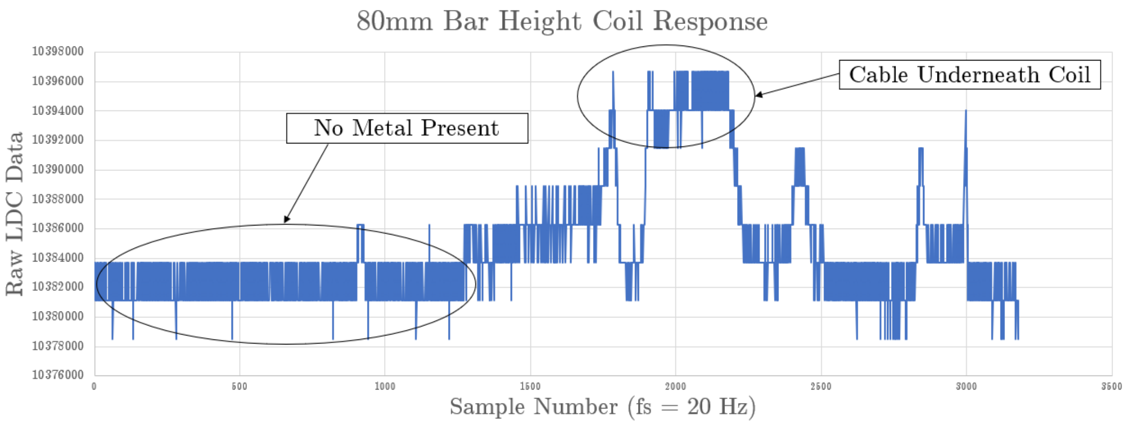


Figure 5.6: LDC Response at Operating Height ($80mm$)

From Eq. (2.3) and Eq. (2.4), $80mm$ was found to give the most reliable detection given the experimental setup. For the highest sensitivity (most turns) coils, the response was around 0.125% higher than the resting "undetected" value, however the 28 bit resolution of the LDC made this change quite apparent. Using `double` types on the microcontroller ensured that the preprocessed signals did not lose any information, and finally the 80mm bar height was deemed satisfactory for the proof of concept AEH. Next, an example response from an array of three coils is shown in Fig. 5.7, mounted at the selected 80mm height.

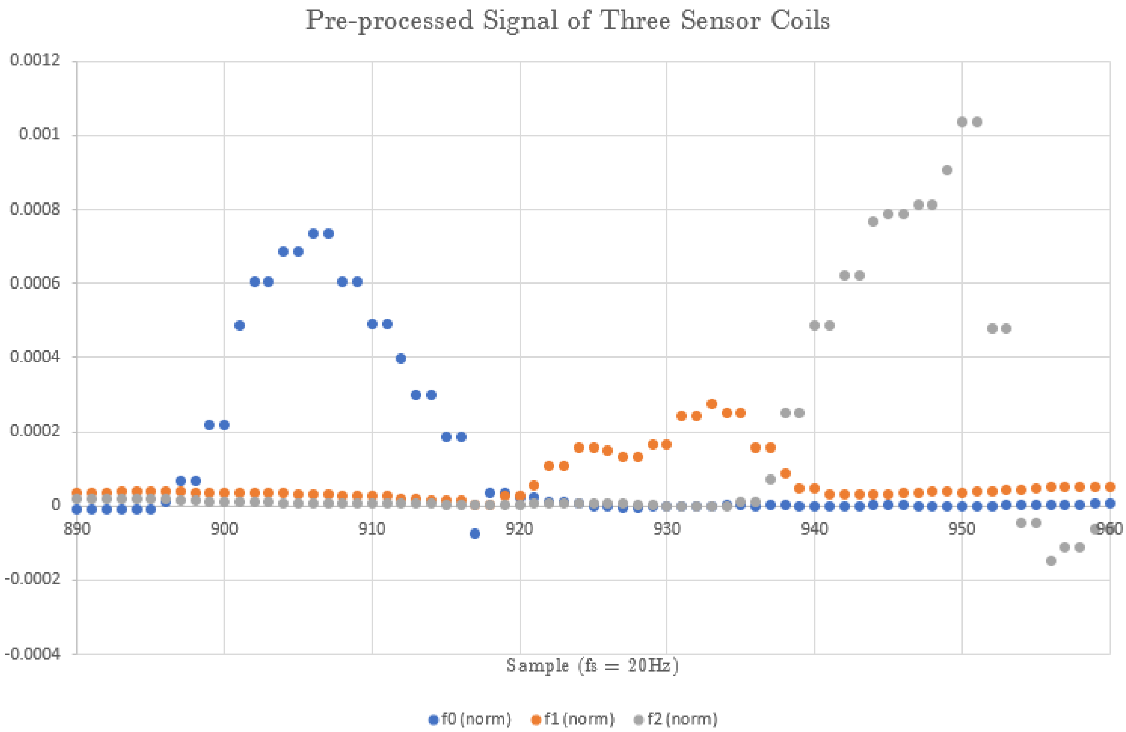


Figure 5.7: Pre-processed Sensor Bar Data

Therefore, from Fig. 5.7 the rudimentary, discrete cable locations are estimated as:

- Coil 0 — at sample no. 905;
- Coil 1 — at sample no. 935; and
- Coil 2 — at sample no. 950.

There is still the fact that the responses in Fig. 5.7 are not uniform, which is likely due to the construction of the coils not being equal, as discussed in Section 4.2. This basic response of a prototype sensor bar verified the functionality at the operating height, meaning the location algorithm could be tested.

5.4 Detection and Localisation Outcomes

The sensor bar was mounted to the AEH, and the test track from Section 4.3 was constructed. By driving the AEH manually, in a straight line along the track, it was expected that the localisation system would roughly trace the test track. The results of the are shown in Fig. 5.8, and Fig. 5.9 shows when the AEH detected the cable.

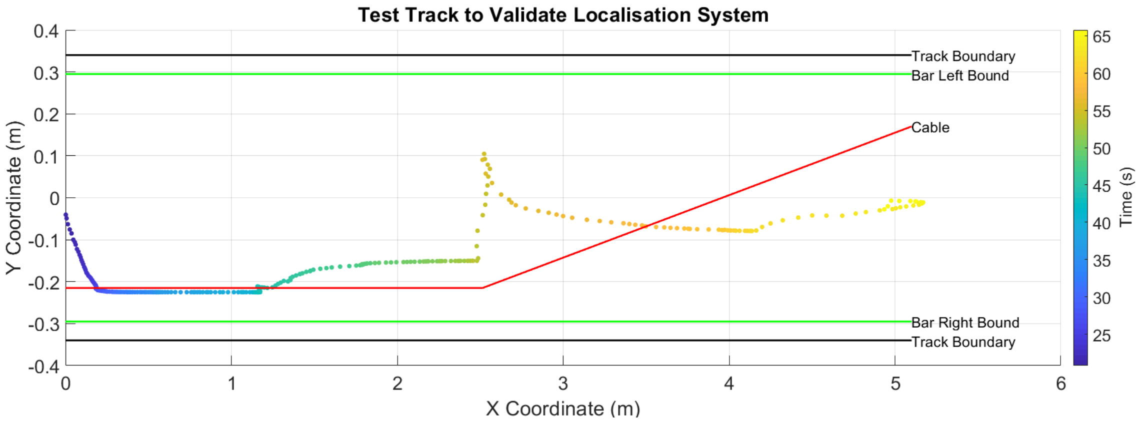


Figure 5.8: Location Algorithm Test Results

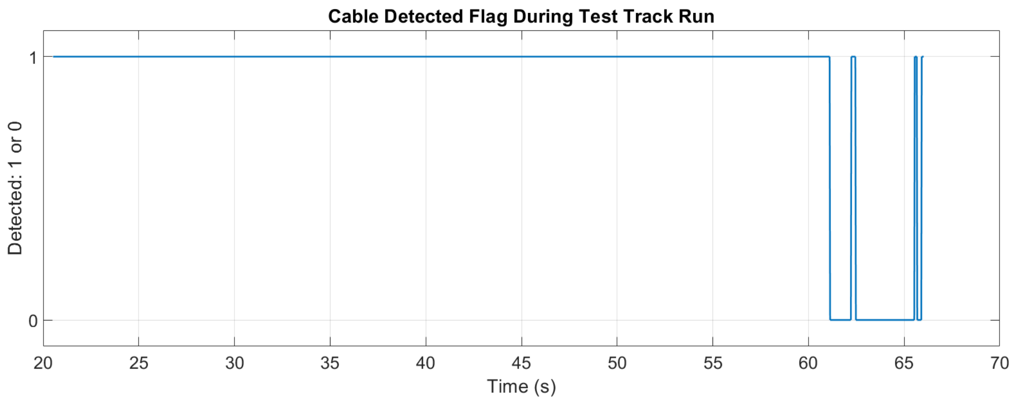


Figure 5.9: Detection Algorithm Test Results

This experiment had some flaws, namely:

- False readings from under-floor pipes;
- Reliance on the uniform, and in particular, *straight* driving of the AEH on the test track; and
- Lack of on-board odometry readings due to indoor test setup.

One effect of this flawed design was near the point $(2.5, 0.1)$ — the AEH detected an electrical outlet built into the floor[1], from which the sensor bar evidentially received a strong response which it interpreted as a cable detection. However, without applying steering corrections and ignoring the spike, the general shape of the location was close enough to the desired that it warranted testing on another test track.

[1]This can be seen in Fig. 4.7

5.5 Navigation Outcomes

The AEH on-wire navigation system functionality was tested along a test track constructed outdoors on flat terrain, consisting of a straight $3m$ section followed by a $3m$ radius left hand turn, as shown in Fig. 4.11. The location of the sensed cable, and subsequent steering input is shown in Fig. 5.10. The location setpoint is

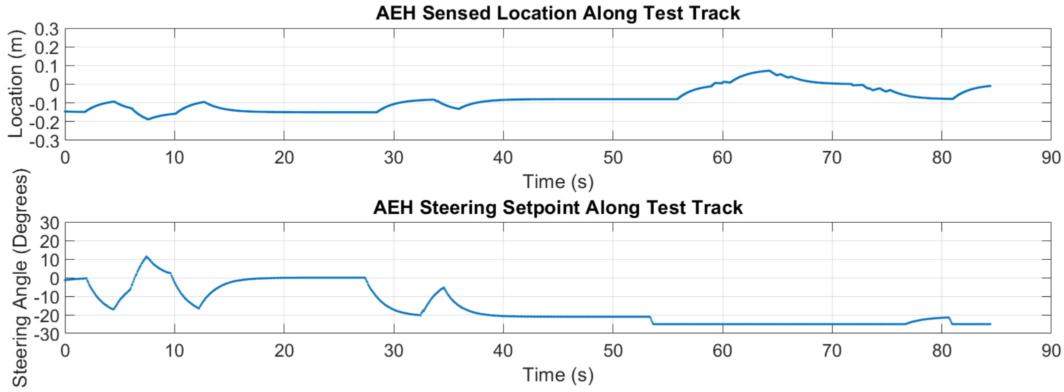


Figure 5.10: Location and Steering Input from Test Track Navigation

$-0.15m$, and for the first 30 seconds, the AEH locates itself on average in the correct position. There seems to be some drift in the location signal, but this appears to be compensated by the steering angle turning at the same time. Finally, the on-board odometry was used to track the position of the AEH while it was following the test track, which is shown in Fig. 5.11. The error between the actual cable location and the AEH on-board odometry is shown in Fig. 5.12.

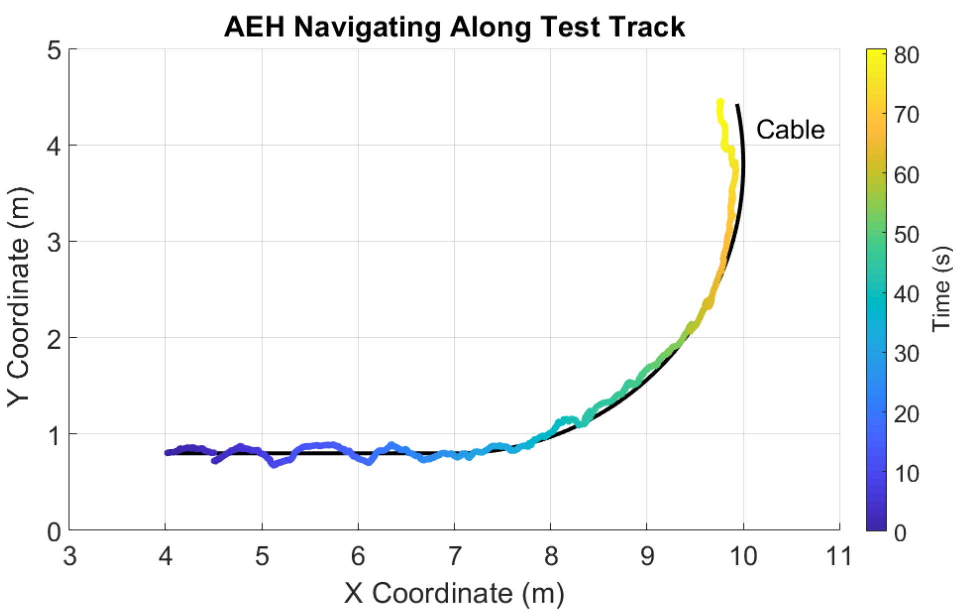


Figure 5.11: AEH On-Wire Navigation Demonstration Using On-board Odometry

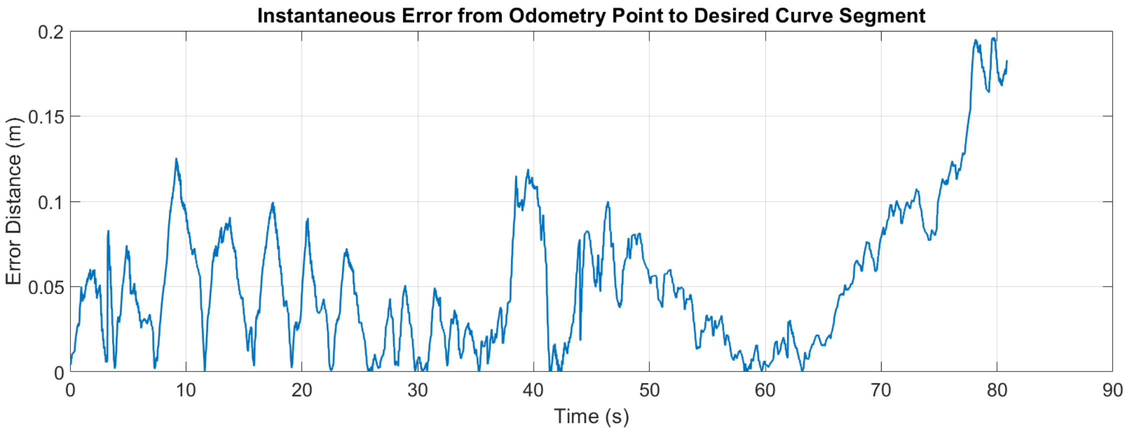


Figure 5.12: Error in Odometry and Desired

While the AEH is on the straight section, up to roughly 35s, the mean error was $4cm$. As the AEH moves onto the arc, the mean error for the remainder of the test was $6cm$, but increased to $20cm$ towards the end of the arc. This, coupled with the steering data from Fig. 5.10 and the software lockout angles would suggest the AEH could not turn sharply enough to navigate the turn. However, while on the straight section, the error is considered acceptable for a proof of concept.

The navigation is not perfect, but the data in Fig. 5.11 does indeed suggest that the AEH successfully navigated along a piece of test track, using only wireless, magnetic sensing. Therefore, Fig. 5.11 demonstrates the on-wire navigation proof of concept, and so too the main project goal.

6. Conclusions

The overarching goal of the AEH project was to produce a working prototype of an on-wire navigation system, which required:

- Construction of a platform vehicle;
- Design and construction of sensor hardware;
- Design and implementation of cable detection and localisation algorithm; and
- A navigation controller.

The platform vehicle was completed in as modular way as possible to allow for the extension of additional perihperals, and is therefore deemed complete for the AEH project. Additionally, from the available sensor options, the sensor bar hardware is considered complete given the time-frame and scope of the project. This is also true of the localisation/detection algorithm and navigation controller, as a working prototype was seen to effectively sense and follow a test track of cable. Therefore, the project was considered successful, and the design goals were met.

Of course, there exist many areas of improvement, additional research opportunities and refinements within the on-wire navigation project. The goal of the research was not optimisation of particular aspects of the system, but rather to build a proof of concept vehicle to demonstrate an on-wire navigation system in its entirety. The results support this statement, as the AEH was able to navigate a test track under fully autonomous control.

6.1 Recommendations

The recommendations for the project encompass the areas of sensing, locating and actuating, and are summarised in Fig. 6.1.

The most important areas of improvement are discussed in the following subsections, with the focus being on the sensor hardware design.

6.1.1 Optimisation of Coil Design

The coils used in the sensor bar were not uniform, and had many variances from each other, including:

- Inductances ranging from $50\mu H$ to $85\mu H$;
- Differing number of turns, from 20 to 25;

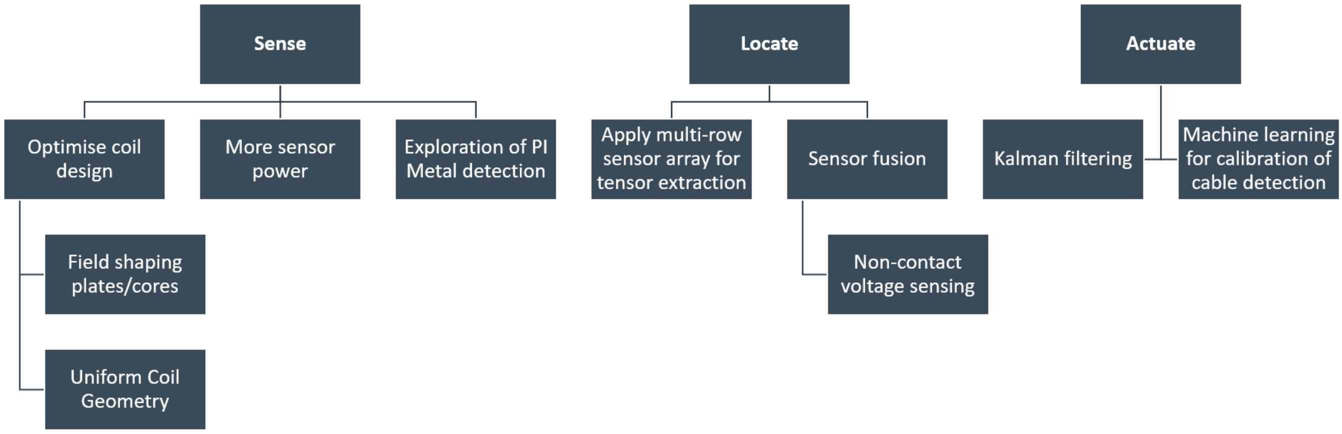


Figure 6.1: Project Recommendations

- Differing number of "layers"[1]; and
- Slight variations in shape due to mounting.

PCB coils could aid in suppressing these differences, ensuring responses from the coils are as similar as possible. Furthermore, Texas Instrument's online coil designer and benchmarking tool [51] could be used optimally design the coil for suitable diameter, drive current and number of turns.

6.1.2 Exploration of Inductive Metal Detection Techniques

The main limitation to using PI metal detection technology in this project was the complexity and particularly, time constraints. One main advantage is that more current can be used to increase the detection resolution (see Eq. (2.3)). Research in [14], [37] and [35] utilise PI metal detectors for small object location, which supports the recommendation to persue this topic for the AEH.

6.1.3 Mine Suitability

The purpose of the on-wire project is to produce a suite of sensor hardware and software which can be implemented on a prototype vehicle, which is intended to be deployed in a mine. Any future work or technology should consider this the forefront requirement, which the current work and research into the on-wire navigation system has followed. The conditions and limitations of a mining environment for the project are difficult, yet necessary. Seemingly, these are the reason there exists a gap in the existing research on this specific topic, thus allowing the possibility of future work in this field, however a feasibility study on this technology in a mining environment should first be conducted.

[1] That is, how the layers of the coils stacked upon each other

A. Project Analysis

In order to achieve the goal outlined in Section 1.3.1 and present the deliverables, a project plan was set out in Microsoft Project. Updated project analysis is presented in this appendix.

A.1 Resources

The main resource required for the success of the project is a functioning prototype of the AEH. This can then be broken down into on-wire specific and general necessary resources.

A.1.1 General Resources

- AEH chassis and driveline — a platform to work from;
- Open source motor controllers, steering actuators, and sensors for these;
- Batteries and accompanying chargers to run the above;
- Ubuntu capable laptop to run ROS;
- General microcontrollers — Arduino Mega/Due/Uno or similar;
- Software packages to write/run C++, python, Matlab;
- Various electronics connectors, cables, crimps, etc;
- General electronics equipment — soldering irons, oscilloscopes, logic analysers;
- Space to test AEH; and
- Dropbox or other file sharing client, as this is a group project.

A.1.2 On-Wire Specific

- Various sensors — particularly of interest is LDC1614;
- Access to materials and tools to make test rigs for testing sensor bar;
- Computers to write, run and test sensors;
- Matlab — Peter Corke's toolboxes;
- Cable to simulate the WPTS;

- Software, including ANSYS Maxwell, Altium PCB Designer and sensor evaluation software ;
- Metallic object “free” zones to test the sensors without the presence of metals; and
- A longer WPTS geometry for late-stage testing (test track).

A.2 Updated Project Timeline

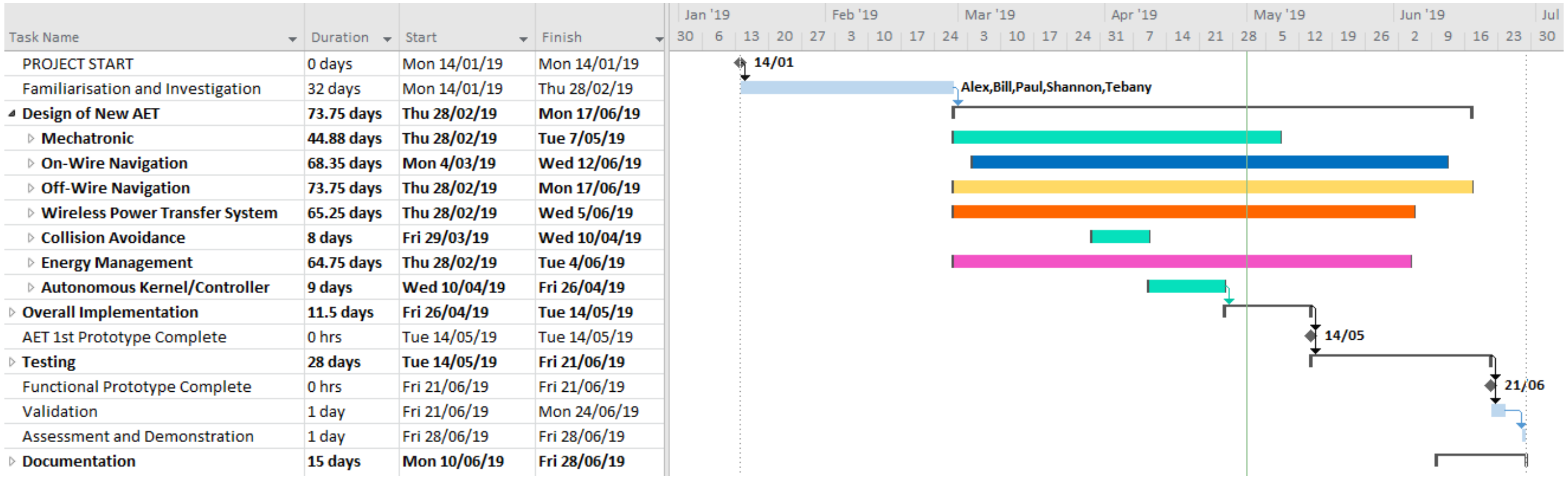
The Gantt chart in Fig. A.1 from Microsoft Project is a combined best estimate of the time the project will take. Table A.1 shows the colour legend for the project gantt charts (Fig. A.1 and Fig. A.2), and milestones for the project are in Table A.2.

Table A.1: Gantt Chart Colour Legend

Alex — On-Wire Navigation
Tebany — Mechatronic
Paul — Off-Wire Navigation
Shannon — Energy Management
Bill — WPTS

Table A.2: Project Milestones

AEH Overall Milestone	**Date**
Remote Control AEH Complete (motor drivers, steering all work)	7 May
Autonomous Kernel Complete	26 April
Implemetation Complete — First AEH Prototype	3 June
Functional Prototype Complete	18 June
Project Completion	28 June
On-wire Specific Milestone	**Date**
Sensor Selection Complete	10 March
Sensor Bar Designed	15 May
Integration with ROS and AEH Complete	14 June
Testing and Validation Complete, Debugging performed	25 June
Project Completion	28 June



Task Name	Duration	Start	Finish
PROJECT START	0 days	Mon 14/01/19	Mon 14/01/19
Familiarisation and Investigation	32 days	Mon 14/01/19	Thu 28/02/19
Design of New AET	**73.75 days**	**Thu 28/02/19**	**Mon 17/06/19**
Mechatronic	**44.88 days**	**Thu 28/02/19**	**Tue 7/05/19**
On-Wire Navigation	**68.35 days**	**Mon 4/03/19**	**Wed 12/06/19**
Off-Wire Navigation	**73.75 days**	**Thu 28/02/19**	**Mon 17/06/19**
Wireless Power Transfer System	**65.25 days**	**Thu 28/02/19**	**Wed 5/06/19**
Collision Avoidance	**8 days**	**Fri 29/03/19**	**Wed 10/04/19**
Energy Management	**64.75 days**	**Thu 28/02/19**	**Tue 4/06/19**
Autonomous Kernel/Controller	**9 days**	**Wed 10/04/19**	**Fri 26/04/19**
Overall Implementation	**11.5 days**	**Fri 26/04/19**	**Tue 14/05/19**
AET 1st Prototype Complete	0 hrs	Tue 14/05/19	Tue 14/05/19
Testing	**28 days**	**Tue 14/05/19**	**Fri 21/06/19**
Functional Prototype Complete	0 hrs	Fri 21/06/19	Fri 21/06/19
Validation	1 day	Fri 21/06/19	Mon 24/06/19
Assessment and Demonstration	1 day	Fri 28/06/19	Fri 28/06/19
Documentation	**15 days**	**Mon 10/06/19**	**Fri 28/06/19**

Figure A.1: Overall Project Timeline from Microsoft Project

Task Name	Duration	Start	Finish
On-Wire Navigation	**68.35 days**	**Mon 4/03/19**	**Wed 12/06/19**
Sensor Type Selection	**27.5 days**	**Mon 4/03/19**	**Wed 10/04/19**
Wire Detection Sensor	4 days	Mon 4/03/19	Fri 8/03/19
Wire Following Sensors	3 days	Fri 5/04/19	Wed 10/04/19
Sensor Calibration/Familiarisation	**29.25 days**	**Wed 17/04/19**	**Mon 3/06/19**
Test sensors for data type etc	10 days	Wed 17/04/19	Tue 7/05/19
Final Decision on number and types of sensors	2 days	Thu 30/05/19	Mon 3/06/19
Implement Sensors with ASICs	**4.6 days**	**Mon 3/06/19**	**Mon 10/06/19**
Arduino Implementation	1 day	Mon 3/06/19	Tue 4/06/19
Integration with ROS	3 days	Tue 4/06/19	Fri 7/06/19
Decide on Sensor Location on vehicle	0.5 days	Fri 7/06/19	Mon 10/06/19
Re-do FK	0.1 days	Mon 10/06/19	Mon 10/06/19
Navigation	**11.88 days**	**Wed 8/05/19**	**Thu 23/05/19**
Design Control Plant	1 day	Wed 8/05/19	Wed 8/05/19
Design Controller	3 days	Thu 9/05/19	Mon 13/05/19
Implement Controller in Python for ROS	1 day	Tue 21/05/19	Wed 22/05/19
Test Controller	1 day	Wed 22/05/19	Thu 23/05/19
Optimisation	**13.6 days**	**Thu 23/05/19**	**Wed 12/06/19**
Simulate and Test Optimal Coils	5 days	Thu 23/05/19	Thu 30/05/19
Implement Optimal Coils	2 days	Mon 10/06/19	Wed 12/06/19

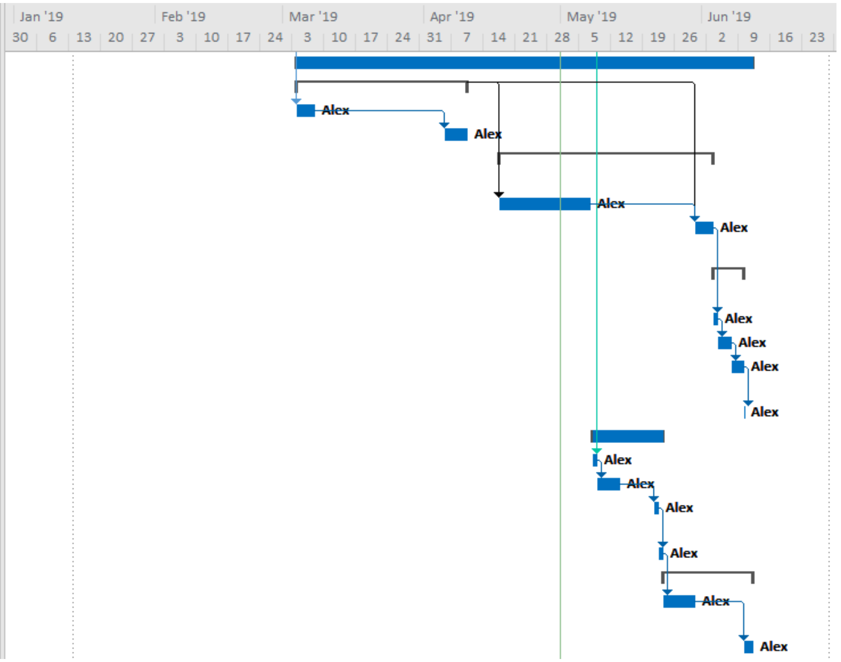


Figure A.2: On-Wire Specific Project Timeline

A.3 Project Plan Accuracy

The tasks for the project plan are mostly unchanged from the proposal. The durations of tasks were initially estimated correctly, though the order in which they were completed was not necessarily consistent with the project plan. This had little effect on the final outcome, as everything was completed to at least a satisfactory standard.

A.4 Risk Analysis

The risk analysis largely remains the same as the project proposal; predominantly, the differences will be highlighted. The risk register in Appendix B spans the entire project, showing that it is still relatively low appetite for risk. A summary of risks with a medium or higher initial rating, and any which have changed since the project proposal, are presented in Table A.4. The analysis section was done in accordance to Mining3's risk assessment methodology, in Fig. A.3, using the definitions of likelihood and hazard in Appendix B. No changes to the risk assessment were made since the interim report, and the following is consistent with the final risk assessment of the AEH project.

	Hazard Effect/ Consequence				
	1 Insignificant	2 Minor	3 Moderate	4 Major	5 Catastrophic
Likelihood	Risk Rating				
A (Almost certain)	15 (M)	10 (H)	6 (H)	2 (Ex)	1 (Ex)
B (Likely)	19 (M)	14 (M)	9 (H)	4 (Ex)	3 (Ex)
C (Possible)	22 (L)	18 (M)	13 (H)	8 (H)	5 (Ex)
D (Unlikely)	24 (L)	21 (L)	17 (M)	12 (H)	7 (H)
E (Rare)	25 (L)	23 (L)	20 (M)	16 (M)	11 (H)

Figure A.3: Mining3 Risk Matrix

Table A.3: Summary of Key Risks in the AEH Project

Risk	Controls: Existing	Controls: Planned	Residual Risk Rating
(P) Crushing fingers, hands	When assembling the scooter, use 2 prople to assist with the lifting and positioning.	Put warning tape on the AEH (keep hands clear).	21 (L)
(P) Muscle Injury	Appropriate lifting training (Do not lift items > 20kg by hand without help). Minimise lifting.	Students trained in manual lifting and moving.	22 (L)
(P) Electrical shock	Earth leakage circuit breaker. Design for low voltage (< 50VAC and < 100VDC), utilise PPE and test incrementally.	Design verified by electrical engineer before building.	22 (L)
(P) Person to vehicle collision	Low speeds, collision avoidance systems, remote operation with remote control disable. Warning lights on truck.	Create and operate in fenced, chained area only.	21 (L)
(P) Batteries, supercapacitors exploding due to excess heat	Design includes heat sinking. Accumulators located inside protective housing. Store truck away from heat sources (incl. full sun).	Proper circuit design for charge/discharge reviewed by electrical engineer. Purchase and use a fite-proof bag for battery storage and charging	21 (L)
(P) Electromagnetic fields interracting with electronic devices (e.g. pacemakers).	Measure field strength to determine hazard. Manual power switch.	Design primary coil that senses truck and switches on. Purchase/install signage (if required)	23 (L)
(R, E) Runaway vehicle	Operate AEH as a group, with one person spotting.	Design hardware E-stop and firmware failsafes. Put E-stop on easily accessible part(s) of the AEH	23 (L)

B. Risk Register

The full risk register is presented over the following pages. It details all risks, OH&S and commercial in nature. The definitions of liklihood and hazard/consequence are given below in Table B.1 and Table B.2 respectfully.

Likelihood	Likelihood Examples (use only as a guide for evaluation of uncontrolled hazards)
A (Almost certain)	Likely that the unwanted event could occur several times per year at this location
B (Likely)	Likely that the unwanted event could occur several times per year in Mining3; or could happen annually
C (Possible)	The unwanted event could well have occurred in the mining industry at some time in the past 10 years
D (Unlikely)	The unwanted event has happened in the mining industry at some time; or could happen in 100 years
E (Rare)	The unwanted event has never been known to occur in the mining industry; or is highly unlikely that it could ever occur

Table B.1: Definitions of Liklihood

1 Insignificant	2 Minor	3 Moderate	4 Major	5 Catastrophic
Slight injury or health effects – first aid/ minor medical treatment level	Minor injury or health effects – restricted work or minor lost workday case	Major injury or health effects – major lost workday case/ permanent disability	Permanent total disabilities, single fatality	Multiple fatalities
Environmental nuisance	Material environmental harm	Serious environmental harm	Major environmental harm	Extreme environmental harm
Slight damage <$5000. No disruption to operation	Minor damage $5000 to $50,000. Brief disruption to operation	Local damage $50,000 to $500,000. Partial shutdown	Major damage $500,000 to $1M. Partial loss of operation	Extreme damage > $1M. Substantial or total loss of operation
Slight impact – public awareness may exist but no public concern	Limited impact – some local public concern	Considerable impact – regional public concern	National impact – national public concern	International impact – international public attention

Table B.2: Definitions of Hazard

1	**Construction**																		
	Soldering	Solder in eyes.	Safety glasses. Other PPE.	P	Moderate	Rare	20	M	1. Soldering training, as required 2. Eye wash station	Minor	Rare	23	L	Yes	No	1-Feb	1. Joji / students 2. Mary to order	1. Induction completed 2. TBD	1. 12/2/2018 2.
		Solder fumes.	Ventilation.	P	Insignificant	Rare	25	L		Insignificant	Rare	25	L	Yes	No				
		Soldering iron burn.	Appropriate iron resting apparatus. Switch off when not in use.	P	Minor	Rare	23	L		Minor	Rare	23	L	Yes	No				
	Moving/lifting	Muscle injury.	Appropriate lifting training (Do not lift items >20kg by hand without help.) Mininmise lifting.	P	Minor	Possible	18	M	3. Students trained in lifting	Insignificant	Possible	22	L	Yes	No	15-Mar	3. Mary / students	3. Manual handling training in progress	
		Crushing fingers, hands	When assembling the scooter use 2 people to assist with the lifting and positioning	P	Minor	Possible	18	M	14. Put signs on the AET - keep hands clear while in operation.	Minor	Unlikely	21	L	Yes	No				
		Tripping	Students must keep a clean work area, utilising bench space to work on	P	Insignificant	Possible	22	L		Insignificant	Possible	22	L	Yes	No				
	Electronic testing	Short-circuits causing burns, as well as fire or smoke in equipment.	Fire extinguisher. Fuses. Circuit breakers Verify design before building.	P	Insignificant	Possible	22	L		Insignificant	Possible	22	L	Yes	No				
		Electrical shock.	Earth leakage circuit breaker. Design for low voltage (<100V). PPE Test incrementally.	P	Minor	Possible	18	M	4. Design verified by electrical engineer before building.	Insignificant	Possible	22	L	Yes	No		4. Aaron / Stuart		
	Power tools	Bodily injury.	PPE	P	Minor	Possible	18	M	5. Operators trained in first aid and use of power tools	Minor	Unlikely	21	L	Yes	No	1-Mar	5. Mary / students	5. Handtool training completed	26-Feb-18
	Day-to-day	RSI from long periods of typing, staring at computer monitors	UQ Workstation Guidelines and taking regular breaks	P	Insignificant	Possible	22	L		Insignificant	Possible	22	L	Yes	No				

Figure B.1: Risks Associated with AEH Construction

2	**Operation**																		
	Vehicle operation	Loading truck by hand.	Minimise hand loading. Use Dingo for loading where needed.	P	Insignificant	Possibl e	22	L		Insignificant	Possible	22	L	Yes	No				
		Person to vehicle collisions.	Low speeds. Minimise momentum. Collision avoidance algorithims. Remote operation. Design with no sharp edges on vehicle. Use of kill switch and remote control disable. Warning light on truck.	P	Moderate	Unlikely	17	M	6. Create and operate in fenced/taped area	Minor	Unlikely	21	L	Yes	No	30-Mar	6. Mary / site		
		Lithium batteries or super capacitors exploding from excessive heat.	Design includes heat sinking. Accumulators located inside protective housing. Store truck away from heat sources (incl. full sun).	P	Minor	Possibl e	17	M	7. Proper circuit design for charge/discharge, reviewed by an electrical engineer. 8. Purchase and use a fire-proof bag for use when charging and stopring the batteries.	Minor	Unlikely	21	L	Yes	No		7. Aaron / Stuart 8. Meetkumar	7. TBD 8. Purchased	7. 8. 26/2/18
		Electromagnetic fields interfering with electronic devies. E.g. Pacemakers	Measure field strength to determine hazard. Manual power switch.	P	Minor	Possibl e	18	M	9. Design primary that senses truck & switches on. 10. Purchase/install signage (if required)	Minor	Rare	23	L	Yes	Yes??		9. Aaron / Stuart 10. Aaron / Mary		
		Runaway vehicle	Loss of equipment, potential to cause injury to bystanders or property	R, E	Minor	Possibl e	18	M	12. Design in E-stops and failsafes in the firmware 13. Put Hardware E-stop on the vehicle	Minor	Rare	23	L	Yes	No				
3	**Ongoing Risks**																		
		Theft of IP	Private dropboxes, repositories Previously organised IP contracts with UQ	A	Insignificant	Unlikely	24	L	Note: insignificant at this stage, as research progresses this may become more significant.	Insignificant	Unlikely	24	L	Yes	No				

Figure B.2: Risks Associated with Operation and Ongoing Parts of the AEH Project

C. Project Reflection

Self-reflection is crucial for upwards growth and forwards progress. This appendix will present a reflection on the AEH project to date, key learnings and the relation of these learnings to the Engineers Australia (EA) Competencies.

The AEH project has been challenging, yet extremely rewarding. The placement differed to my initial expectations that it would be like another Team Project. Instead, it was a much more wholesome experience which aided my skill development in many more areas than a team project would have been able to. Especially because the placement was conducted in a workplace environment, communication skills and were so much more important, especially when asking for help/assistance from other staff. This project also seemed to be much more intertwined with all aspects than previous team projects — that is, large portions of the project actively required input from all team members.

C.1 Skills Developed

The AEH project at Mining3 provided opportunities to develop engineering skills in the areas described by the Engineers Australia Competencies.

C.1.1 Knowledge and Skill Base

The on-wire navigation project certainly proved to be technically challenging. It combined many of the fields I have studied throughout my coursework, but have especially required me to draw upon:

- Electromagnetic physics;
- Digital signal processing; and
- Control system design.

It was extremely interesting being able to combine these aspects into a high-level system, while also considering the implications of the project's context within the mining industry. Although this consideration was forefront in my development of the on-wire navigation system, it is still of course a prototype vehicle, so adherence to electrical standards and mining standards was not necessary.

Once the prototype was initially complete, designing a fair and complete experiment to test the system empirically a valuable experience. Of course, a simple video of the AEH would suffice to demonstrate its ability to follow the cable, though this is impossible to present in the medium of a report. Data analysis is extremely important for engineers, and so too data visualisation; so having the opportunity to present the findings across several mediums has helped me develop my skills in this regard.

C.1.2 Engineering Application Ability

I found the AEH project particularly interesting because the deliverable was a prototype vehicle. Applying the knowledge gained through study is something I am passionate about, and I am overall satisfied with how the project managed to come together. This was of course not without several technical, logistical and resourcing issues throughout the project.

My high level problem solving skills were certainly challenged throughout the project. For example, I noticed the potential of a safety hazard on the AEH after conversing about lipo batteries with work colleagues. Both the previous and current (at the time) AEH had only a circuit breaker, and the bus bars at battery level potential were completely exposed. I then completed a proposal schematic of a new safety system and after approval from my supervisor to purchase the components, the safety system was implemented, and then checked by other engineers at Mining3. To see this whole process come to completion was satisfying, as was the project in general — the successful application of prior knowledge to a working prototype is always rewarding.

C.1.3 Professional and Personal Attributes

Professional communication and conduct were skills that were regularly practiced at Mining3 throughout the placement. There were a number of occasions which required intervention and assistance by other staff, such as:

- Requesting help machining/manufacturing parts;
- Checking electrical schematics and physical wiring;
- Justifying purchase orders; and
- Borrowing equipment.

In addition, we were presented with a number of opportunities to gain more experience in this mining electric vehicle industry, as well as the mining industry in general. Through these presentations, showcases and seminars I was able to conduct myself with professionalism while showing genuine interest in the industry. On occasion, our supervisor would bring guests to show the AEH, which were important times to test and improve my ability to succinctly summarise key points.

C.2 Learning Events

Three of the key learning events from the placement will be presented. They have been identified as the most important lessons learned throughout the placement.

C.2.1 Project Managment Tools — Self Organisation

I found it beneficial to use project management tools (in this case, Microsoft Project Planner) to manage my time throughout the project. This was not only for time management, but to extend my project management skills, which are certain to be necessary as a professional engineer. I showed initiative in adapting code versioning tools to the project, as I understood from past experience how messy these large scope, multi-person, multi-disciplinary projects can become.

I found the practical and necessary application of these tools extremely valuable for my own learning, and the experience I have gained, especially using Git within the group has certainly made me more confident in my abilities.

C.2.2 LiPo Safety — Proactive Action

The lipo battery protection was certainly a learning event in itself, though my take-home message was more significant. Engineers can have a great deal of responsibility for others' safety, and proactive thinking about risk management and avoidance is a key skill I've learned during my time at Mining3. Aside from formal risk analyses, the attitude towards safety at Mining3 put me in the right mindset to realise the problem with the lipo, and then do something about it.

C.2.3 Work, Life, University — Balance

The balance of working to achieve a successful project, while still putting in effort for the academic side of the course was sometimes tricky. On the one hand, I felt obliged to produce a working prototype of the project to my placement supervisor; yet simultaneously having to take time off to complete the assessment in the course. I will take this as another reminder that "real world engineering" is not all practical fun, but must contain some amount of reporting. In the future, to avoid having to work the equivalent of overtime, I should plan the reporting as far in advance as possible, but also to better subdivide the work into manageable pieces.

C.3 Improvements

Overall I believe the project to have gone sucessfully, though in hindsight there are a few aspects for which I would rethink my approach.

I believe there was too much time spent on developing the platform vehicle. For example, in the early weeks of the project, the gearbox of the AEH would occasionally lock up. Another student and myself sought to fix the gearbox so we would have an operational prototype to test the additional technologies from. In hindsight, I would have had substantially more time to spend on the sensing, locating and actuating of the vehicle had a platform which accepted γ and v been readily available.

Finally, I believe the ground work is set in place with the on-wire project. Though with slightly more time or future research on this topic, the sensing and location fields have the potential to become quite advanced.

Bibliography

[1] J. Mazumdar, “All electric operation of ultraclass mining haul trucks,” in *2013 IEEE Industry Applications Society Annual Meeting*, Oct 2013, pp. 1–5.

[2] ICMM. (2019) All electric mine of the future. [Online]. Available: https://www.icmm.com/en-gb/case-studies/all-electric-mine-of-the-future

[3] F. Brito, J. Martins, D. D. R. Pedrosa, V. D. F. Monteiro, and J. L. Afonso, “Real-life comparison between diesel and electric car energy consumption,” 2013.

[4] Caterpillar. (2019) Cat command for hauling. [Online]. Available: https://www.cat.com/en_US/by-industry/mining/articles/catcommandforhauling-expanding.html

[5] (2017) Volvo CE Unveils the NExt Generation of its Electric Load Carrier Concept. [Online]. Available: https://www.volvoce.com/global/en/news-and-events/news-and-press-releases/2017/conexpo-vegas-2017/volvo-ce-unveils-the-next-generation-of-its-electric-load-carrier-concept/

[6] D. Gleeson. (2018) Trolley assist up and running at boliden’s aitik copper mine. [Online]. Available: https://im-mining.com/2018/11/15/trolley-assist-running-bolidens-aitik-copper-mine/

[7] C. Panchal, S. Stegen, and J. Lu, “Review of static and dynamic wireless electric vehicle charging system,” *Engineering Science and Technology, an International Journal*, vol. 21, no. 5, pp. 922 – 937, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S221509861830154X

[8] Komatsu. (2007) Komatsu 930e-4 electric drive truck. [Online]. Available: https://www.webcitation.org/5nwccAClr?url=http://www.equipmentcentral.com/north_america/data/new_equipment/930E_4_AESS743-00_FINAL.pdf

[9] Cateripllar. (2019) Ad60. [Online]. Available: https://www.cat.com/en_AU/products/new/equipment/underground-hard-rock/underground-mining-trucks/18349061.html

[10] R. D. Knight, *Physics for Scientists and Engineers: A Strategic Approach with Modern Physics, Global Edition.* Pearson Education UK, 2016.

[11] NDT Resource Center. (Unknown Date) Depth of penetration and current density. [Online]. Available: https://www.nde-ed.org/EducationResources/CommunityCollege/EddyCurrents/Physics/depthcurrentdensity.htm

[12] P. Corke, *Robotics, Vision and Control: Fundamental Algorithms In MATLAB® Second, Completely Revised, Extended And Updated Edition*, ser. Springer Tracts in Advanced Robotics. Cham: Springer International Publishing, 2017, vol. 118.

[13] Y. Elattar, S. Metwalli, and M. Rabie, "Pdf versus pid controller for active vehicle suspension," 04 2016.

[14] C. Bruschini, "A multidisciplinary analysis of frequency domain metal detectors for humanitarian demining," Ph.D. dissertation, Vrije Universiteit Brussel, 2002. [Online]. Available: https://www.gichd.org/fileadmin/pdf/database/PhDBruschiniFinalv2.pdf

[15] K. R. Krueger, J. H. McClellan, and W. R. Scott, "Tensor amplitude extraction in sensor array processing," in *2013 IEEE International Conference on Acoustics, Speech and Signal Processing*, May 2013, pp. 3895–3899.

[16] K. R. Krueger, W. R. Scott, and J. H. McClellan, "Extracting target orientation for different electromagnetic induction sensing geometries," in *2014 IEEE Geoscience and Remote Sensing Symposium*, July 2014, pp. 3156–3159.

[17] M. Nehring, P. Knights, M. Kizil, and E. Hay, "A comparison of strategic mine planning approaches for in-pit crushing and conveying, and truck/shovel systems," *International Journal of Mining Science and Technology*, vol. 28, no. 2, pp. 205 – 214, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S209526861630221X

[18] M. Principato. (2014) For the long haul. [Online]. Available: https://www.mtu-report.com/mining/haul-trucks/for-the-long-haul

[19] J. Paraszczak, K. Fytas, and M. Laflamme, "Feasibility of using electric trucks in deep metal mines," *Mine Planning and Equipment Selection*, pp. 1265–1275, 2014.

[20] E. Isokangas, "A novel transport system," 2018.

[21] P. Darling, *SME Mining Engineering Handbook*. Littleton: SME, 2011.

[22] American Cancer Society. (2015) Dielsel exhaunst and caner. [Online]. Available: https://www.cancer.org/cancer/cancer-causes/diesel-exhaust-and-cancer.html

[23] S. Taylor and B. Lewis. (2018) First new all-electric mine dumps diesel - cuts costs, pollution. [Online]. Available: https://www.reuters.com/article/us-mining-electric-goldcorp/first-new-all-electric-mine-dumps-diesel-cuts-costs-pollution-idUSKBN1JH2FI

[24] S. Lukic and Z. Pantic, "Cutting the cord: Static and dynamic inductive wireless charging of electric vehicles," *IEEE Electrification Magazine*, vol. 1, no. 1, pp. 57–64, Sep. 2013.

[25] KAIST. (2019) On-line electric vehicle. [Online]. Available: https://olev.kaist.ac.kr/en/

[26] Google. (2019) Googl style guides. [Online]. Available: http://google.github.io/styleguide/

[27] Q. Dou, L. Wei, D. R. Magee, P. R. Atkins, D. N. Chapman, G. Curioni, K. F. Goddard, F. Hayati, H. Jenks, N. Metje, J. Muggleton, S. R. Pennock, E. Rustighi, S. G. Swingler, C. D. F. Rogers, and A. G. Cohn, "3d buried utility location using a marching-cross-section algorithm for multi-sensor data fusion," *Sensors*, vol. 16, no. 11, 2016. [Online]. Available: http://www.mdpi.com/1424-8220/16/11/1827

[28] Fargo Controls. (2018) Operating principles for inductive proximity sensors. [Online]. Available: http://www.fargocontrols.com/sensors/inductive_op.html

[29] Texas Instruments. (2018) LDC1612, LDC1614 Multi-Channel 28-Bit Inductance to Digital Converter (LDC) for Inductive Sensing. [Online]. Available: http://www.ti.com/lit/ds/snoscy9a/snoscy9a.pdf

[30] P.-J. Bristeau, F. Callou, D. Vissière, and N. Petit, "The navigation and control technology inside the ar.drone micro uav," *IFAC Proceedings Volumes*, vol. 44, no. 1, pp. 1477 – 1484, 2011, 18th IFAC World Congress. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1474667016438188

[31] T. Moore and D. Stouch, "A generalized extended kalman filter implementation for the robot operating system," in *Proceedings of the 13th International Conference on Intelligent Autonomous Systems (IAS-13)*. Springer, July 2014.

[32] J. C. McCall and M. M. Trivedi, "Video-based lane estimation and tracking for driver assistance: survey, system, and evaluation," *IEEE Transactions on Intelligent Transportation Systems*, vol. 7, no. 1, pp. 20–37, March 2006.

[33] S. TEMEL, S. YAĞLI, and S. GÖREN. (Unknown Date) P, pd, pi, pid controllers. [Online]. Available: https://www.researchgate.net/file.PostFileLoader.html?id=54685991d11b8bc9668b461a&assetKey=AS%3A273635200176128%401442251123954

[34] D. J. Daniels, *Ground Penetrating Radar*. Wiley, 2005. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/0471654507.eme152

[35] S. Masunaga and K. Nonami, "Controlled metal detector mounted on mine detection robot," *International Journal of Advanced Robotic Systems*, vol. 4, no. 2, p. 26, 2007. [Online]. Available: https://doi.org/10.5772/5692

[36] P. Ngan, "Data fusion technique for handheld standoff mine detection system (hstamids)," vol. 3392, no. 1. SPIE, 1998, pp. 1150–1160.

[37] C. V. Nelson, C. B. Cooperman, W. Schneider, D. S. Wenstrand, and D. G. Smith, "Wide bandwidth time-domain electromagnetic sensor for metal target classification," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 39, no. 6, pp. 1129–1138, June 2001.

[38] IDT. (2018) ZMID520x Position Sensors. [Online]. Available: https://www.digikey.com.au/en/product-highlight/i/idt/zmid520x-position-sensors

[39] Microsemi. (2015) LX3301A Inductive Sensor Interface IC with Embedded MCU. [Online]. Available: https://au.mouser.com/datasheet/2/523/lx3301a_pb_v2-1112694.pdf

[40] T. M. Grzegorczyk, B. E. Barrowes, F. Shubitidze, J. P. Fernandez, and K. O'Neill, "Simultaneous identification of multiple unexploded ordnance using electromagnetic induction sensors," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 49, no. 7, pp. 2507–2517, July 2011.

[41] S. N. Mustafa Oezdemir, Eric L. Miller, "Localization and characterization of buried objects from multifrequency array inductive data," 1999. [Online]. Available: https://doi.org/10.1117/12.357054

[42] J. H. M. Ali C. Gurbuz, Waymond R. Scott, "Location estimation using a broadband electromagnetic induction array," 2009. [Online]. Available: https://doi.org/10.1117/12.819837

[43] J. H. M. Kyle Krueger, Waymond R. Scott, "Location and orientation estimation of buried targets using electromagnetic induction sensors," 2012. [Online]. Available: https://doi.org/10.1117/12.919558

[44] Standards Australia, *Electrical Installations — "Wiring Rules"*, SAI AS/NZS 3000:2018, 2018.

[45] M. Ferguson and A. Stambler. (2018) Rosserial arduino. [Online]. Available: http://wiki.ros.org/rosserial_arduino

[46] M. Lundberg, "simple-pid," 2019. [Online]. Available: https://pypi.org/project/simple-pid/

[47] B. Vedder. (2016) Vesc — open source esc. [Online]. Available: http://vedder.se/2015/01/vesc-open-source-esc/

[48] A. Agarwal, A. Anders, A. Fishberg, S. Karaman, and T. Henderson. (2016) Vesc driver. [Online]. Available: https://github.com/mit-racecar/vesc/tree/master/vesc_driver

[49] Electracables. (Unknown date) nge circular power cable (0.6/1kv). [Online]. Available: http://electracables.com.au/index.php?page=0-6-1kv

[50] Omron. (2013) Cylindrical proximity sensor — e2b. [Online]. Available: https://assets.omron.eu/downloads/datasheet/en/v1/d116_e2b_cylindrical_proximity_sensor_datasheet_en.pdf

[51] Texas Instruments. (2019) Coil designer. [Online]. Available: https://webench.ti.com/wb5/LDC/#/spirals