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Navigation and Control of an Unmanned Surface Vessel

by

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Final Report

Study leader: Prof Jaco Versfeld

July 2022

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20725728

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EXECUTIVE SUMMARY

Student: L.E.V Kingwill

Title of Project
Navigation and Control of an Unmanned Surface Vessel.
Objectives
The development of an independent navigation and control system that can be implemented on an unmanned surface vessel that uses electrical thrusters for propulsion and steering.
What is new in this project?
A new control system is going to be created to control the power to the thrusters and thereby steer the vessel. Building on this a navigation system will be created so that the vessel can navigate to a designated point autonomously.
If the project is successful, how will it make a difference?
With a successful navigation and control system, the system could be moved to vessels with better range and seafaring ability and these unmanned vessels can be used for research data collection, patrolling and search and rescue.
What contributions have/will other students made/make?
N.A.
Which aspects of the project will carry on after completion and why
For the vessel to be completely autonomous, a further project should investigate an obstacle avoidance system and power regeneration. This will be beneficial to avoid other sea vessels as well as fixed obstacles such as rocks and the shore. The power regeneration will extend the range of the vessel.
What arrangements have been/will be made to expedite contiuation?
All the research and project documents will be archived with the university and the code-base will be thoroughly commented for ease of understanding.

Student | Date | Lecturer

ECSA EXIT LEVEL OUTCOMES

ECSA Outcomes Assessed in this Module	
ECSA Outcome	**Addressed in Sections:**
ELO 1. Problem Solving: Demonstrate competence to identify, assess, formulate and solve convergent and divergent engineering problems creatively and innovatively.	
ELO 1. Problem Solving: Demonstrate competence to identify, assess, formulate and solve convergent and divergent engineering problems creatively and innovatively.	
ELO 2. Application of scientific and engineering knowledge: Demonstrate competence to apply knowledge of mathematics, basic science and engineering sciences from first principles to solve engineering problems	
ELO 3. Engineering Design: Demonstrate competence to perform creative, procedural and non-procedural design and synthesis of components, systems, engineering works, products or processes	
ELO 5. Engineering methods, skills and tools, including Information Technology: Demonstrate competence to use appropriate engineering methods, skills and tools, including those based on information technology.	
ELO 6. Professional and technical communication: Demonstrate competence to communicate effectively, both orally and in writing, with engineering audiences and the community at large.	
ELO 8. Individual, Team and Multidisciplinary Working: Demonstrate competence to work effectively as an individual, in teams and in multi-disciplinary environments	
ELO 9. Independent Learning Ability Demonstrate competence to engage in independent learning through well-developed learning skills	

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Chapter 1

Introduction

1.1 Background

As technology has improved over the years, processes and systems have become more automated. Initially factories were replacing manual labour with automated machines but recently companies have been investigating self-driving cars and trucks. All over industries tasks are being automated or done remotely with fewer human involvement.

The ocean is the perfect area for unmanned surface vessels (USV) to be used as many of the issues faced with autonomous land vehicles such as self-driving cars are mitigated by open water. On the open water one gets a 360Â° of the surroundings of the vehicle and although there can still be high volumes of traffic in certain areas such as commercial shipping lanes, due to the expanse of the ocean these high traffic areas are avoidable. Finally, and probably the most desirable mitigating factor is that where a surface vehicle would need to look where the road surface is to follow it, an ocean vessel can move directly from point to point on any piece of water.

In South Africa there is a growing need to USVs with regards to ocean research and conservation. There has been a growing use of acoustic sensory systems to track dolphins and whales around the world. By combining this with the technology of USVs, a far larger area can be surveyed.

1.2 Objectives

This project will focus on the navigation and propulsion control of the USV. This is the building block of the USV upon which a future project can build by adding an obstacle avoidance system or renewable power sources to keep the USV operational for longer. This project will have the following objectives:

1. Design and manufacture an electric surface vessel.
2. Designing and manufacturing the control system that will give a pilot manual control over the electric surface vessel.
3. Building on the manual control and implementing navigation control so that the electric surface vessel will navigate to prescribed points.

1.3 Motivation

Currently the marine community is using these acoustic systems as stationary systems. By using the USV in conjunction with the acoustic monitoring the area that is studied can be greatly increased with fewer acoustic platforms than have been used in past projects. Furthermore, the technology can be adapted for use in other industries such sonar surveying, defence and search and rescue. The use of USVs is becoming more prominent as a USV can be cheaper to operate and therefore organisations can either save costs in the case of sonar and acoustic research or in the case or marine patrols and search and rescue, USVs can be used to fill up the ranks of vessels and close the area between vessels.

The tasks previously mentioned are often time consuming and the crew of the assigned vessel need time to rest whereas a fully autonomous USV can operate constantly, stopping only to replenish its energy source and with further developments such as solar charging, USVs could begin to operate indefinitely, having to only come in for services or if there is a problem with the system.

This report will first look at what a USV is and what equipment and knowledge is required for a USV. It will also cover a review of literature around these technologies to offer a background and explain the concepts. Following on, the designed system is described before going into more detail on each component, both hardware and electronics and the software and algorithms used in the system. Finally the report will describe how each system can be tested and the results will be discussed before a conclusion on the system is be made.

Chapter 2

Literature Review

2.1 USV

A USV is an unmanned surface vessel, and most often refers to an autonomous unmanned surface vessel, Patterson *et al.* (2022). With advancements in technology leading to unmanned drones and development into autonomous cars, unmanned surface vessels is a natural progression. There are a wide range of uses for unmanned surface vessels from research and surveying to rescue and military. The obvious benefit of an unmanned surface vessel over conventional naval vessels is the lack of any personal on-board. This means that the vessel can go into more dangerous situations such as rough weather without the risk loss of life, Oceanalpha. Furthermore, the vessel can operate 24hrs a day as long as it has an energy source. Finally, an unmanned surface vessel with the right power regeneration equipment can operate for months or years without having to resupply provided there are no unforeseen issues. Other benefits of an unmanned vessels, is that because they are often electrically powered they are more easily controlled by software and can make use of renewable energy sources in order to remain self sufficient for long periods of time. A USV can have a carbon footprint as low as 10 % of its manned counter part, Fugro.

The primary concern when trying to navigate open water is that you need to know where you are and in which direction you need to go. Historically sailors used a combination of the stars as well as tracking their progress based on speed and time. However, this allows for inaccuracies as it does not account for cross winds and it can be difficult to determine your speed in stormy seas. In modern day naval navigation, GPS systems are used that can accurately pinpoint the location of the vessel anywhere in the world. The next step is to know in which direction you need to travel. Both historically and in modern day navigation you can use a mechanical compass that uses the earth's magnetic fields to determine which way is north and

Figure 2.1: Early GPS receivers were large, heavy devices. (USAF) (1978)

from which you can then determine in which direction you need to travel.

Using these navigation techniques, a USV needs at minimum, a GPS receiver to know its position and a digital compass to know its direction. However, there are other technologies that can be added to improve the performance and self-sufficiency of the USV. These include cameras and radar for surface obstacle avoidance such as debris, rocky outcroppings or ships, Oceanalpha. Sonar can be used to detect and avoid shallow waters or other obstacles below the waters surface. And solar and wind generators can be used to recharge the vessels power supply so that it can remain at sea for longer periods.

2.2 GPS

2.2.1 History of GPS

Global Positioning System (GPS) is an everyday thing in our lives today and has become a luxury that most take for granted. There is GPS in our phones, laptops and even cars. We are using it to find directions on our commutes, hail taxis or ride shares and even for recreational sport, tracking how far we travelled.

The origins of GPS or rather any global satellite navigation system begins with the space race. It starts, in 1957, with the first satellite to successfully orbit the earth, the Russian satellite Sputnik. During its orbiting flight of the earth, Sputnik was emitting a radio signal which could be picked up on earth. During this orbit scientists from John Hopkins University in America were monitoring the radio signals emitted by the Sputnik satellite when they saw the Doppler Effect in action with the radio signals, as the satellite drew closer, the radio signal frequency increased and vice versa. These scientists theorized that if they could determine the location of the satellite based on its signal frequency, the opposite would also be true, they could determine the location of a receiver on the ground given the satellites location. Aerospace (2021)

The first instance of a global satellite navigation system was the Transit. It was developed in 1958 by the Advanced Research Projects Agency and the first satellite was launched in 1960. The Transit satellites were mostly used by the military, specifically the Navy's missile submarines. The program was transferred to the Navy during the mid-1960s. During this time there were further Transit satellites launched and by 1968 the entire constellation of Transit satellites was operational, a total of 36 satellites. Aerospace (2021)

There was plenty of other research that was being conducted around the same time to improve on the current Transit. One such researcher was Phillip Diamond. Diamonds concept, from his study in 1963, lead to the Air Force forming a new satellite navigation program which he called 621-B. Further studies were undertaken by James Woodford and Hideyoshi Nakamura, which completed in 1966, proposed using four satellites. The use of four satellites would mean that the receivers no longer needed to be equipped with high-accuracy clocks. This was the first step in reducing the size and cost of the receivers. Aerospace (2021)

There was a range of technological advancements that help progress the satellite navigation systems such as new bandwidth utilization techniques, advancements in computers and the introduction of solid-state microprocessors. These technological advancements helped reduce the size and weight of the GPS receivers to what we now know today. Figure 2.1 shows how large and cumbersome the early GPS receivers were. However, one significant technological advancement was the development of atomic clocks. This development led to another satellite navigation system known as Timation (Time Navigation). The third of three Timation satellites launched in 1974, became the first satellite equipped with an atomic clock, the previous two contained crystal oscillator clocks. The use of the atomic clock led to vast improvements in the accuracy of the navigation system and provided three-dimensional location coverage. Aerospace (2021)

There were now three satellite navigation systems, and so when in the 1970s, the Department of Defence wanted a robust and stable system, the project team developed a new concept by cherry-picking the best aspects of all three, Transit, Timation and 621-B. This system was designated, Navigation System with Timing and Ranging (NAVSTAR), this was later changed to GPS I, the precursors to the GPS system we know today. The first NAVSTAR satellite was launched in 1978 and further satellites were launched in the following years, the system reaching its fully operational state with 24 satellites in 1993. Mai (2017)

Although the satellite navigation systems were operational and orbiting the earth, they were still used mostly by the military and the receivers were expensive. However, this began to change in 1983 when President Ronald Reagan authorized commercial airlines use of the NAVSTAR system. This was the start of civilian use of GPS. His (2011)

2.2.2 Modern GPS

The cost of GPS receivers began to decrease in the late-1990s, early-200s, the first cell phone containing GPS technology was released in 1999. The cost reduction can be attributed to the American government approving more non-military signals as well as the technological advances in processors that was leading to cheaper processing chips. And naturally from the cheaper access, GPS use began to grow, putting more tax on the system which although upgraded to GPS II was not equipped to handle the modern requirements. In 2000 a plan was formed to add new signals to satellites that had not yet been launched in order to handle the increased use. Furthermore, a new system was to be developed, GPS III, that could fully meet the modern requirements. The first of the GPS III satellites was launched in 2018 with a couple more in the following years and the remaining 6 to be launched by 2023. Aerospace (2021)

2.2.3 How GPS works

There are a total of 31 GPS satellites currently sitting in a medium earth orbit. These are the satellites that are sending the radio signals that a GPS receiver can use to determine its location.

The signal that the satellites broadcast has a range of information that is used by receivers. This information contains data needed to determine the location of the satellite as well as the time that the signal broadcast, using the satellites atomic

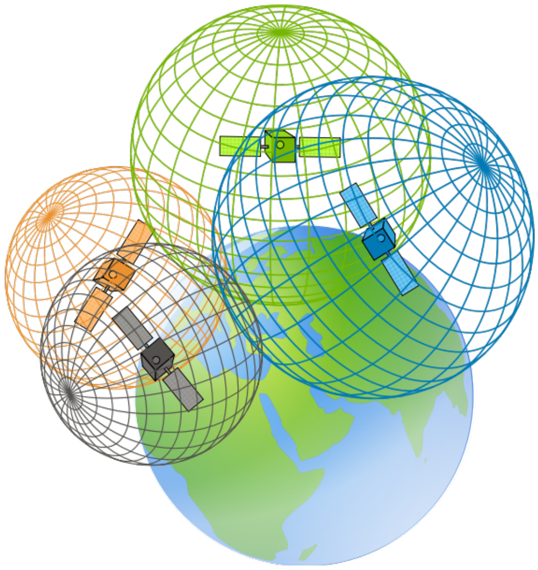


Figure 2.2: Distance spheres around each satellite intersect at one point

clock. Based on the time taken for the signal to reach the receiver and corrected for propagation delays or delays from the signal passing through the ionosphere and troposphere, the receiver can calculate the distance between itself and the satellite. This creates a sphere around the satellite upon which the receiver must lie. By adding in a second and third satellite and their distance spheres, there will be only two points of intersection between the three spheres. The one will be the receiver's location, while the other will be impossible location in space. However, to accurately calculate the distance, the receiver would have to have a synchronized atomic clock to determine exactly how long the signal takes to reach it. As it was mentioned earlier, highly accurate clocks were taken out of the receivers by adding a measurement from a fourth satellite to ensure that the distance calculation is accurate. Figure 2.2 illustrates the concept of the distance spheres and their intersection being the location of the GPS receiver. (Federal Aviation Administration)

2.3 Digital Compass

Compasses have been used extensively over the past centuries for navigating, surveying, and map-making. The compass is thought to have been in use from around the 12th century in Europe and possibly earlier in east Asia Jones (2019). Although as many things have over the years been digitalized, so has the compass. The digital compass uses a technology called magneto-induction. This allows the digital

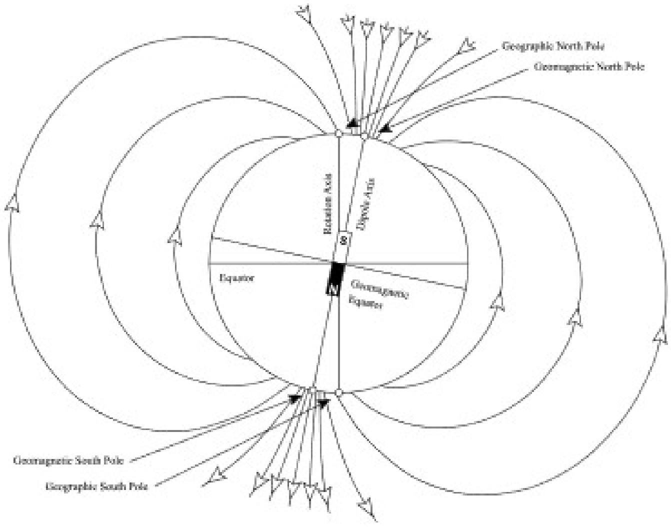


Figure 2.3: The differentiation between magnetic and true north

compass to electronically detect the earth's magnetic field. Being as sensitive as it is, an embedded microcontroller is needed to filter out any magnetic fields from ferro-magnetic materials or other electrical systems that are creating a magnetic field. (Advanced Safety Devices) (2013)

2.3.1 What is magnetic north

True north is always fixed and is the direction that is directly in line with the north pole. However, compasses do not point to true north, they point to magnetic north. This is because a compass aligns itself with the magnetic field caused by the earth's magnetic core. The deviation between true north and the magnetic field at magnetic north is shown in figure 2.3. To further complicate the matter however, the earth's magnetic core experiences changes and these cause small shifts in the magnetic field around the earth which alters the deviation between true north and magnetic north. Jones (2019)

2.4 PWM

Pulse Width Modulation (PWM) is a technique of using a digital signal to represent an analogue signal which is used to control analogue systems. The cost of switching a digital circuit between on (high) and off (low) is a cheaper alternative to creating an analogue circuit that will incur no drift over time. These PWM signals are

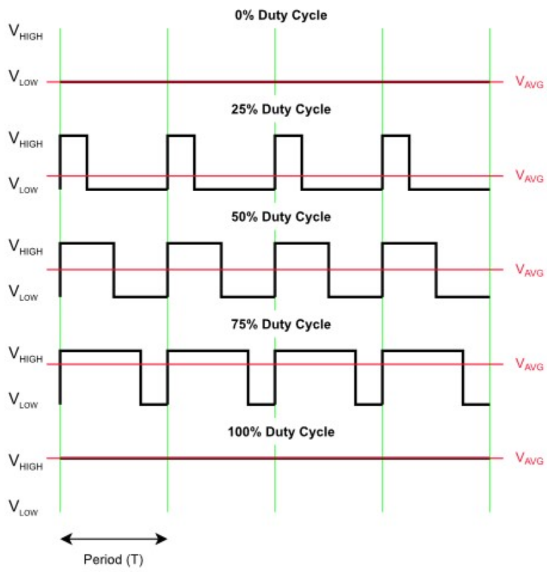


Figure 2.4: Duty Cycle of PWM Signal

mostly used in speed control of DC motors or controlling the brightness of light bulbs. Christ and Wernli (2014)

PWM is a digital signal that is switched between high and low, leading to the generation of a square wave signal. The time that the signal goes high can be modulated to vary the power delivered to the system. Typically, microcontrollers are used to generate and control the PWM to power an external system. There are a few signal parameters that will be highlighted in this explanation of a PWM signal.

The signal amplitude: This is the maximum voltage that can be supplied to the external system. If the microcontrollers output voltage is insufficient for the external system, the signal can be passed through an amplifying circuit to provide the required voltage.

The signal period: And therefore the frequency as they are inversely proportional, is the total time for one signal wave to propagate. The frequency is set depending on the requirements of the system, but this frequency will be needed later to help with the calculation of the duty cycle.

The duty cycle: The ratio between the time the signal is high and the time the signal is low. It is always a value between 0 and 1, however, the duty cycle is often expressed as a percentage.

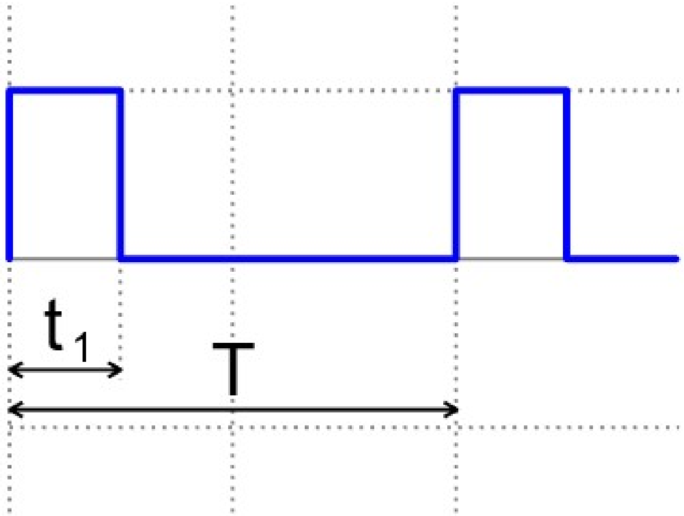


Figure 2.5: The relation between the time the signal is high and the signal period.

A PWM varies the voltage supplied to the system by varying the duty cycle. A small duty cycle means that the signal is high for a short portion of the signal period while a large duty cycle means that the signal is low for a large portion of the signal period. The system that is being supplied with power then uses the average voltage of this period. Therefore, a low duty cycle, a short high signal followed by a long low signal, would lead to a low average voltage. The variation in duty cycle and the associated average voltage is shown in figure 2.4. Ibrahim (2014)

To determine how long the signal must go high, the duty cycle is multiplied by the signal period. The duty cycle is often expressed as a percentage and so the duty cycle is the percentage of time that the signal is high. Therefore, by multiplying the duty cycle with the period gives the time for which the signal is pushed high (t1). Figure 2.5 shows the relationship between t1, the time the signal is high, and T, the signal period.

2.5 Analogue vs Digital Signals

Signals are used to convey data and information from point to point. For this project only electrical signals will be used although there are plenty of other mediums through which signals can be sent. There are two predominant signals that are used when regarding electrical signals, analogue and digital.

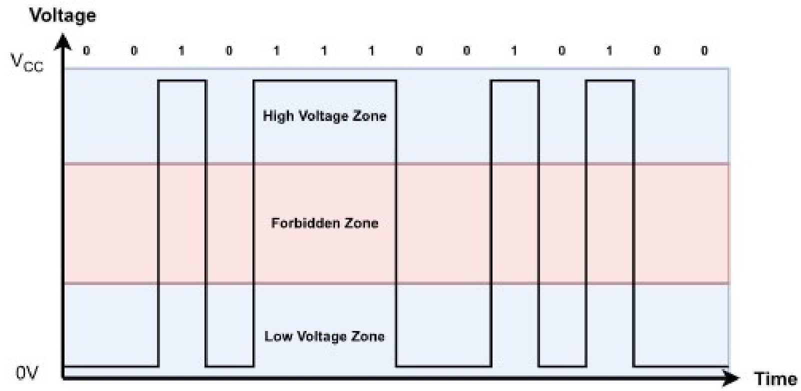


Figure 2.6: A digital signal and its three zones.

A digital signal, most simply represents discrete values, more precisely 2 discrete values. This makes digital signals perfect for conveying data in a binary data format but slightly more troublesome when more than two values are required. It will transmit a signal as either a low voltage, a zero, or a high voltage, a one. The low voltage is generally 0V while the high voltage is the voltage supply of the driving device. However, because voltages can have small fluctuations and will therefore not always be exactly 0V or equal to the nominal voltage, a range is pre-set whereby the receiving device can denote the value as low or high. A buffer zone is also incorporated, a voltage range around half the value of the nominal voltage, to prevent a small fluctuation in the voltage possibly altering the value of the signal. This buffer zone along with the area in which the signal can be read as high or low is shown in figure 2.6. This buffer is called the forbidden zone and any signal received within the forbidden zone is considered floating and will be randomly assigned as either high or low.

An analogue signal on the other hand is continuous and where the digital signal ranged from 0 to an upper voltage, an analogue signal ranges from a low voltage to a high voltage. Typically, $\pm V_C C$, the voltage of the microcontroller, is used for these upper and lower limits. An example of a continuous analogue signal between $\pm V_C C$ is shown in figure 2.7. An analogue signal can therefore transmit an infinite number of values between these limits. By assigning an upper and lower limit to the sensor that will transmit the data, a max min transformation can be computed, and the transformed value transmitted along the analogue signal. Because the analogue signal is continuous, it can also be used in tracking the change in a value over time by computing the integral of the signal wave.

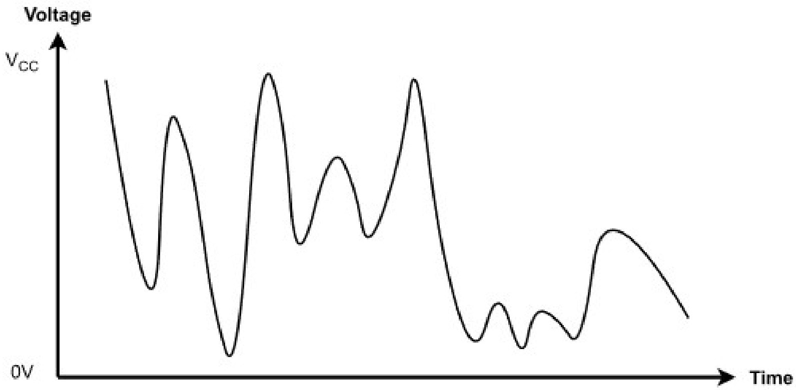


Figure 2.7: Analogue signal

Chapter 3

Methodology and Design

This chapter will describe the methodology used in the project. Firstly, it gives a general description of the system and how the components relate to each other and where they are on the system. This broad overview is to create a point of reference so that in later sections the specific details of the system can be discussed without spending too much time on the broader aspects. A brief discussion on the software enviroment is also included to provided a justification for the use of the chosen enviroment. Finally, the chapter will go into the design of the system. The design will discuss the objectives and requirements and then move onto the specifics of the hardware, electronics, software and the control system. The focus of this project is the control system and so the hardware discussion will focus on how it is relevant and how it is integrated with the system. The electronics form integral parts to the control system and so they are discussed in further detail and finally the software and control system are the focus of the project and will be described in full.

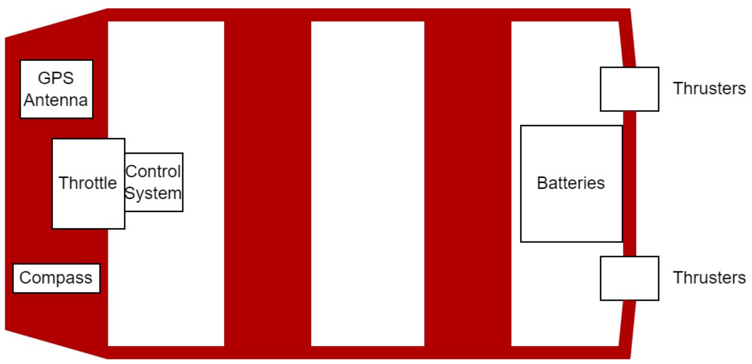


Figure 3.1: Broader System Diagram

3.1 System Description

This section will give a broad overview of the system as a whole and provide a reference of how the individual elements fit together both in the broader system and the narrower control system. The broader system is shown in Figure 3.1 and shows the vessel and the positions of the thrusters, batteries, control system throttle and mounting of the GPS antenna and compass. The control system refers to the 'motherboard', a PCB containing the microcontroller and other electronics including the GPS, SD module, logic level converter and the control box of switches and display LEDs. The wiring diagram of Figure 3.2 shows the PCB as a grey dotted line. The control box is shown outside of the PCB as it has its own housing but is affixed to the control system housing and is therefore considered part of the control system. Figure 3.2 also shows the wiring to the other elements that can be seen on the broader system diagram of Figure 3.1.

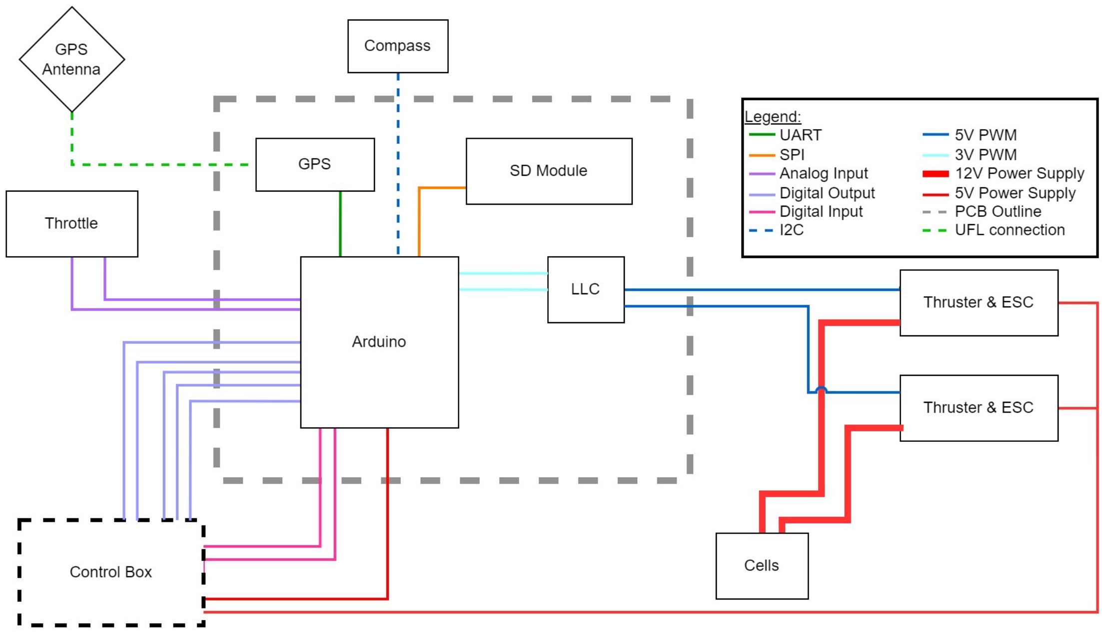


Figure 3.2: Wiring Diagram for the System

3.2 Software Environment

The microcontroller that was chosen for this project is an Arduino DUE. An Arduino microcontroller was chosen for the wide range of Arduino libraries available online, as well as several forums and code examples. Furthermore, the Arduino environment uses the C language which has been extensively covered through the course of the engineering degree.

3.3 System Design

3.3.1 Objective

The system needs to be designed to be deployed for long periods of time between services. The future addition of power regeneration such as solar or wind can be used to improve the deployable range and period of the vessel, but the energy storage must be designed to handle an extended period of 'dark time', any time when the power regeneration is negligible.

The vessel must be autonomous and, having received a set of navigation points before deployment, navigate between these points until retrieval. Even under non ideal circumstances the vessel should be able to correct its course and continue to navigate to the set navigation points.

This system is a proof of concept that is designed to be able to be sized up to a larger vessel. Therefore, the prototype vessel should be able to handle any conditions that could be encountered in testing and all electronics should be sufficiently sealed so that no damage is incurred. It is not expected that the prototype vessel would be able to handle rough and storm weather conditions.

3.3.2 Engineering Requirements

The prototype is a proof of concept that can be scaled up to a larger vessel and so a small vessel that can accommodate at least two people is required. This is preferred to a smaller vessel which cannot accommodate the weight of a person as the weight to power ratio of a small vessel could have an adverse effect on the steering capability of the vessel and therefore the control system. Furthermore, a working vessel is going to require a large battery bank and this is easily accommodated in a larger vessel. The energy source can then be scaled up by adding cells in both parallel and series to create the required power supply for the working vessel.

The autonomous nature of the vessel means that an electronic control system is required to control the vessel. There are other elements that are required to make up the system, however these are not integral to the autonomous nature of the system but integral to the entire system.

Figure 3.3: The vessel, a Spider 3.

3.3.3 Hardware

Vessel

The vessel is outside the scope of this project as it was acquired before the start of the project. The project was designed around the use of the vessel for testing only as in actual use a vessel would be used that could handle severe weather conditions and hold an array of sensory equipment. The vessel pictured in Figure 3.3 is a Spider 3, a small single hulled fibreglass boat. The vessel measures $1.3\,\mathrm{m} \times 3.2\,\mathrm{m}$ and is rated to carry four people and a 15 Hp traditional outboard motor.

Thrusters

The thrusters are electrical and a complete unit together with the ESC, and all the electronic interfacing to drive the thrusters is accomplished through it. The ESC is described later in the report. Therefore, the thrusters are considered general hardware and are there only as a means of testing the control system. They are outside the scope of the project as they were acquired prior to the start of the project, but are integral to the performance of the overall system.

The propulsion system consists of two electric thrusters mounted at the back of the vessel. These thrusters are each capable of producing up to 18 kg of thrust. An aluminium mount designed and manufactured by the Stellenbosch University Electrical Engineering workshop allows for the thrusters to be raised during the launching and retrieval of the boat to avoid fouling on the trailer. The mounts are removable and are removed for transport. Each thruster has an integrated ESC that regulates the power supplied to the electric motor and therefore the thrust provided.

Power Supply

The initial design was to use a bank of four Lithium Iron Phosphate (LiFePO) cells to form a 12 V battery. This was also procured before the start of the project. However, upon testing, it was seen that 12 V was not enough voltage to provide the thrusters with enough power to move the boat at a reasonable rate. Each cell has a voltage of 3.3 V and a capacity of 100 A h. Therefore, the next course of action was to source more cells and increase the size of the battery. However, due to the high cost of these cells and a lack of suppliers this was not plausible. LiFePO cells are expensive because they are designed to have a deeper life cycle than standard lead acid cells. These cells in particular were also expensive due to their large capacity.

Therefore, the decision was made to change the power source to a battery consisting of two lead acid cells in order to test the control system. The lead acid cells were each 12 V and had a capacity of 50 A h. A lead acid battery can generally be drained to about 80 % capacity without doing much damage to the cell, a LiFePO cell has a deep cycle of about 40 %-50 %. Therefore these cells would be used for short tests and recharged between tests. However, for a working system it would be recommended that a large LiFePO battery bank were used.

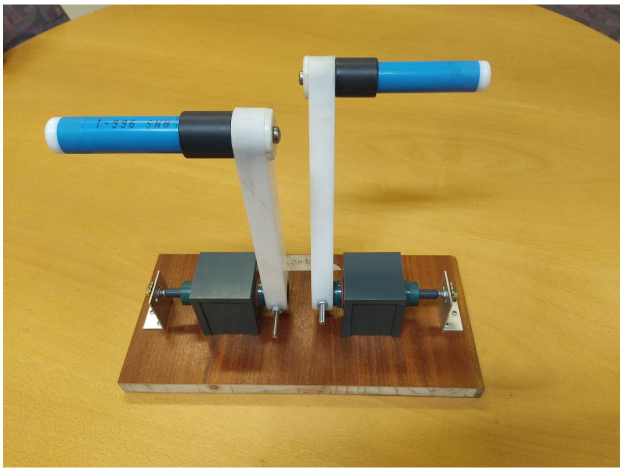


Figure 3.4: Final throttle system with two potentiometers (POT) on either end.

Throttle

The initial concept was to purchase two throttles capable of moving independently from each other and two electronic throttle levers were purchased to be used. However, when these components arrived, they were much smaller than they had appeared and had a very small range of movement. An alternate solution was designed consisting of two throttle arms that could each turn a shaft. These shafts were then connected to a linear potentiometer which would provide the required analogue input from the throttle. The throttle is shown in Figure 3.4. An initial concept design was given to the electrical engineering department who then refined and manufactured the design.

3.3.4 Electronics

Arduino Due

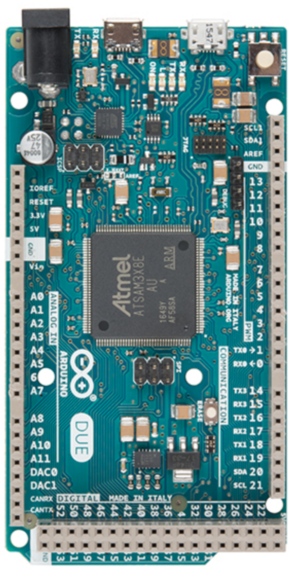


Figure 3.5: The microcontroller used: an Arduino DUE

The microcontroller was selected by considering the initial design and possible peripherals that would be used in the system. The minimum requirements for the microcontroller to be used are as follows, with regard to the peripherals of the GPS, SD card modules, the ESC and POTs as well as several inputs and outputs:

1. 2 PWM pins.
2. Voltage regulators of 3 V and 5 V.
3. 5 digital IO pins.
4. 4 analogue input pins.
5. 1 SPI connection.
6. 1 UART connection.
7. 1 I^2C connection.
8. 256 kB programmable flash memory.

Based on these requirements, the Arduino Uno was considered. It is the standard Arduino board used in projects and meets most of the minimum requirements for the project. However, the Arduino Uno has only one UART connection and does not allow for any possible design alterations that might need a second UART connection. Finally, the Arduino only has 32 kB of programmable flash memory which does not meet the requirements.

The next consideration was the Arduino DUE. This has 4 UART connections, plenty of digital IO pins and several analogue inputs. This offers a range of versatility to any design progression or alterations that might occur. Furthermore, the DUE has 512 kB of programmable flash memory which is double that of the minimum requirement. The one flaw with the Arduino DUE is that its IO pins operate at 3.3 V as opposed to the generally standard 5 V. However, this was easily overcome by implementing a logic level converter to shift the required signals to 5 V while keeping the signals' shape. Keeping the signals' shape is particularly important for the PWM signal controlling the ESCs. The final microcontroller selected was the Arduino DUE.

SD Card Module

The SD card is used as an external storage device. Data can then be written to the SD card during operation and the data can be downloaded for analysis. The SD card module is a standard SD card module that is attached to the microcontroller as shown in the wiring diagram Figure 3.2. The SD card uses SPI communication and there are built-in libraries that are available for use.

GPS Module

Initially a PmodGPS was used as the GPS module. However the PmodGPS has a built-in antenna and there were signal strength issues. The GPS was slow at acquiring a GPS fix when the control box was closed. Therefore, an alternate GPS module with an external antenna was sourced. The antenna can be fed out of the control box and positioned where a strong signal can be received. Both GPS modules use UART to communicate the data to the microcontroller. The GPS modules send a string of characters along the UART connection, and the microcontroller must then decode the characters. The GPS module transmits the current longitude, latitude, date and time and speed of the vessel to the microcontroller. The UART is set-up to use a baud rate of 9600, 8 data bits, no parity and 1 stop bit. It has two connectors J1, which has 6 pins and J2 which has 2 pins. J1 is used to power the GPS module as well as connect to the MCU using UART communication.

Compass

The digital compass used can be more accurately referred to as a magnetometer. The module used in this project, a Pololu LSM303 shown in Figure 3.6, is a combination magnetometer and accelerometer, however only the magnetometer is used. Pololu has a range of Arduino libraries including a compass library for the LSM303 which is used to calibrate the module and to get an accurate compass bearing.

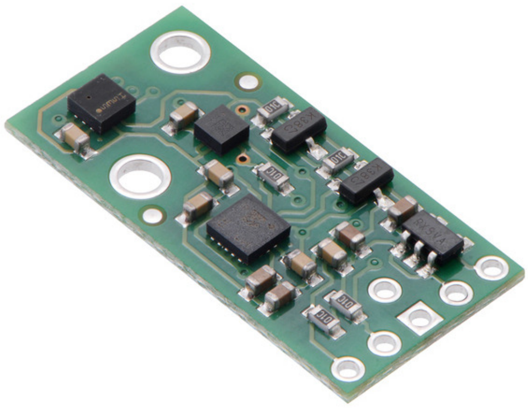


Figure 3.6: Pololu LSM303 AltIMU module.

ESC

There are two ESCs, one for each thruster and are submersible. The ESC has two inputs, the control input, and the power input. Th power input can range between DC 12 V and DC 50 V and a maximum constant current of 100 A and in this project the input is 24 V supplied by the battery cells. The control input is a 5 V signal that is used to control the speed of the thrusters. This is a PWM signal whose duty cycle determines the thrusters RPM and therefore the speed and direction of the vessel.

POT

Table 3.1: The digital values of the ADC used to calibrate the physical limits and neutral range of the throttle potentiometers.

Throttle Position	**Left POT**	**Right POT**
Full Forward	655	720
Neutral	440	505
	485	572
Full Reverse	285	352

The POT is a standard 10 kΩ potentiometer that has three pins as shown in Figure 3.7: high voltage, ground, and output. The high voltage and ground are connected to the outer pins on the POT and the output is connected to the centre pin. As the shaft of the potentiometer is rotated, the resistance varies from almost no resistance to the full 10 kΩ which causes the voltage to vary from input, 3.3 V to an almost ground voltage, 0.1 V.

The output is connected to analogue input pins on the microcontroller which uses an ADC, with a 10 bit resolution, to convert the signal to a value between 0 and 1024. However, the potentiometer has a 300° range of motion but the throttle has approximately 150° range of motion. The software can correct for the difference by determining the total maximum and minimum range of motion of both throttle levers while in operation. The forward range is set between an offset middle point and maximum range for each device. Similarly, the reverse range is set between the offset middle point and the minimum range for each device. This offers a neutral range buffer to make the throttle easier to use i.e. the controller can be placed in the neutral position by returning the lever to the general neutral position. The extents of the measured forward and reverse ranges are listed in Table 3.1.

Switches and LEDs

The control box shown in Figure 3.9 consists of 3 switches and 5 state display LEDs. Two of the switches are configured using pull down resistor configuration with the output of the pull down circuit connected to a digital input on the microcontroller. The LEDs all use simple LED circuits driven by the digital outputs of the microcontroller. The final switch, the power switch, is wired to cut-off the 5 V power supply to the microcontroller. The control box circuit is shown in Figure 3.8 and can also been seen in the overall wiring diagram of the system in Figure 3.2. A description of each switch and LED is given in Fable 3.2.

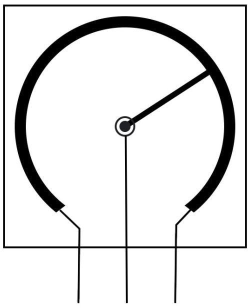


Figure 3.7: Simple illustration of a linear potentiometer

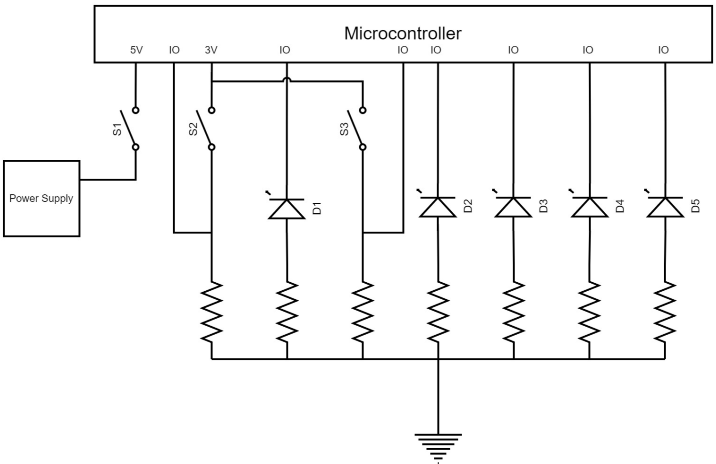


Figure 3.8: The wiring circuit inside of the control box.

3.3.5 Software

PWM Signal

The thrusters are each controlled by a 5 V PWM signal. There is limited information on the datasheet for the ESC. The signal boundaries, full forward, full reverse and neutral positions are described in the unconventional terms of the time that the signal is high. The values are shown in Table 3.3. Initially it was thought that the ESC operated at 50 Hz, however there was no response from the thruster at any duty cycle when using this frequency.A PWM signal generator IC, shown in Figure 3.10, was connected to ESC to ensure the correct PWM signal was being sent through and to quickly vary both the frequency and the duty cycle. Trial and error later determined that the ESC began responding to a signal above 60 Hz. It was then decided to push the frequency up to the maximum of 500 Hz as this offers the finest control because it has the maximum allowable duty cycle difference between the signal boundaries.

Figure 3.9: The control box with its 3 switches and 4 LEDs.

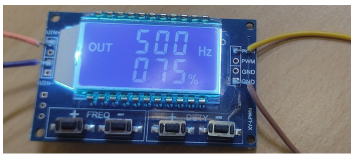


Figure 3.10: The PWM signal generator used to ensure the ESC was working.

Table 3.2: Description of the switches and LEDs on the control box.

Component	Designation	Description
Power Switch	S1	This switch is used to cutoff the power being supplied to the microcontroller.
Navigation Mode Switch	S2	This switch allows the user to quickly switch between the manual navigation mode and the autonomous navigation mode.
Calibration Switch	S3	This switch is used to put the system into compass calibration mode.
On LED	D1	This LED indicates that the microcontroller is powered on.
Active LED	D2	This LED blinks on and off during the operation of the program and indicates that the program is alive and active and there has not been a crash in the program.
GPS LED	D3	This LED is turned on when GPS has a valid connection.
M LED	D4	This LED indicates that the system is in manual control mode.
A LED	D5	This LED indicates that the system is in autonomous navigation mode.

Table 3.3: ESC boundaries and PWM duty cycle at various frequencies.

Position	Time (µs)	Duty Cycle @		
		50 Hz	60 Hz	500 Hz
Full Forward	2000	10 %	12 %	100 %
Neutral	1500	7.5 %	9 %	75 %
Full Reverse	1000	5 %	6 %	50 %

The Arduino libraries contain a function, *analogueWrite(value, pin)*, which takes the duty cycle and the output pin as parameters. This will output a PWM wave of the given duty cycle on the given pin. However, the default frequency of the Arduino DUE PWM pins is 1000 Hz. Therefore, the frequency had to be manually changed by changing the timer settings driving the PWM signal.

The information needed to change the timer settings is available in the Arduino Datasheet. The process to configure the PWM outputs is as follows. First, the peripheral clocks for timer channels 6 and 7 were enabled. Secondly, the pins' input-output controller on peripheral A needed to be disabled and the pins switched to peripheral B. Then came the configuration of the timer itself. The channel mode was set to waveform mode using clock 1 with the timer counter being incremented on the rising edge. Furthermore, the waveform was set to UP mode (signal is set high) being triggered when the counter reached the register C (RC) value and the signal being cleared when the counter reached the register A (RA) value. Once the timer is configured, values can be assigned to the RA and RC values, and the interrupt set to trigger when the counter reaches RC. Finally, an interrupt handler needs to be added to read the status register, since the flags in the status register are automatically reset when it is read at the end of every period.

The signal is cleared when the counter reaches RA and set high when the counter reaches RC. Therefore, RC can be equated to the period of the signal and RA to the time when the signal is high. Since the clock is set to clock 1 which is the MCU clock (MCK) divided by 2, and by using the above comparison, the RA and RC can then be expressed in terms of MCK, frequency and duty cycle, as shown in Equations 3.1 and 3.1. RC is kept constant throughout while RA is changed to adjust the duty cycle of the PWM signal sent to the ESC, thereby controlling the ESC and thrusters.

$$RC = \frac{\frac{MCK}{2}}{Frequency} \tag{3.1}$$

$$RA = RC \times DutyCycle \tag{3.2}$$

Analogue to Digital Converter

As mentioned previously, the ADC is used to convert the analogue signal from the potentiometers connected to throttle to a digital signal between 0 and 1024. Furthermore, using Table 3.3 and Table 3.1 a relationship can be created to determine the RA value for a given throttle position. Because the forward operation is in the duty cycle range 75 % to 100 %, the analogue input from the POT needs to be linearly mapped to represent an equivalent duty cycle in this range. Equation 3.3 shows how this is done for the forwards operation. The same logic can be used to determine the duty cycle for reverse as Equation 3.4 shows. For neutral however, the RA value needs to be exact, but this is difficult to achieve using the throttle, therefore, a neutral range is used on the potentiometer whereby any value in the range will be seen as neutral and the neutral value will be written to the RA register.

$$DutyCycle_{Forward} = 100 - (100 - 75)\left(\frac{POT_{MAX} - POT_{Input}}{POT_{MAX} - POT_{Neutral}}\right) \tag{3.3}$$

$$DutyCycle_{Reverse} = 75 - (75 - 50)(\frac{POT_{Neutral} - POT_{Input}}{POT_{Neutral} - POT_{MIN}}) \quad (3.4)$$

GPS

The GPS module transmits a series of five sentences containing various information. Each sentence begins with a '$GP' and then the specific message ID. The data is then sent through comma separated and finally ends with a checksum at the end of line characters <CR><LF>. For this project the Recommended Minimum Specific (RMC) sentence is the only sentence of interest as it contains all the necessary information: longitude, latitude and speed over ground in knots. An example of the RMC sentence is shown below.

$GPRMC,064951.000,A,2307.1256,N,12016.4438,E,0.03,165.48,260406,3.05,W,A*55<CR><LF>

The entire sentence is read by the MCU before it starts to pick the specific data out of the string using the commas and full stops as the guide to which array position is which data. The latitude and longitude are given in the format 'DDmm.mmmm' and must first be converted to decimal degrees as this is easiest to use in calculations. The Equation 3.5 shows this conversion. Each piece of data is then added to an instance of a GPS structure that can then be easily parsed to the navigation algorithm and analyzed. The variables within the GPS structure are shown in Table 3.4.

$$DecimalDegrees = Decimal + \frac{Minutes}{60} \quad (3.5)$$

Table 3.4: Variables and their types within the GPS structure.

Name	**Type**	**Description**
UTC	int	Coordinated Universal Time in the format (hhmmss).
latDecimal	int	The decimal portion of the latitude.
n_s	char	A character indicating North or South.
longiDecimal	int	The decimal portion of the longitude.
e_w	char	A character indication East or West.
knots	float	The speed over ground in knots.
course	float	The course over ground in degrees.
date	int	The date in the format (ddmmyy).

Compass

There was very little software to develop for the compass as there are extensive Arduino libraries which were used. The code used to calibrate the compass and to get the compass heading was all derived from the relevant calibrate and heading example projects provided by the libraries.

3.3.6 Control System

The control system is the scope of this project and the part of the project that should not require much alteration to scale the system up to a larger system. The control logic is all implemented through the software on the microcontroller. This section will detail the control logic with the aid of flow diagrams and pseudo code.

State Machine

Algorithm 1 State Algorithm

Require: Declare variables and initialize PWM, SPI, I^2C and UART.

```
loop:
if manual control = true then
    call updatePWM()
    call powerThruster()
else
    call receivedGPSdata()
    if GPS data is valid then
        call navigate()
    else
        Delay 1 second
    if Last point has been reached then
        Halt receiving GPS data
goto loop.
```

The system makes use of a state machine to switch between tasks. There are four different states in which the system can be, waiting for valid GPS, manual navigation, autonomous navigation and halt. Figure 3.11 shows the relationship between these states. The algorithm shown is executed in the main while loop of the microcontroller and shows one cycle. The loop starts by checking the user input. The user can select to switch between the manual and autonomous operation at any point. However, if autonomous navigation is selected and the GPS data is

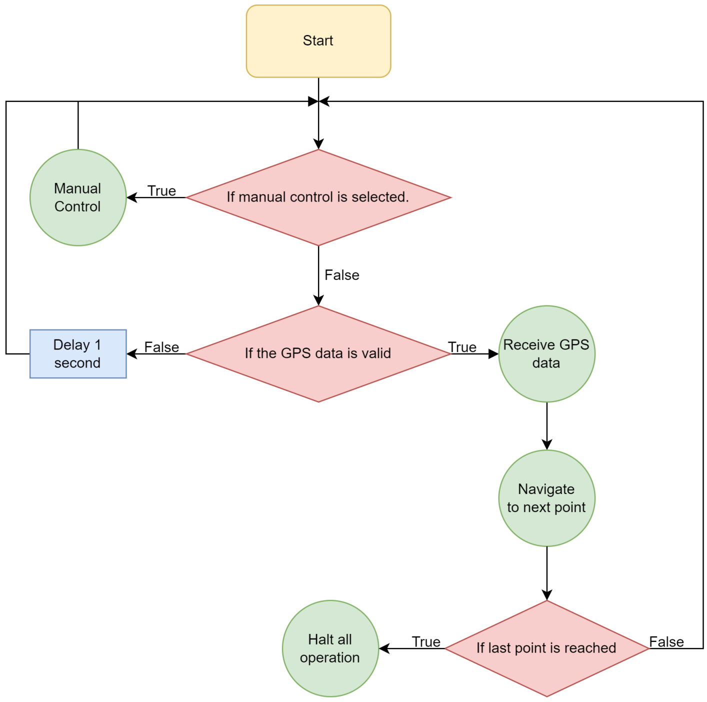


Figure 3.11: Flow diagram of the main states in the system.

valid, the system will only enter manual control once the cycle has been completed. The psuedo code for this loop is shown in Algorithm 1.

Manual Control

The manual control involves receiving an input from the user and translating this to correctly power the thrusters. As seen in Algorithm 1, the manual control involves the call of two functions: the first where most of the processing is done and the second is updating the RA register to produce the correct PWM signal. Firstly, the flow diagram of the first one, *updatePWM()* is shown in Figure 3.12. This shows the process to read one side's input and calculate the required duty cycle for that side's thruster. This is carried out for both sides in each cycle. As mentioned, the second function *powerThruster()* simply writes the required value to RA register for the appropriate duty cycle. The psuedo for both functions are shown in the Algorthim 2.

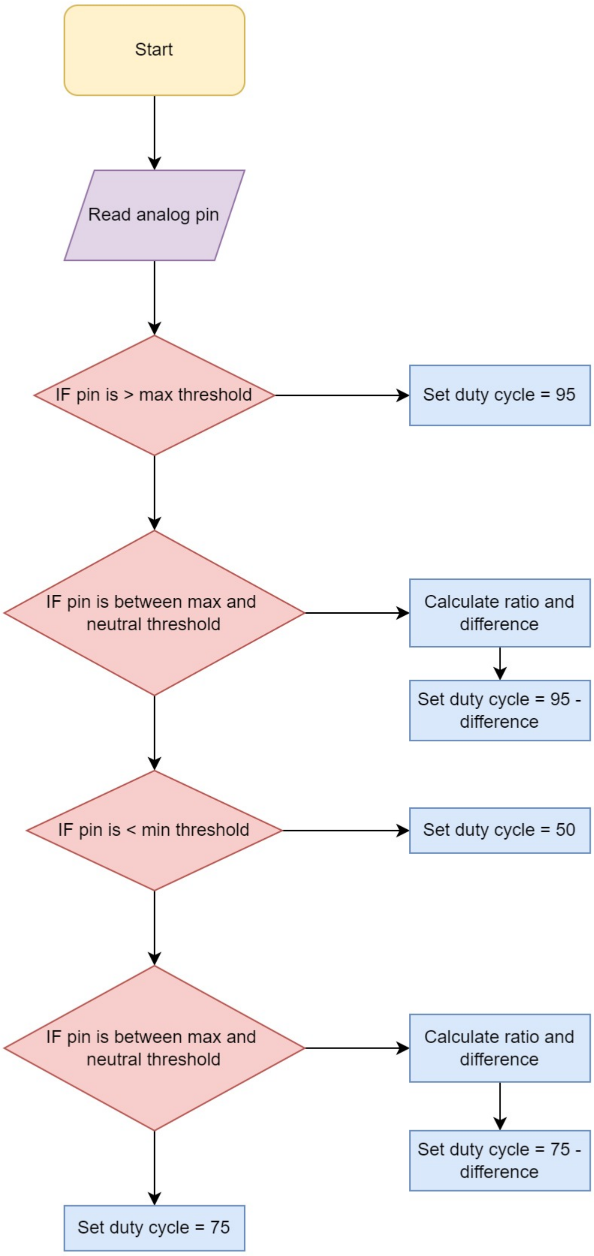


Figure 3.12: Flow diagram of *updatePWM()*.

Algorithm 2 Pseudo code for manual control

```
procedure updatePWM
    analog ← analogRead(analogPin)
    if analog > maximum threshold then
        duty cycle ← 95;
    else if analog > neutral threshold then
        analog ratio ← ratio forward (equ. 3.3) as float
        difference ← (95 − 75) × analog ratio as float
        duty cycle ← 95 − difference
    else if analog < minimum threshold then
        duty cycle ← 50;
    else if analog < neutral threshold then
        analog ratio ← ratio reverse (equ. 3.4) as float
        difference ← (75 − 50) × analog ratio as float
        duty cycle ← 75 − difference
    else
        duty cycle ← 75;
procedure powerThrusters
    RA ← RC × duty cycle%;
```

Receiving GPS Data

The GPS data is received with serial UART communication and is a string of characters as shown previously. To receive the correct data line, the microcontroller receives each line and then checks that it is the required line. Given the required line, the line is processed and the struct is updated with the newest data. A few small tools were written to assist in this. They are all relatively simple and so their pseudo is unnecessary but a brief description follows for context.

findAllInstacesOf()

This function takes an integer array, a character array to search, a character to search for and the size of the character array to search as parameters. It returns the integer array with the index positions of the character searched for.

charToInteger()

This function takes a character array and a start and end index as integers. It returns an integer as it would be seen as the character string. For example, the character string '4862' would be returned as 4862 as an integer.

charToDecimals()

This function is similar to the integer version but it returns a float with the numbers as the decimals. For example a character string of '4862' would be returned as 0.4862.

The overall process to receive the GPS data and populate the struct is shown in the flow diagram of Figure 3.13. The struct is populated by using the two arrays, containing indexes full stops and commas indexes withing the character array, to split up the character array into the necessary information. This is easily done as the string from the GPS has a standard form.

Algorithm 3 Pseudo code for receiving GPS data

```
msgReceived ← false
rxCnt ← 0
while !msgRecieved do
    while rxByte! = 10 do
        rxByte ← SerialRead()
        if rxByte! = −1 then
            rxData(rxCnt) ← rxByte
            rxCnt ← rxCnt + 1
    if rxData(3) = 'R' AND rxData(4) = 'M' AND rxData(5) = 'C' then
        call updateStructRMC(rxData, rxCnt)
        msgReceived ← true
    rxCnt ← 0
    rxByte ← 0
```

Autonomous Navigation

The autonomous navigation will only begin executing when valid GPS data has been received. Therefore, there is no need to check the data when the navigation algorithm begins. The target points for the navigation are written into a text file prior to launching. The program reads these points into a struct at the start of operation to be ready for the autonomous navigation. The autonomous control calculates the distance and bearing to its destination and the error between its current bearing and its target bearing. If the distance and bearing error are above a set threshold, the system will move at full power using full steering. However, once it is within the distance threshold, it will begin to slow down proportional to how close it is. The amount of throttle as a percentage is determined by a ratio of the remaining distance and the distance threshold. Furthermore, once the distance is reduced below the arrival threshold, the point is marked as 'passed' and the system will begin navigating to the next point or halt operation if there are no more points. Similarly for the steering, the amount of steering as a percentage is a ratio of the bearing error and the steering threshold. Finally, the direction to steer in is determined using an equation that accounts for the 360°/0° turnover point. If

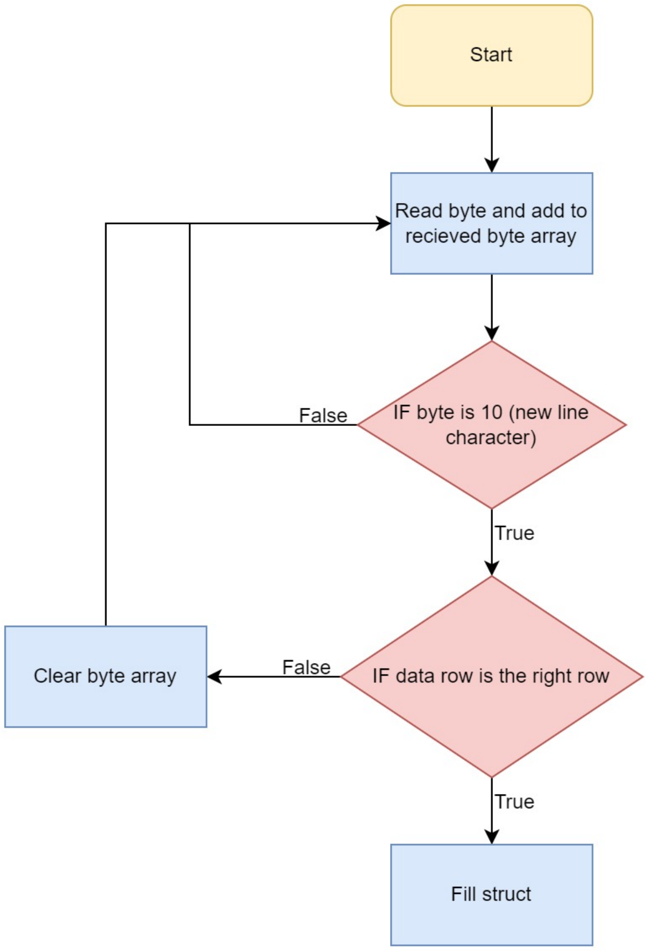


Figure 3.13: The flow diagram of receiving the GPS data.

the target bearing is anywhere within 180° to the right of the current bearing, it will turn right and visa versa. This logic and pseudo code can be seen in the flow diagram of Figure 3.14 and Algorithm 4. In the pseudo code only the procedure for *steerLeft()* is shown as the procedure for *steerRight()* follows the exact same logic but with the thruster sides inverted.

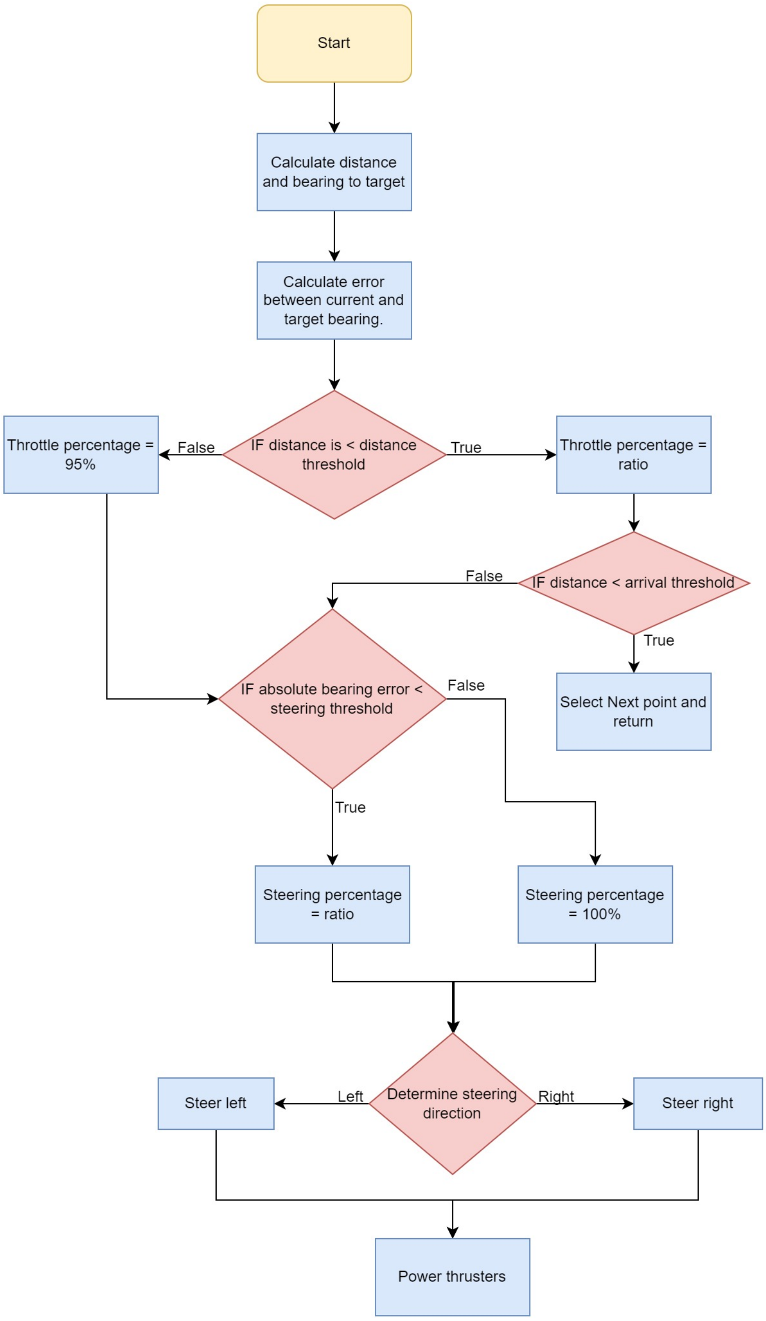


Figure 3.14: Flow diagram of the autonomous navigation

Algorithm 4 Pseudo code for the autonomous navigation

Require: Read the target GPS points from SD card.

procedure NAVIGATE()
    Calculate distance to target
    Calculate bearing to target
    Calculate the error between current and target bearing
    if *distance* < *distance threshold* **then**
        $\textit{throttle percentage} \leftarrow \frac{\textit{distance}}{2 \times \textit{distance threshold}}$
        if *distance* < *arrival threshold* **then**
            call NextPoint()
            return
    else
        throttle percentage ← 95
    if *abs(bearing error)* < *steering threshold* **then**
        $\textit{steering percentage} \leftarrow \frac{\textit{abs(bearing error)}}{\textit{steering threshold}}$
    else
        steering percentage ← 100
    maxBearing ← *max(bearing error, target bearing)*
    minBearing ← *min(bearing error, target bearing)*
    if $(\textit{maxBearing} = \textit{target bearing}) \textit{XOR} (\textit{maxBearing} - \textit{minBearing}) > 180)$ **then**
        call steerLeft()
    else
        call steerRight()
    call powerThrusters()
procedure NEXTPOINT()
    points(targetIndex).passed ← *true*
    targetIndex ← *targetIndex* + 1
    if *points.targetIndex does not exists* **then**
        state ← *Halt navigation*
procedure STEERLEFT()
    $\textit{throttle difference} = 2 \times \textit{throttle percentage}$
    $\textit{rightSide.duty Cycle} \leftarrow 75 + (25 \times (\textit{throttle percentage}\%))$
    $\textit{leftSide.duty Cycle} \leftarrow \textit{rightSide.duty Cycle} - (25 \times ((\textit{throttle difference} \times (\textit{steering percentage}\%))/100))$

Chapter 4

Testing and Results

In order to test the system a series of tests were conducted to test each system individually before the overall system was tested. The individual systems tested are the GPS and compass, the PWM output, throttle, and the individual thrusters. Finally the full system was tested on the Stellenbosch canoe dam.

4.1 GPS and Compass

The GPS and compass were tested on land. A baseline was established using a tracking application on a cellphone. The GPS and compass together with the cellphone were placed in a bag and a route was walked. The tracking data from both sources can then be downloaded and formatted as a Keyhole Markup Language (.kml) file and displayed on a map or plotted as has been done in figure 4.1.

In order to have a bearing to compare the compass reading with, the last two GPS points were used to calculate the bearin on which the vessel is pointing. Figure 4.2 shows the calculated bearing and the GPS bearing plotted together.

As can be seen in figure 4.1, the two sets of GPS data match each other very closely with only a few areas where the systems GPS moves away from the baseline GPS points. In order to quantify the accuracy of the GPS, the distance between the coinciding points of the baseline GPS and the system GPS was calculated and plotted on box and whisker chart of figure 4.3a. As you can see the GPS is accurate to within 5 m with only a few outliers, making up less than 4 % of the data, falling slightly outside the 5 m mark.

Similarly it can be seen on figure 4.2 that the systems compass bearing is closely following the calculated baseline bearing. Figure 4.3b shows a box and whisker plot of the error between the two bearings, with most of the data falling within a $20°$ range. There are more outliers than in the GPS test, however this is due to calculated bearing having several spikes. These spikes occur when the because the

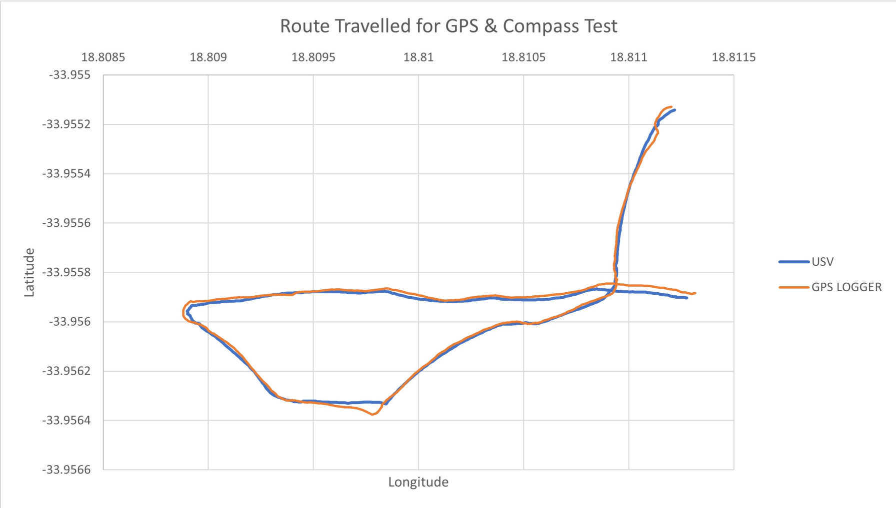


Figure 4.1: The path used to compare the system GPS and the baseline GPS logger.

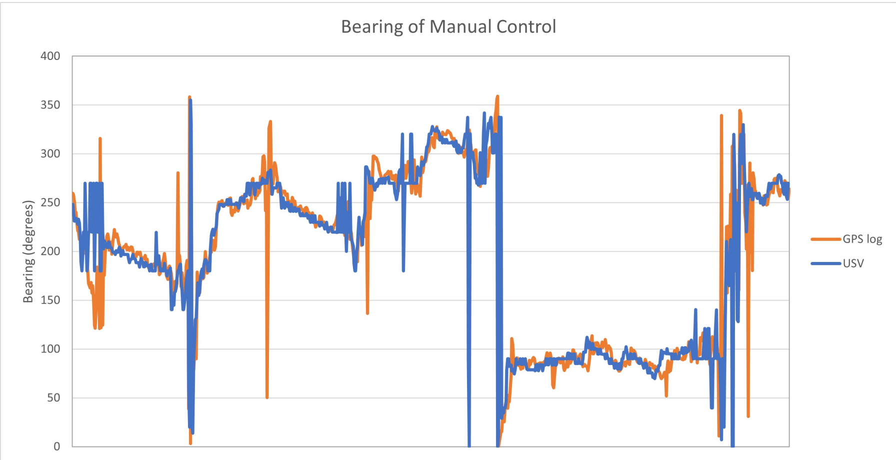
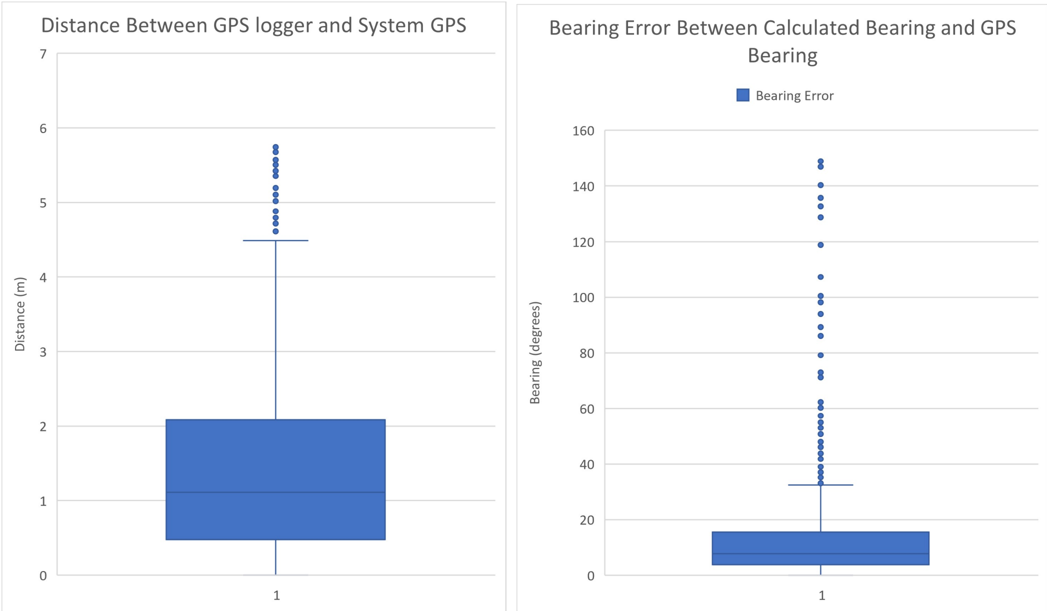


Figure 4.2: The calculated bearing and compass bearing overlay.



(a) Distance. (b) Bearing

Figure 4.3: Box and Whisker Graphs Of Distance and Bearing Between the System and the Baseline.

bearing is being calculated between GPS points that are often within 1m of each other and some accuracy can be lost. The noticeable spike of the system compass in figure 4.2 is not an error but caused by the bearing going around passed 360° to 0°.

4.2 PWM Output

In order to adjust the speed of the thrusters, the PWM output must vary based on the throttle input. The PWM signal can easily be measured using an oscilloscope, therefore the system was set-up as shown in figure 4.4. The throttle was connected to microcontrollers analogue inputs as it would be for the full system. The PWM outputs where then attached to the oscilloscope probes and the Arduino native programming port was used to power the system from a laptop. Each PWM signal was first tested individually before finally, both signals were tested simultaneously, each one on its own channel.

As the throttle is adjusted the PWM signal should vary. There are three distinct positions, full forward, neutral and full reverse. that can be noted in table 3.3.

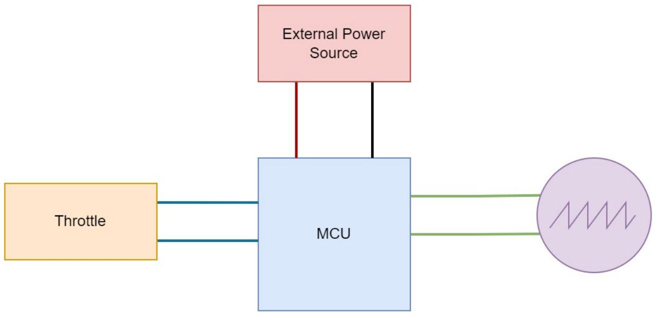


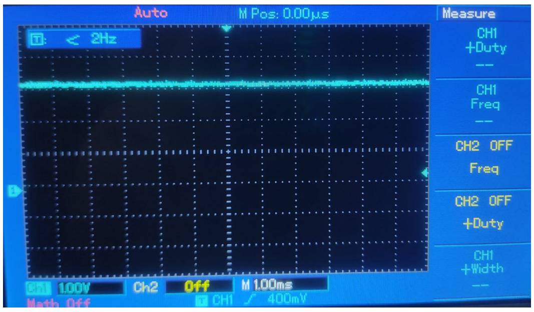
Figure 4.4: Wiring diagram for the PWM oscilloscope test.

Theses three positions were tested to ensure that the range of the throttle was correctly calibrated. Finally the PWM signal was observed while slowly adjusting the throttle to ensure that the PWM signal varied linearly and in with a timely response. The results of the oscilloscope test are shown in figure 4.5.

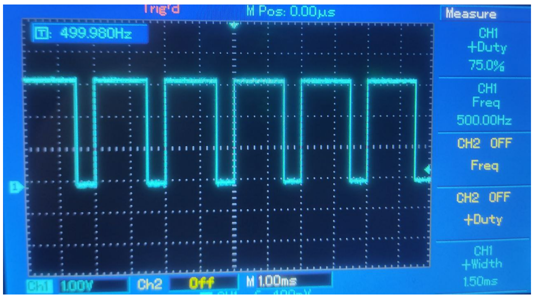
It can be seen that the PWM responded well to the throttle inputs and met all three of the notable positions perfectly. Figure 4.5d also shows that the two PWM outputs can have independent values to control each thruster as required. It should be noted that the images in figure 4.5 all show a amplitude of 3.3 V as the output was measured directly off of the Arduino microcontroller and before the signal was amplified using the logic level converter. It was confirmed that the converter accurately amplified the signal while maintaining the frequency and duty cycle of the signal.

4.3 Throttle

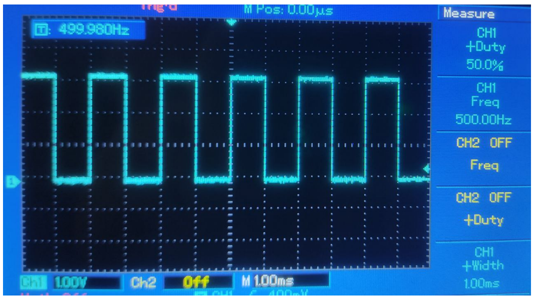
In order to test the response of the throttle and to show that the linear potentiometers have good accuracy the graph in 4.6 was plotted. It can clearly be seen that the potentiometers are meeting the upper and lower thresholds listed in 3.1 and can move independently of each other without interference. Figure 4.6 also shows that in the neutral position there is some variation caused by user input when moving the other throttle. As one pushes on the one throttle one, will slightly pull on the other without realizing. Furthermore, even if it looks like the throttle is back in the neutral position, even a small amount off from the original position results in a different value. This is why the neutral buffer in 3.1 was applied and it can be seen that buffer covers the slight variations.



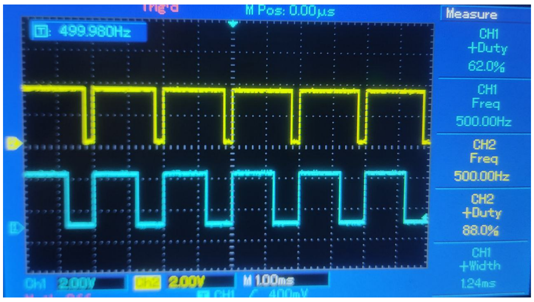
(a) Full Forward



(b) Neutral



(c) Full Reverse



(d) Both Outputs

Figure 4.5: Results of the PWM output displayed on an oscilloscope.

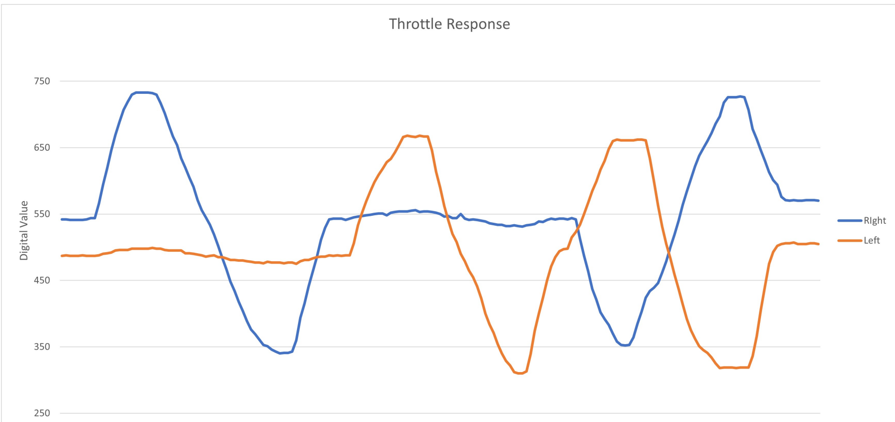


Figure 4.6: The digital response of the throttle.

Figure 4.7: The thruster in a bucket of water to test it without 'dry running'.

4.4 Thrusters

The thrusters are designed to be operated in water as the water flow across the ESC is designed to dissipate the heat generated and prevent the ESC from overheating. Furthermore, the thruster is designed to push water and not air which have very different densities, so for these reasons the thrusters should not be 'dry run', and should only be operated while submerged. Figure 4.7 shows how, during the design and testing of the thrusters, a temporary water source was provide with a large bucket wherein the thrusters could be submerged to ensure that the thruster is responding to the PWM signal and giving the desired results.

4.5 USV

The final testing was conducted on the entire system as a whole by launching the vessel and operating it as a complete system. This section will first detail the procedure for setting up the system for a test followed by the details of how each test was carried out. Finally, the results of the full system tests will be discussed.

4.5.1 Set-up Procedure

The full system tests were carried out on the Stellenbosch canoe dam as it is a large enough body of water to sufficiently test the vessel and it is just outside

Table 4.1: Procedure to set-up the vessel and safety equipment

To Check:	Checked
All bungs are in place and secured.	
All tie downs are removed and stowed.	
The personal floatation device is aboard.	
The electrical fire extinguisher is aboard.	
There is no physical damage to the vessel that could cause leaks.	

of Stellenbosch so it is easily accessible. The system is transported completely disassembled so as to avoid any possible damages that could occur during transport. Therefore, before testing the vessel as well as the rest of the components must be set-up and checked before the vessel can be launched and the test can begin. Firstly the vessel and all safety equipment must be checked and prepared by following the checklist in table 4.1. Once the vessel has be prepared the system can be assembled by following the checklist in table 4.2. Once both of these checklists have been followed a final cursory sweep should be conducted to ensure that nothing has been missed and the vessel can be launched. Once the vessel is off of the trailer and in the water, the thrusters can be dropped down into their operational position. This will conclude the set-up of the vessel and the test can begin.

4.5.2 Testing

The testing occurred in two phases, the manual test and the autonomous test. The manual test was carried out by using the throttle to manually control the vessel and ensure that the thrusters are responding correctly and that the system is fully operational. The GPS points that the boat would navigate to under autonomous control were chosen while doing the manual test to ensure that the vessel would not navigate into any of the obstacles on the dam such as buoys and pumps.

Finally, for the autonomous test, the vessel was driven back to the starting position and the system was reset and autonomous navigation was selected. The vessel was still manned so that manual control could be taken at any point if it looked as though the vessel would collide with any obstacles. Once the vessel had navigated to its final point, manual control was selected to return the vessel to shore.

4.5.3 Results

Finally, after all the testing had been completed, the results could be analysed and assessed to determine the validity and performance of the control system.

Table 4.2: Procedure to set-up the equipment and control system

To Check:	Checked
Mount the throttle plate and secure the attaching bolts.	
Mount the control system under the throttle plate and secure the GPS and Compass onto the nose.	
Ensure that the thrusters are in the upright position and mount them onto the transom.	
Place the batteries at the back of the vessel, just in front of the transom.	
Ensure that the cut-off switch is in the off position and connect the thrusters to the batteries.	
Connect the control system to the thrusters.	
Check all connections to see that they are secure and that there are no open wires.	
Close the battery box and secure the battery box.	
Turn on the cut-off switch to power the system and check that the control system powers on. The thrusters should beep twice signifying that they are connected and receiving a signal.	
Wait until the GPS indicator light is on, signifying that the GPS has an valid GPS fix.	

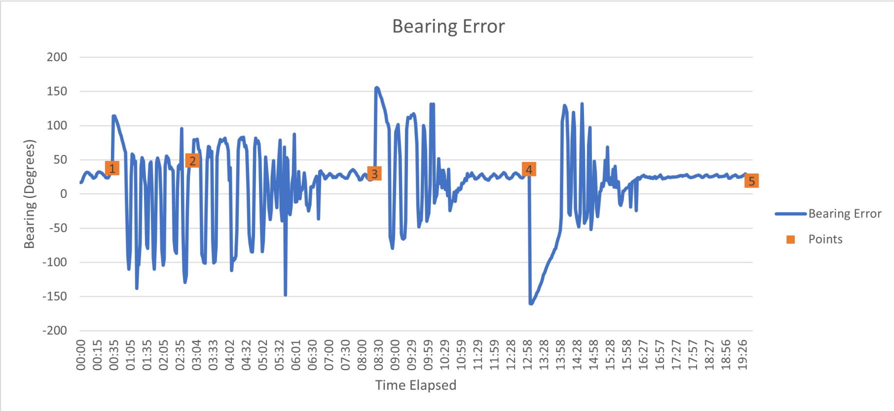
The results will be discussed with the aid of graphs draw from the data collected during the tests. The performance of the control system will be determined by how accurately it stays on the course to the target location and the validity of the system will be determined by if the vessel reached the target points.

Looking at figure 4.8b, which shows the distance to the target point over time, it can be seen that the vessel always gets to within the allowable distance of the target location. The system is working and navigates to all the given locations.

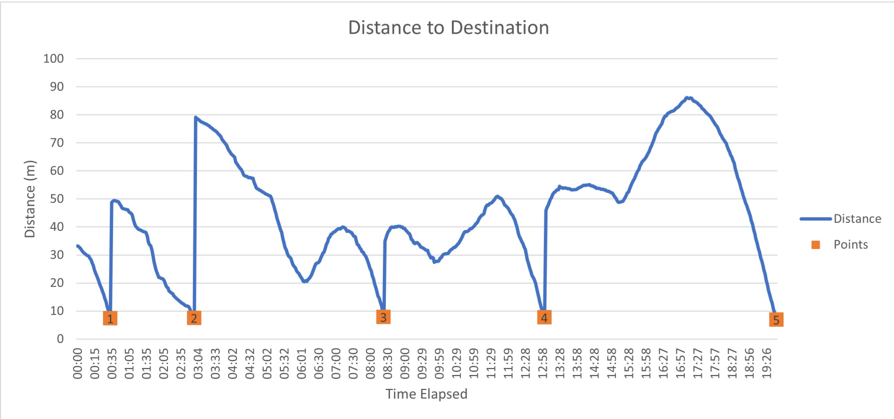
However, having a valid system is only useful if the system is accurately navigating to these points and not simply randomly lucking onto the target. To determine the performance of the system we can look at figures 4.8a and 4.8c. 4.8a shows the error or difference between the vessels bearing and the bearing it should be following to reach the target. In a perfect system, this graph should be a flat line along the x-axis with spikes after the point has been reached and the bearing to target has been reached. Figure 4.8c would similarly, show the vessel bearing following the target bearing exactly with the only deviation being as a point reached where the target bearing drastically changes and the vessel bearing must work its way back to the target bearing.

Looking at the area between point 1 and 2 on 4.8a, it can be seen that the graph is oscillating significantly around the x-axis with a heavier bias to the negative. This is not indicative of good performance, however when combining this with the plotted course in 4.9 it can be seen that the vessel is making lots of small corrections but maintaining a relatively straight course to the target point.

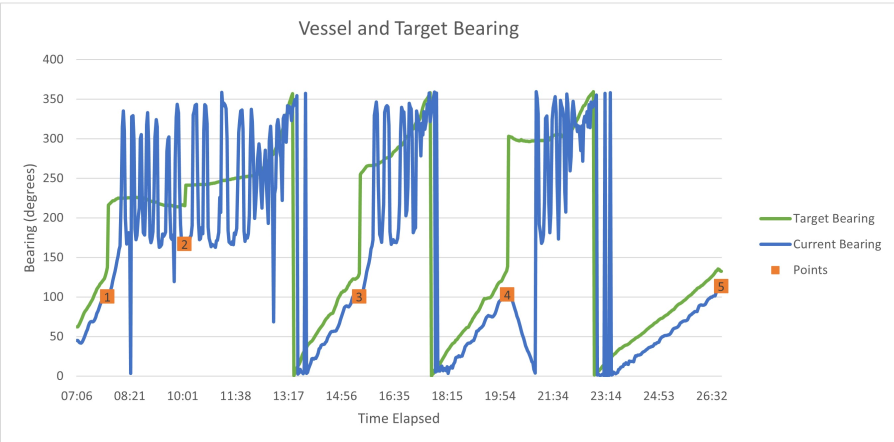
Staying with 4.9, it is clear that after point 2, it looses performance as it begins to do large unnecessary loops to reach the target. This can also be seen in figure 4.8b that the vessel begins to get closer until it is passed it and gets further away before looping around and once again getting closer and reaching the target. However, 4.8a and 4.8c show that the vessel bearing is still oscillating around the target bearing as between points 1 and 2. This is due to the compass loosing calibration and having 'dead spots'. The compass was not returning an accurate bearing and the system thought it was on the correct course. Once it had looped around and out of the compass 'dead spot' and it began returning the correct bearing, and could accurately navigate to the target location.



(a) Bearing Error.



(b) Distance to Target



(c) Bearings Comparison

Figure 4.8: Results of the PWM output displayed on an oscilloscope.

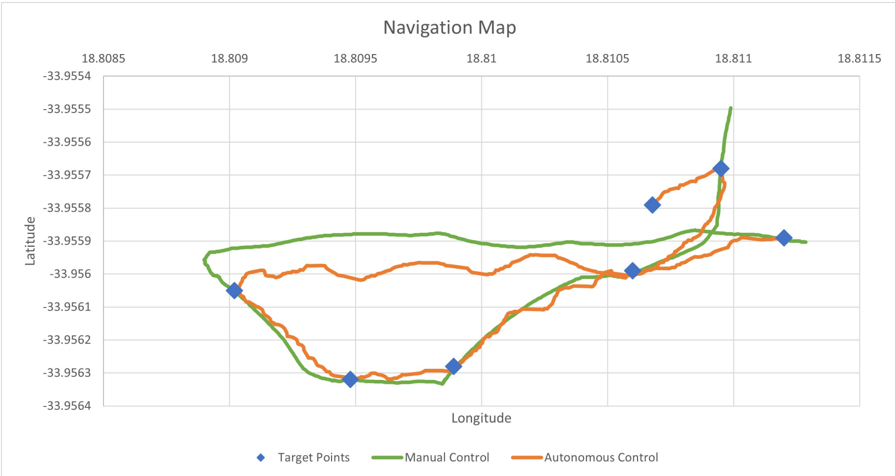


Figure 4.9: map

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