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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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Date:

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 add an obstacle avoidance system. This will be beneficial to avoid other sea vessels as well as fixed obstacles such as rocks and shore.
What arrangements have been/will be made to expedite continuation?
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

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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 360° 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.

1.3 Motivation

Currently the marine community is using these acoustic systems as stationary systems. By using the USV in conjunction with the USV the area that is studied can be greatly increased with fewer acoustic platforms as have been used in passed 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 of marine patrols and search and rescue, USVs can be used to fill up the ranks of vessels and close the possible.

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 is a USV and what equipment and knowledge is required to for a USV. 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 is tested and the results will be discussed before a conclusion on the system can 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 [1]. With advancements in technology leading to unmanned drones and development into autonomous cars, unmanned surface vessels is a natural progression. There is 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 [2]. 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 to an unmanned vessels, is that because they are often electrically powered as it is more easily controlled by software and they 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 [3].

The primary concern when trying to navigate open water is that 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 from which you can then determine in which direction you need to travel.



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

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 ?. 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, Sput-

nik 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. ?

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 launch 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. ?

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. ?

There was a range of technological advancements that help progress the satellite navigation systems such as new bandwidth utilization techniques, advancements in computer 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. ?

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. ?

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. ?

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 and 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. ?

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 clock. Based on the time taken for the signal to reach the receiver and corrected

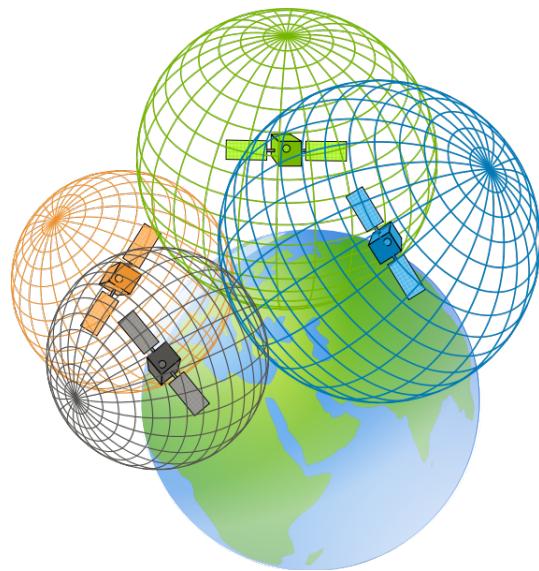


Figure 2.2: Distance spheres around each satellite intersect at one point

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. ?

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 ?. 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 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-

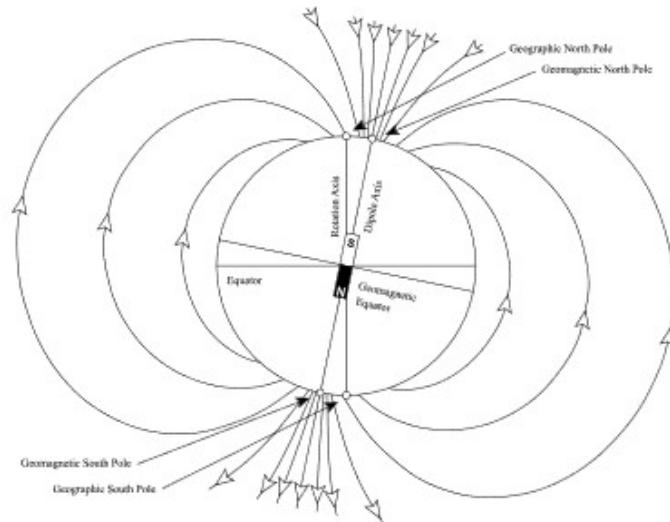


Figure 2.3: The differentiation between magnetic and true north

magnetic materials or other electrical systems that are creating a magnetic field. ?

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 distinction between true north and the magnetic field at magnetic north is shown in figure 2.1. 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. ?

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 not drift over time. These PWM signals are mostly used in speed control of DC motors or controlling the brightness of lightbulbs. ?

PWM is a digital signal that is switched between high and low, leading to the

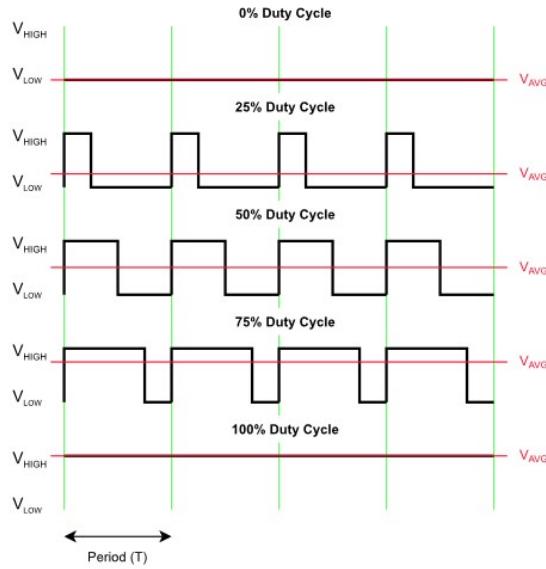


Figure 2.4: Duty Cycle of PWM Signal

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. Secondly is the signal period, and therefore the frequency as they are inversely proportional, and 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 is the final parameter. The duty cycle is 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.

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 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

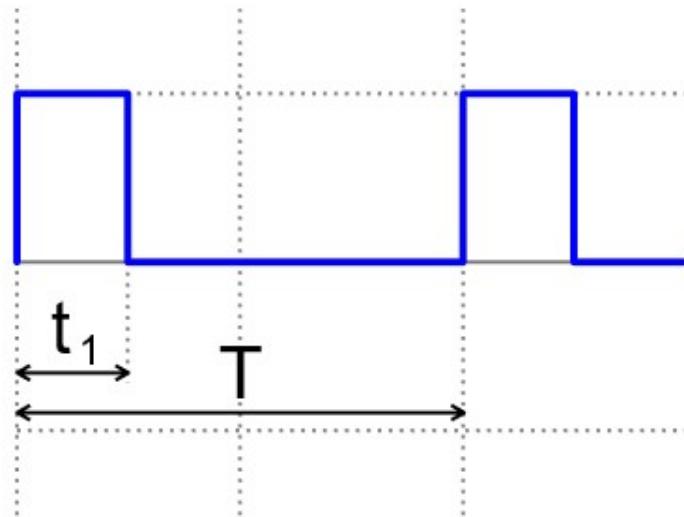


Figure 2.5: The relation between the time the signal is high and the signal period.

the associated average voltage is shown in figure 2.4. ?

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 (t_1). Figure 2.5 shows the relationship between t_1 , 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.

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.

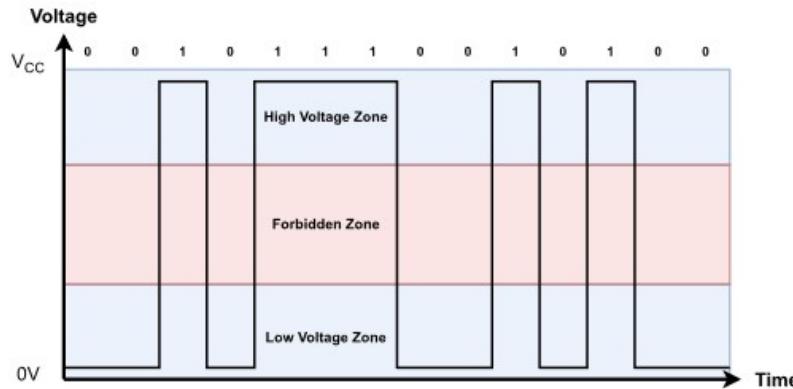


Figure 2.6: A digital signal and its three zones.

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 preset 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 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, $\pm V_{CC}$, the voltage of the microcontroller, is used for these upper and lower limits. An example of a continuous analogue signal between $\pm V_{CC}$ 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.

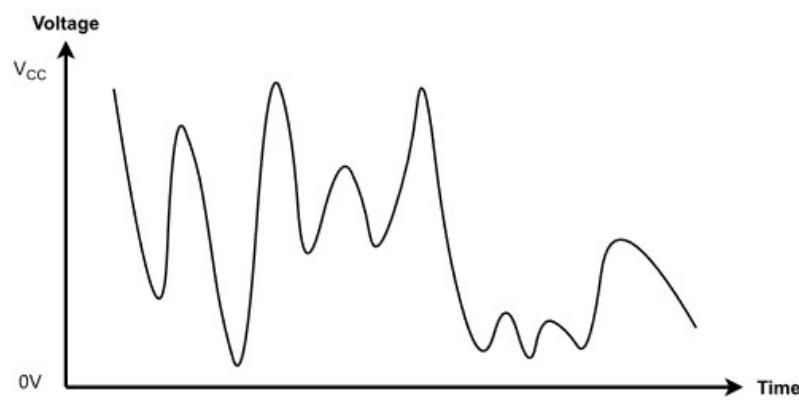


Figure 2.7: Analogue signal

Chapter 3

Methodology and Design

This chapter will describe the methodology used in the project. Firstly, it give 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.

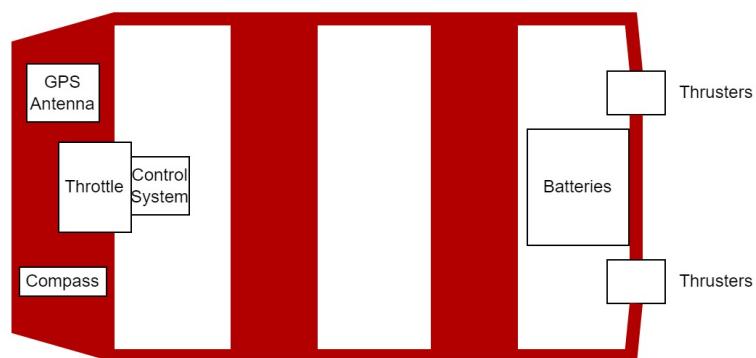


Figure 3.1: Broader System Diagram

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 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.

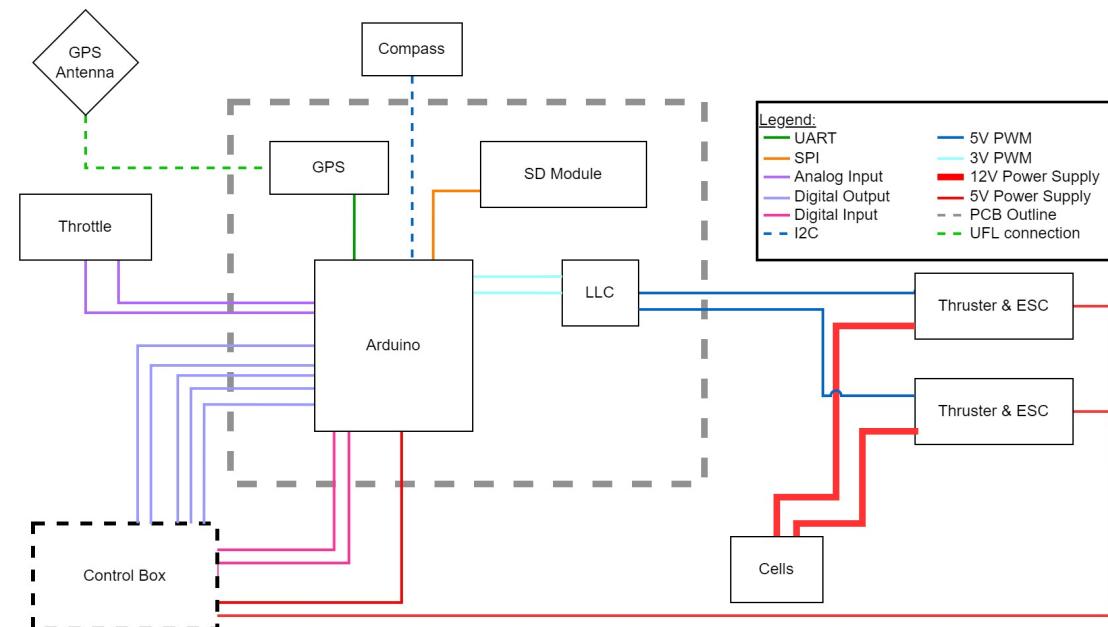


Figure 3.2: Wiring Diagram for the System

3.2 Software Environment

The microcontroller that was chosen for this project is a Arduino DUE. An Arduino microcontroller was chosen as there is a 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 servicing. 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 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 points.

This system is a proof of concept that is designed to be able 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 can 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 2 people is required. This is preferred to a smaller vessel that cannot accommodate the weight of a person as the weight to power ratio of a small vessel would not be as representative and this could influence 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 represented 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 the a electronic control system is required to control the vessel. Furthermore, there are several elements that are



Figure 3.3: The vessel, a spider 3.

required to make up the system however, these are not integral to the autonomous nature of the system but integral to the system as a whole.

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 uses the vessel would be upgraded to handle severe weather conditions and hold an array of sensory equipment. The vessel referred to in this project, pictured in figure 3.3 is a Spider 3, a small single hulled fibreglass boat. The vessel measures $1.3\text{ m} \times 3.2\text{ m}$ and is rated to carry 4 people and a 15hp traditional outboard motor.

Thrusters

Although the thrusters are electrical they are a complete unit together with the ESC, and all electronic interfacing was done with the ESC which then drove the thrusters. Therefore the thrusters are being considered general hardware and similarly to the boat were acquired prior to the project and are only there as a means of testing the control system. They are therefore also out of the scope of the project but are integral to the performance of the system overall.

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 aliminium mount designed and manufactured by the Electrical engineering workshop allows for the thrusters to be raised during the launching and retrieval of the boat so as not to foul on the trailer. The mounts are removable and are removed for transport. Each thruster has a integrated ESC that regulates the power supplied to the electric motor and therefore the thrust provided. The ESC is detailed later in the report.

Power Supply

The initial design was to use a bank of 4 Lithium Iron Phosphate 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.

Finally, it was decided that in order to test the control system, the power source would be changed to a battery of two lead acid cells. 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.

Throttle

The initial concept was to use two throttles that can move independently from each other and purchased to be used. However, when these components arrived, they were much smaller than they had appeared and they had very small range of movement. An alternate solution was designed and consisted of two throttle arms that could each turn a shaft. This shaft was then mounted to a linear potentiometers 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.

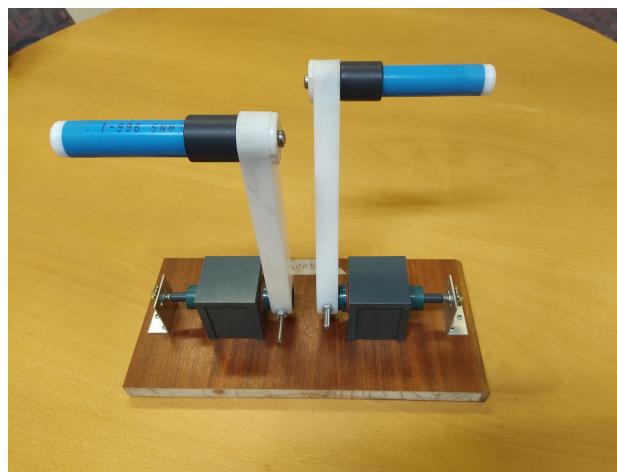


Figure 3.4: The final throttle system with two POTs on either end.

PCB

3.3.4 Electronics

Arduino Due

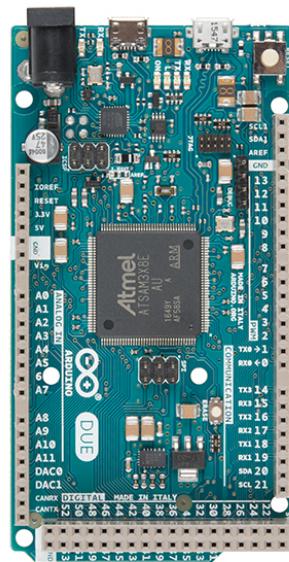


Figure 3.5: The microcontroller used, an Arduino DUE

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 with the peripherals of the GPS, SD card modules and the ESC and POTs as well as several inputs and outputs were as follows:

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 I²C 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 requirements. However, the Arduino Uno has only one UART connection and although this does meet the minimum requirements it 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 and 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 was sourced that has an external antenna that can be fed out of the control box and placed in a position 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 the characters. The GPS module is used to return the current longitude, latitude, date and time, speed and heading. The UART is set-up to use a baud rate of 9600, 8 data bits, no parity and 1 stop bit. 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 with a baud rate of 9600, 8 data bits, no parity and 1 stop bit.

Compass

The digital compass used can be more accurately referred to as a magnetometer. The module used in this project, a Pololu LSM303, 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, shown in figure 3.6, which is used to calibrate the module and to get an accurate compass bearing.

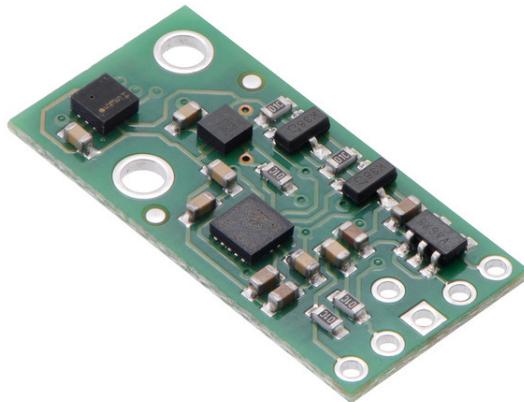


Figure 3.6: Pololu LSM303 AltIMU module.

ESC

There are two ESC, one for each thruster and are submersible and therefore they are attached to the thrusters. The ESC has two inputs, the control input and the power input. The power input can range between DC12V and DC50V and a maximum constant current of 100A and in this project the input is 24V supplied by the battery cells. The control input is a 5V signal that is used to control the speed of the thrusters. This is a PWM signal whose duty cycle determines the thrusters speed and direction.

POT

Table 3.1: Measured physical limits and neutral range of the throttle POTs

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

The POT is a standard 10 kΩ potentiometer that has three pins as shown in figure 3.7, high voltage, ground and the output. The high voltage and ground are connected to the connections on either side and the output is connected to the middle. As the shaft of the potentiometer is turned the resistance varies from almost no resistance to the full 10 kΩ which causes the voltage to vary from input to almost ground voltage.

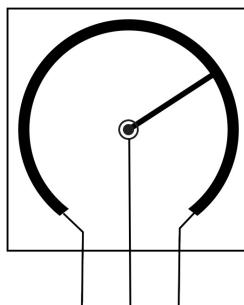


Figure 3.7: Fundamental illustration of a linear potentiometer

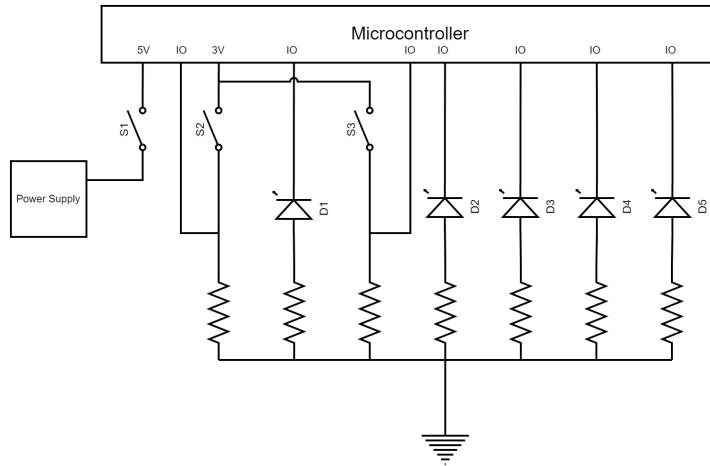


Figure 3.8: The wiring circuit inside of the control box.

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 and the throttle only has about a 150° range of motion and so the software corrects this after having determined the extends of the motion through trial. The extends are measured at the two extremes and the middle point and offers a neutral range buffer for ease of use of the throttle. The measured extends are listed in table 3.1.

Switches and LEDs

The control box shown in figure 3.9 is made up by 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. Whereas, the LEDs all use a simple LED circuits that are driven by the digital outputs of the microcontroller. The final switch is the power switch and it is wired to cutoff 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 table 3.2.

3.3.5 Software

PWM Signal

The thrusters are each controlled by a 5V PWM signal. There is limited information on the datasheet for the ESC and 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.

In order to be sure that the correct PWM signal was being sent through and to be able to quickly vary both the frequency and the duty cycle, a PWM signal generator IC, shown in figure 3.10, was connected to ESC and trial and error was conducted to determine 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



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.
Contingency Switch	S3	This switch is not used and was included and wired in case a design development required another switch.
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 (μ s)	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 %

would offers the finest control because it has the maximum allowable duty cycle difference between the signal boundaries.

The Arduino libraries contain a function that can output a PWM wave, given the duty cycle and the pin to output on as a parameter 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 switch to peripheral type B. Then came the configuration of the timer itself. The channel mode was set to waveform mode using clock 1 with the counter being incremented on the rising edge. Furthermore, the waveform was set to UP mode (signal being 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, the RA and RC values can be filled and the interrupt set to trigger when the counter reaches RC. Finally, the channel control register is set to perform a software trigger, reset the counter and start the clock. There is also a interrupt handler that needs to be added where in the status register is read. This is done because the flags in the status register are automatically reset when the status register is read, at the end of every period.

The signal is being cleared when the counter reaches RA and set high when the counter reaches RC and so RC can be equated to the period of the signal and RA to the time when the signal is high. Using this and that the clock is set to clock 1 which is the MCU clock (MCK) divided by 2, the RA and RC can be expressed in terms of MCK, frequency and duty cycle as shown in equations 3.1 and 3.2. RC is kept constant throughout while RA is changed to change the duty cycle of the PWM signal sent to the ESC and therefore control the ESC and thruster.

$$RC = \frac{\frac{MCK}{2}}{Frequency} \quad (3.1)$$

$$RA = RC \times DutyCycle \quad (3.2)$$

ADC

As mentioned previously, the ADC is used to convert the analogue signal from the throttles potentiometers to a digital signal between 0 and 1024. Furthermore, using table 3.3 and 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 exact and this is difficult to achieve from 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.

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

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

GPS

The GPS module transmits a series of 5 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 and the end of line characters <CR><LF>. For this project the '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 out the specific data out of the string using the commas and full stops as the guide to what array position is what data. The latitude and longitude are given in the format 'DDmm.mmmm' and must first be converted to decimal degrees as this is most easily used 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 analysed. The variables within the GPS structure are shown in table 3.4.

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

Compass

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.

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).

State Machine

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 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.

Algorithm 1 State Algorithm

Require: Declare variables and initialize PWM, SPI, I²C and UART

```

1: loop:
2: if manual control = true then
3:   call updatePWM()
4:   call powerThruster()
5: else
6:   call receivedGPSdata()
7:   if GPS data is valid then
8:     call navigate()
9:   else
10:    Delay 1 second
11:    if Last point has been reached then
12:      Halt receiving GPS data
13: goto loop.

```

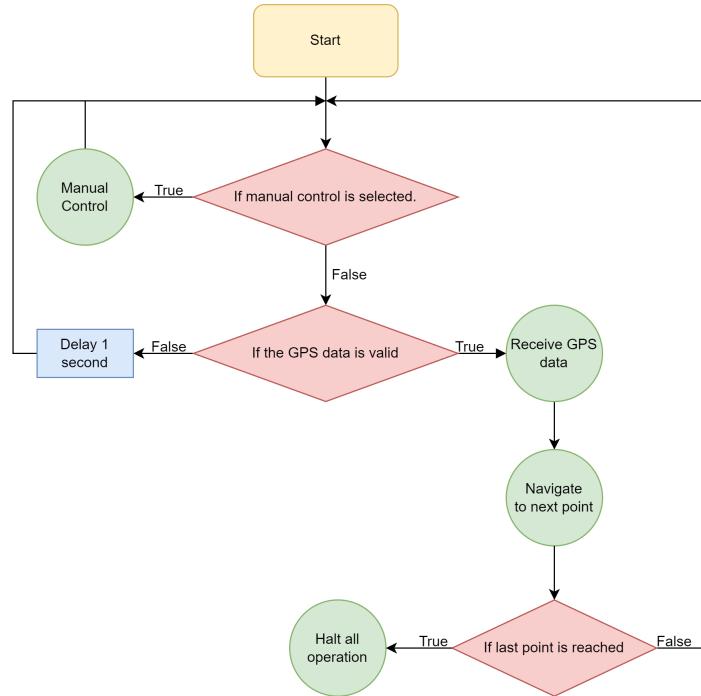


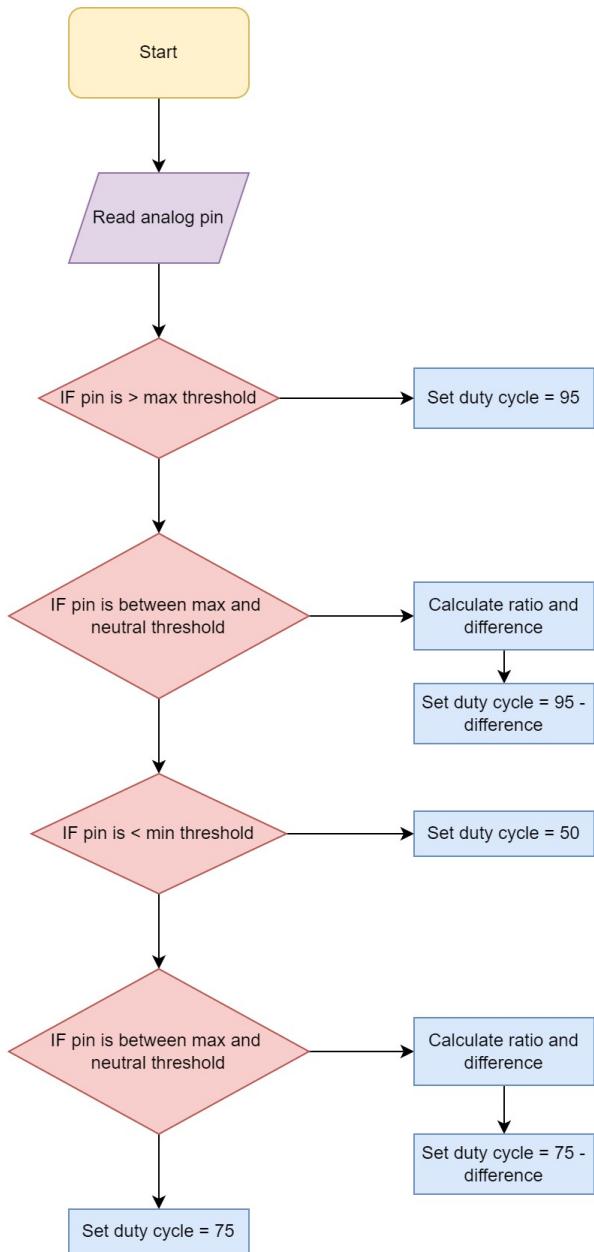
Figure 3.11: Flow diagram of the main states in the system.

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 sides input and calculate the required duty cycle for that sides 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 algorithms 2.

Receive GPS Data

The GPS data is received with the serial UART communication and is a string of characters as shown previously. In order to receive the correct data line, the microcontroller receives each line and then checks that it is the required line. If so, the line is processed and the struct is updated with the newest data. A few

Figure 3.12: Flow diagram of `updatePWM()`

Algorithm 2 Pseudo code for manual control

```

1: procedure UPDATEPWM
2:   analog  $\leftarrow$  analogRead(analogPin)
3:   if analog > maximum threshold then
4:     duty cycle  $\leftarrow$  95;
5:   else if analog > neutral threshold then
6:     analog ratio  $\leftarrow$  ratio forward (equ. 3.3) asfloat
7:     difference  $\leftarrow$  (95 - 75)  $\times$  analog ratio asfloat
8:     duty cycle  $\leftarrow$  95 - difference
9:   else if analog < minimum threshold then
10:    duty cycle  $\leftarrow$  50;
11:   else if analog < neutral threshold then
12:     analog ratio  $\leftarrow$  ratio reverse (equ. 3.4) as float
13:     difference  $\leftarrow$  (75 - 50)  $\times$  analog ratio asfloat
14:     duty cycle  $\leftarrow$  75 - difference
15:   else
16:     duty cycle  $\leftarrow$  75;
17: procedure POWERTHRUSTERS
18:   RA  $\leftarrow$  RC  $\times$  duty cycle%;
```

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.

findAllInstancesOf()

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 received the GPS data and populate the struct is shown in the flow diagram of figure 3.13. The populating of the struct is just using the arrays of full stop and comma indexes 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

```

1: msgReceived  $\leftarrow$  false
2: rxCnt  $\leftarrow$  0
3: while !msgReceived do
4:   while rxByte  $\neq$  10 do
5:     rxByte  $\leftarrow$  SerialRead()
6:     if rxByte  $\neq$  -1 then
7:       rxData(rxCnt)  $\leftarrow$  rxByte
8:       rxCnt  $\leftarrow$  rxCnt + 1
9:     if rxData(3) = 'R' AND rxData(4) = 'M' AND rxData(5) = 'C' then
10:      call updateStructRMC(rxData, rxCnt)
11:      msgReceived  $\leftarrow$  true
12:   rxCnt  $\leftarrow$  0
13:   rxByte  $\leftarrow$  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 half 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 is determined using an equation that accounts for the $360^\circ/0^\circ$ turn over point. If 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 the thruster sides are inverted.

Algorithm 4 Pseudo code for the autonomous navigation

Require: Read the target GPS points from SD card.

```

1: procedure NAVIGATE()
2:   Calculate distance to target
3:   Calculate bearing to target
4:   Calculate the error between current and target bearing
5:   if distance < distance threshold then
6:     throttle percentage  $\leftarrow \frac{\text{distance}}{2 \times \text{distance threshold}}$ 
7:     if distance < arrival threshold then
8:       call NextPoint()
9:       return
10:    else
11:      throttle percentage  $\leftarrow 95$ 
12:      if abs(bearing error) < steering threshold then
13:        steering percentage  $\leftarrow \frac{\text{abs}(\text{bearing error})}{\text{steering threshold}}$ 
14:      else
15:        steering percentage  $\leftarrow 100$ 
16:      maxBearing  $\leftarrow \max(\text{bearing error}, \text{target bearing})$ 
17:      minBearing  $\leftarrow \min(\text{bearing error}, \text{target bearing})$ 
18:      if (maxBearing = target bearing) XOR (maxBearing - minBearing) > 180
then
19:        call steerLeft()
20:      else
21:        call steerRight()
22:      call powerThrusters()
23: procedure NEXTPOINT()
24:   points(targetIndex).passed  $\leftarrow \text{true}$ 
25:   targetIndex  $\leftarrow \text{targetIndex} + 1$ 
26:   if points.targetIndex does not exists then
27:     state  $\leftarrow \text{Halt navigation}$ 
28: procedure STEERLEFT()
29:   throttle difference  $= 2 \times \text{throttle percentage}$ 
30:   rightSide.duty Cycle  $\leftarrow 75 + (25 \times (\text{throttle percentage}\%))$ 
31:   leftSide.duty Cycle  $\leftarrow \text{rightSide.duty Cycle} - (25 \times ((\text{throttle difference} \times$ 
 $(\text{steering percentage}\%))/100))$ 

```

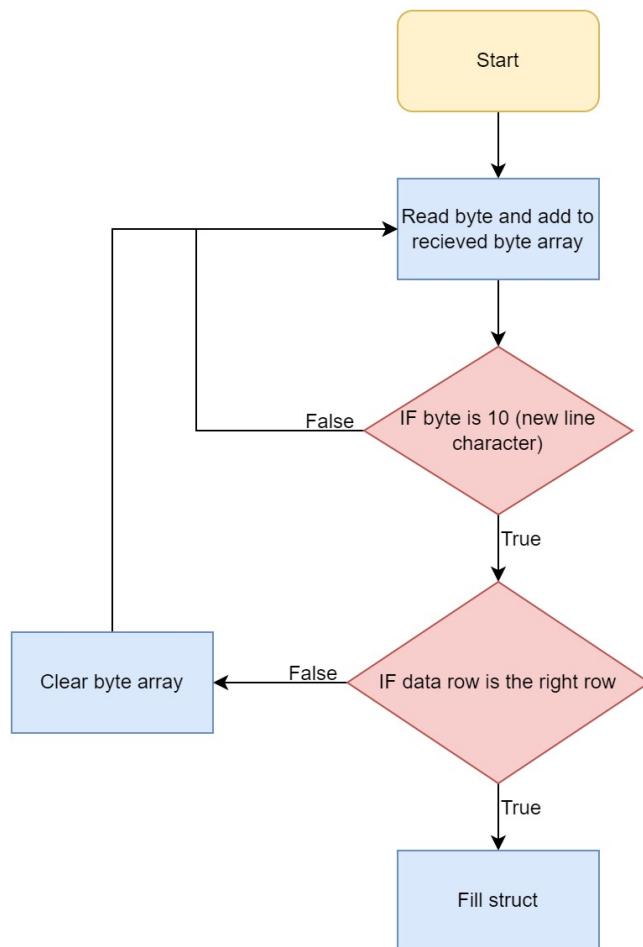


Figure 3.13: The flow diagram of receiving the GPS data.

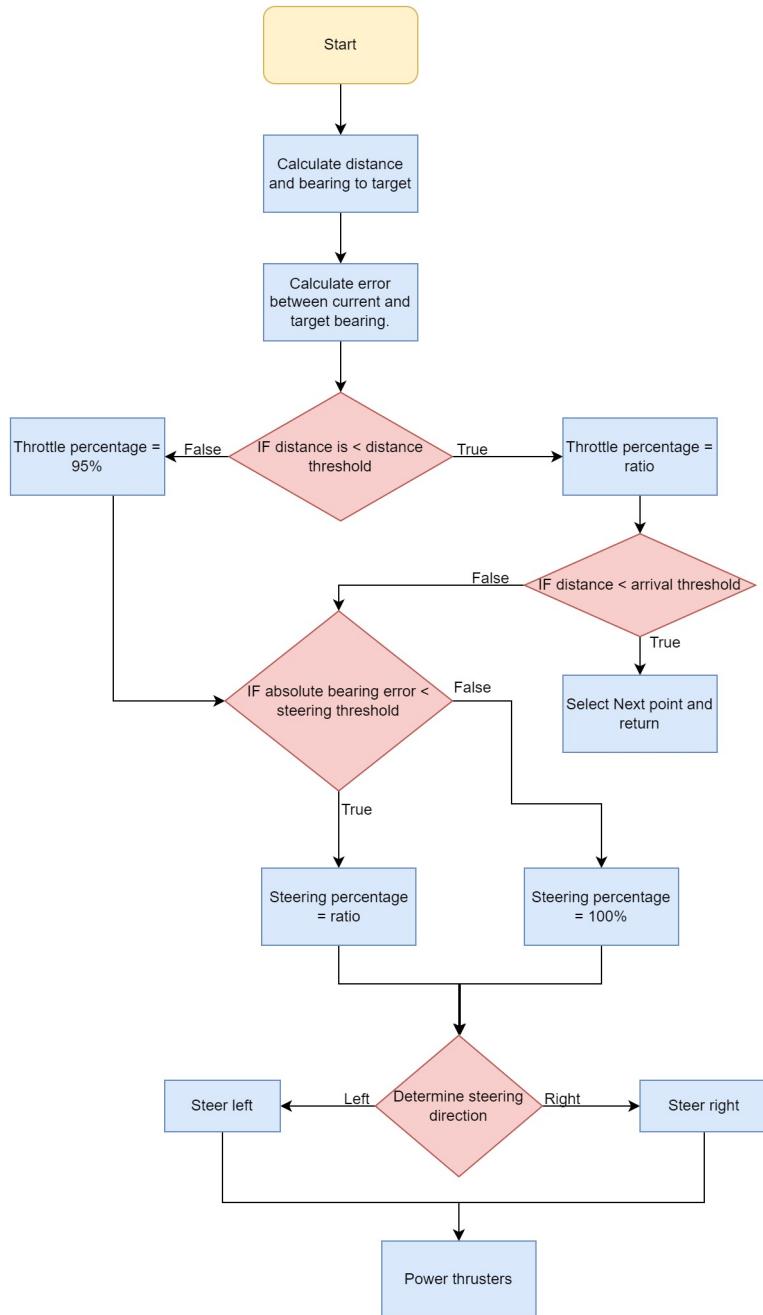


Figure 3.14: Flow diagram of the autonomous navigation

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 bearing 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

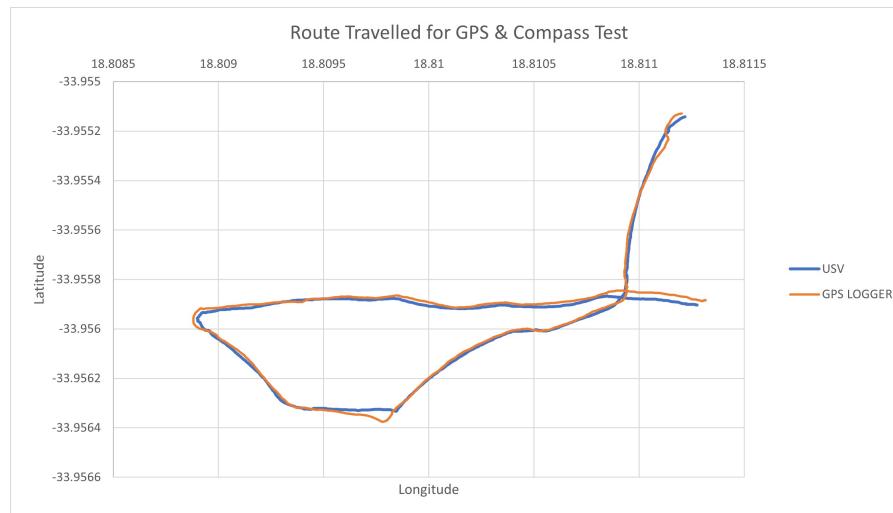


Figure 4.1: The path used to compare the system GPS and the baseline GPS logger.

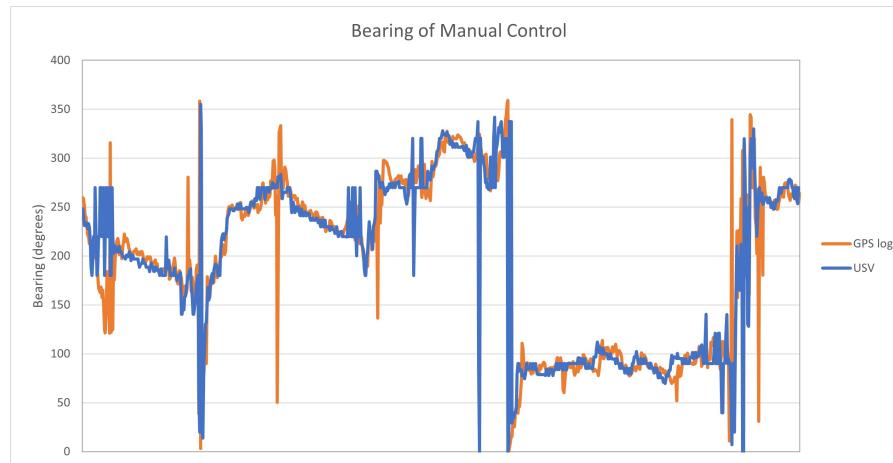


Figure 4.2: The calculated bearing and compass bearing overlay.

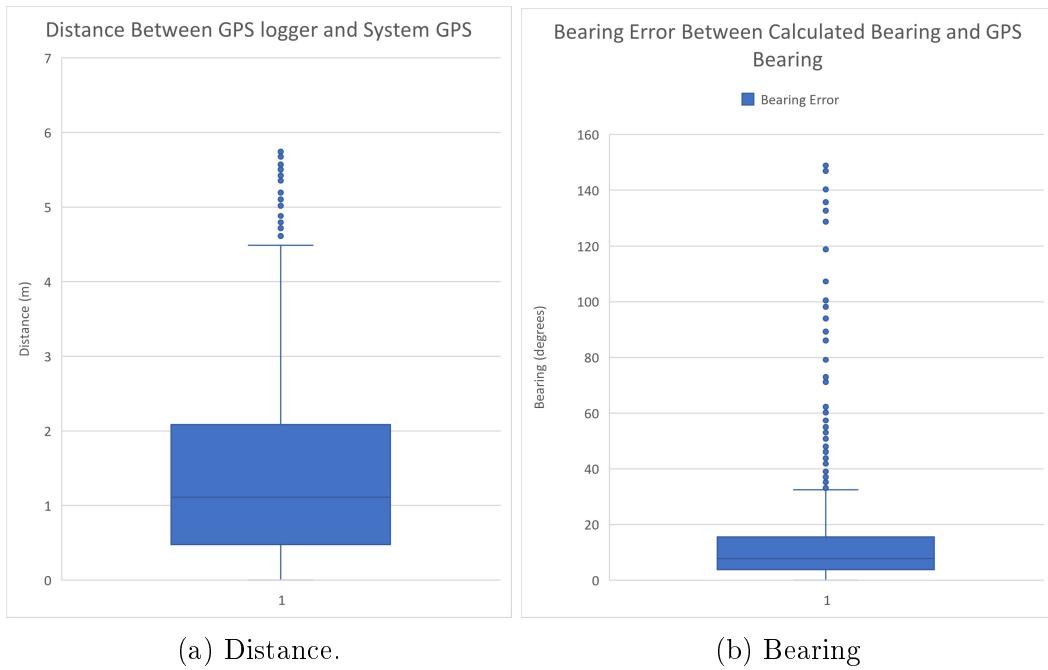


Figure 4.3: Box and Whisker Graphs Of Distance and Bearing Between the System and the Baseline.

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.

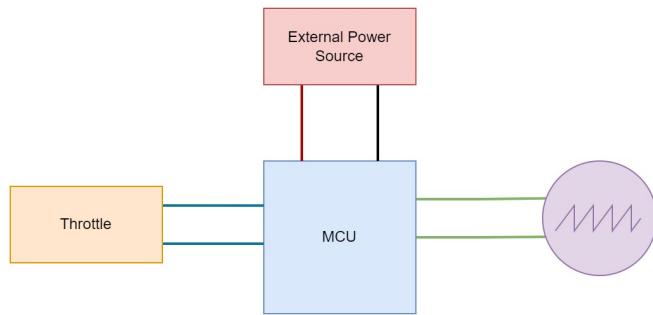


Figure 4.4: Wiring diagram for the PWM oscilloscope test.

These 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.

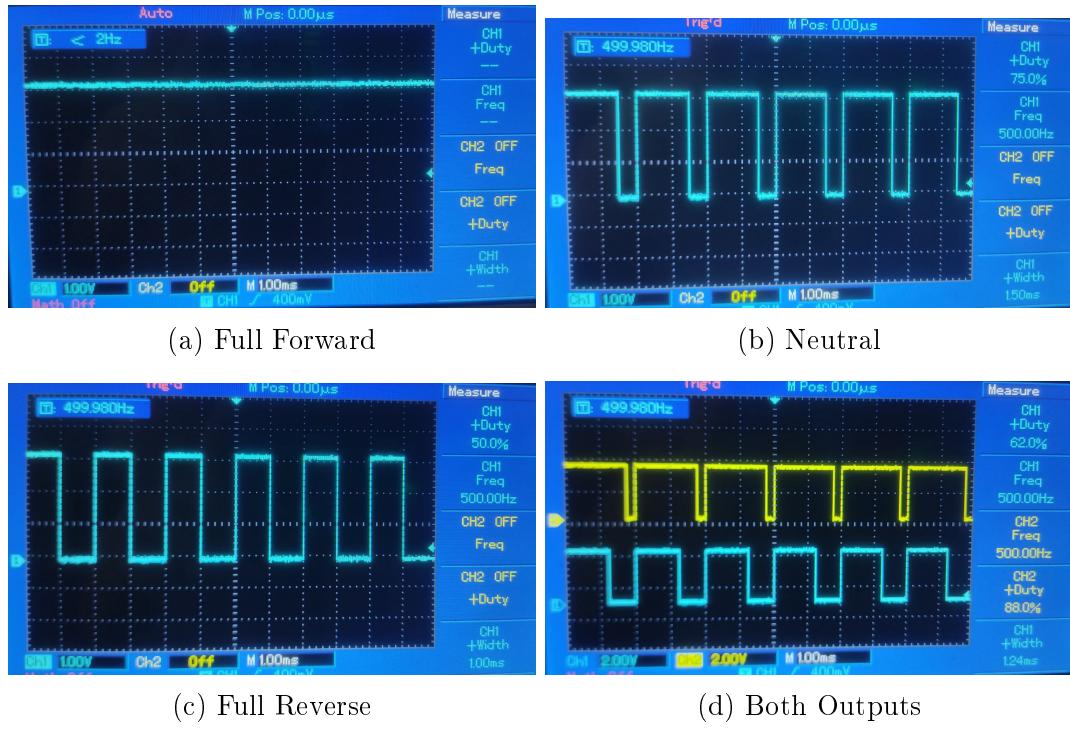


Figure 4.5: Results of the PWM output displayed on an oscilloscope.

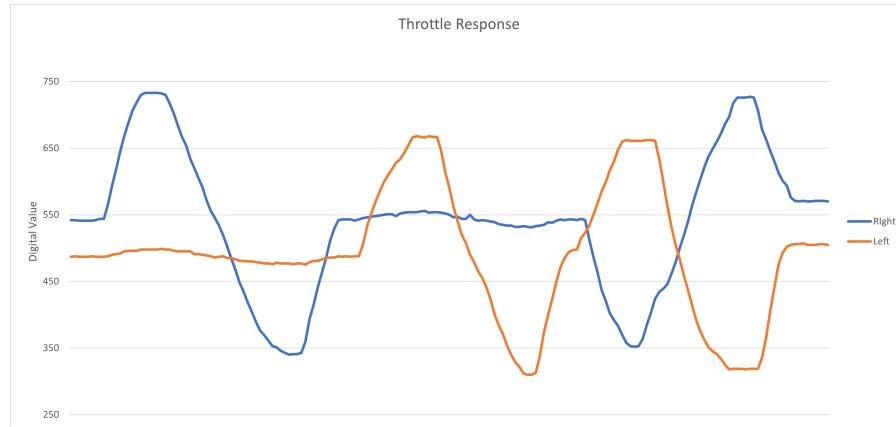


Figure 4.6: The digital response of the throttle.



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 provided 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 been 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 a valid GPS fix.	

The results will be discussed with the aid of graphs drawn 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 vessel's 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 at 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 loses 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.

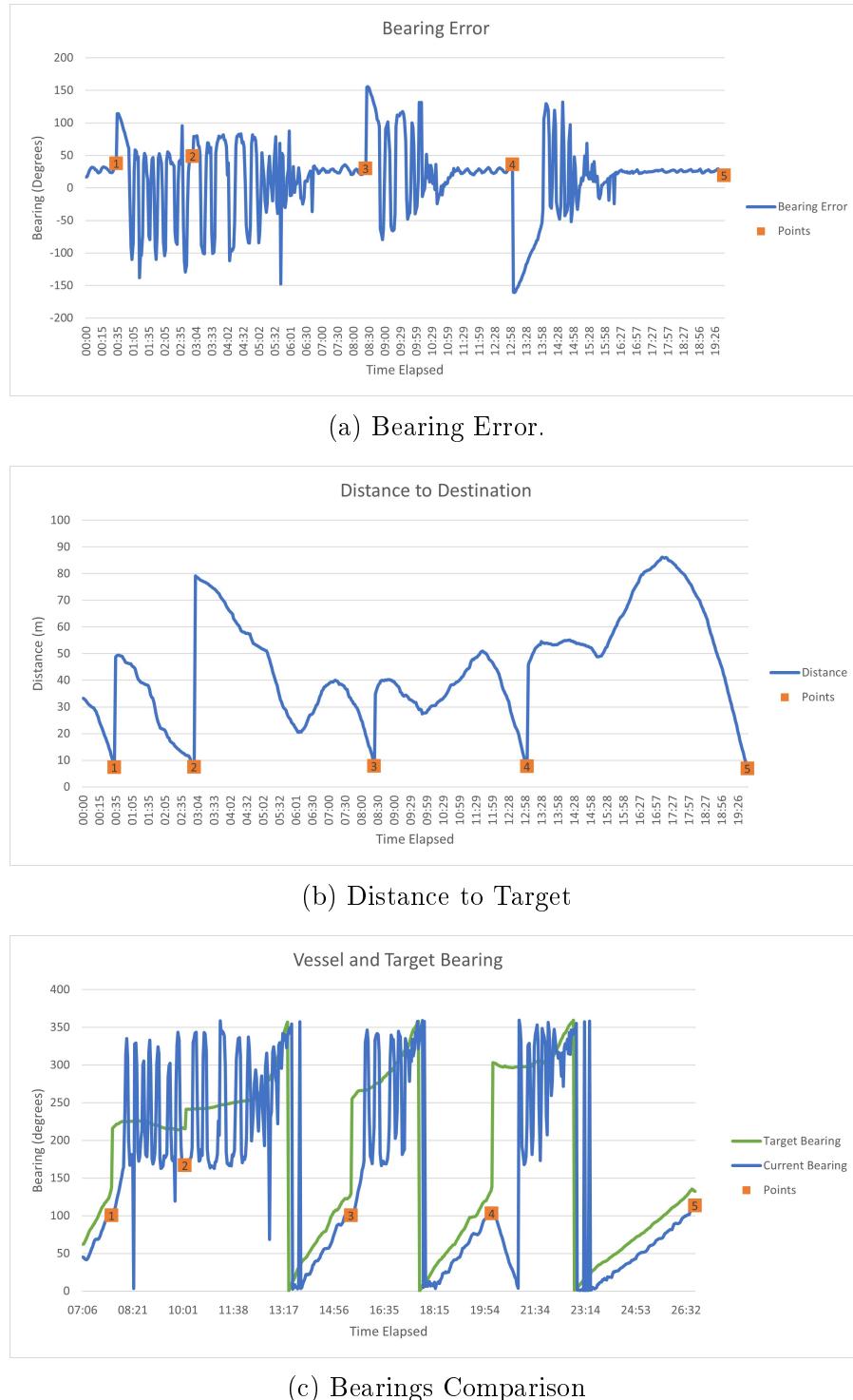


Figure 4.8: Results of the PWM output displayed on an oscilloscope.

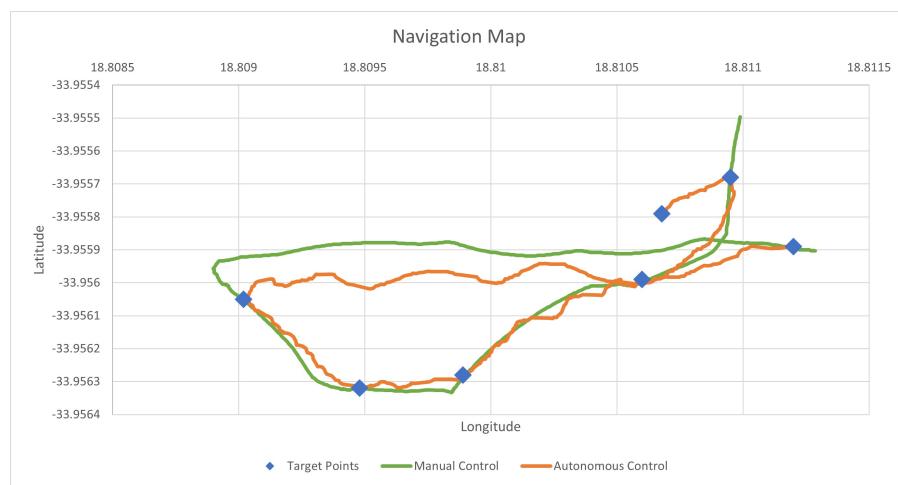


Figure 4.9: map

List of References

(USAF) (1978). GPS Early User Equipment 2.

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