Design of an Autonomous Underwater Vehicle: Vehicle Tracking and Position Control

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As the candidate's supervisor I agree to the submission of this thesis.

Supervisor: Prof. Glen Bright

DECLARATION

I, Servaas Holtzhausen, declare that

(i) The research reported in this thesis, except where otherwise indicated, is my original work.

(ii) This thesis has not been submitted for any degree or examination at any other university.

(iii) This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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ACKNOWLEDGEMENT

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Abstract

This project proposes the development of an autonomous underwater vehicle that can be used to perform underwater research missions. The vehicle can be pre-programmed to complete a specified mission. Missions may include underwater pipe inspection, a survey of the sea floor or just the transport of given sensors to a certain depth or position and take measurements of underwater conditions.

The Mechatronics and Micro Manufacturing group at the CSIR is engaged in developing a portfolio of autonomous vehicles as well as further research into the development and implementation of such vehicles. Underwater vehicles will form part of the portfolio of autonomous vehicle research. Autonomous underwater vehicles (AUVs) are mostly used for research purposes in oceanographic studies as well as climate studies. These scientists use AUVs to carry a payload of sensors to specified depths and take measurements of underwater conditions, such as water temperature, water salinity or carbon levels as carbon is being released by plankton or other ocean organisms. Very little information is available about what is happening below the surface of the oceans and AUVs are being used to investigate this relatively unknown environment.

The area covered by the world's ocean is 361 million km^2 with an average depth of 3790 m. The deepest surveyed depth point in the ocean is at a depth of about 11 000 m at the southern end of the Mariana Trench in the Pacific Ocean. This just shows the need for research into this mostly unexplored world. Research and exploration in the oceans can be achieved through the use of autonomous underwater vehicles.

A big problem to overcome is the fact that GPS is not available for navigation in an underwater environment. Other sensors need to be found to be used for navigational purposes.

The particular vehicle developed for this study will be used to facilitate further research into underwater vehicle navigation and underwater robotics.

Acronyms

PWM Pulse Width Modulation

VNC Virtual Network Computing

IC Integrated Circuit

AUV Autonomous Underwater Vehicle

SPI Serial Peripheral Interface

MISO Master In Slave Out

MOSI Master Out Slave In

CS Chip Select

MSB Most Significant Bit

I/O Input or Output

FET Field Effect Transistor

GPS Global Positioning System

PID Proportional Integral and Derivative

IMU Inertial Measurement Unit

INS Inertial Navigation System

DVL Doppler Velocity Log

ADC Analogue to Digital Converter

LBL Long Baseline

USBL Ultra Short Baseline

SLAM Simultaneous Localisation and Mapping

Contents

Chapter 1.

Introduction

1.1. Background Information and Research Objectives

Autonomous underwater vehicles are ideal platforms for aquatic research and rescue operations. They can also be used for inspection of underwater terrain and structures. The average depth of the ocean is around 4000 m and the deepest point over 11000 m which means there is still much to explore in our oceans. The oceans are seen by many as the earth's final frontier. AUVs can also be used for underwater exploration. These vehicles' usefulness come from their small size and manoeuvrability and also their ease of deployment and use. Manned underwater vehicles are usually quite large in size making them very costly to deploy, and experienced pilots are needed to steer them underwater. An AUV, which is much simpler and safer to use, can be employed instead.

AUVs may be used by ocean scientists to carry a payload of ocean observation sensors and take measurements at specified depths or to follow an underwater pipeline and capture images for maintenance purposes. Whatever the use of the vehicle, it needs to be robust to cope with an unpredictable environment and extreme water pressure. These vehicles also need to have lengthy endurance capabilities to improve on mission time and reduce redeployment and recovery iterations of the vehicle. The present goal in underwater robotics is to create fully self-contained, intelligent decision making vehicles [9]. The factors mentioned above make the design and development of such vehicles a tedious task.

According to [26] the two most significant technological challenges in AUV design are power and autonomy. Power sources limit the mission time of the vehicle and autonomy limits the degree to which an AUV can be left unattended by human operators. Power capabilities and research will not be dealt with in this study. Vehicle autonomy includes the navigation capabilities of the vehicle. According to [31] the primary challenge in AUV navigation is maintaining the accuracy of vehicle position over the course of a mission. Land and air vehicles can usually rely on GPS to track the vehicle's position and movement but in an underwater environment GPS is not available. Different sensors need to be implemented to facilitate a reliable and robust navigation system as underwater vehicles and equipment are very costly and one cannot afford to lose a vehicle in the ocean. Highly accurate sensors may be acquired to track the vehicle position or movement but they are very costly.

The objective of this research study is to try and find low-cost solutions for these navigation problems and develop a small-sized, low-cost AUV. The study will investigate and test different tracking strategies and hardware and implement some level of vehicle control. It will also discuss the obstacles and design steps to develop such a vehicle and to implement it successfully and show the components used to construct the vehicle. The AUV will only be developed for demonstration of the concept in a controlled environment like a water tank or a swimming pool. Another goal of this project is to build the capacity for AUV design and development in South Africa as this is almost non-existent. The oceans around Africa is still mostly unexplored and under studied and local AUV capabilities can make an impact in this.

1.2. Problem Statement and its Significance

AUV research and development has to contend with the problem of vehicle position and movement tracking. For any robotic vehicle to be able to navigate successfully, it needs to know its current position. This is normally determined by using GPS and adding other sensors like magnetometers, odometry sensors, and so forth. In an underwater environment GPS is not available and other sensors are needed to track the vehicle's position accurately. The problem is that most sensors normally used for this purpose in underwater vehicles are really expensive and drive the cost of the vehicle up significantly, making the use of AUVs unaffordable to most people or companies who need them.

Probably the most popular sensor used for underwater navigation is an Inertial Measurement Unit (IMU). Since these units calculate the vehicle's position through odometry, measurement errors add up and the calculated result drifts from the actual position. It is therefore necessary to use a very accurate IMU. These sensors can become extremely expensive as they are normally used for missile guidance systems. This also makes them very difficult to obtain, as sales are closely controlled to avoid the units falling into the wrong hands. Some systems may well end up with an IMU sensor that costs more than the rest of the vehicle. For this study a low-cost IMU will be used together with other relatively low-cost sensors to test the tracking and navigation capabilities of such a system.

The research questions for this study can therefore be constructed as follows:

- Can a small AUV be developed using relatively low-cost tracking sensors and actuators?
- Can such a vehicle accurately track its position in an underwater environment?

- Can such a vehicle reliably navigate and control its position in an underwater environment?

The significance of solving the above stated problems lies in the fact that people or companies that could previously not afford the use of an AUV may now be able to use it. Even though this is a small and specialised market, it may increase the number of users of AUVs as they can be used in many more underwater applications. It may have an effect on how ocean data are collected and reduce the risks of deep sea exploration and rescue missions.

1.3. System Specifications

Depth: The vehicle needs to withstand pressure to a depth of up to 5 m since the available testing environments are all less than 5 m deep. At this depth the vehicle should still be watertight.

Actuation: The vehicle needs to use thrusters for movement in the water. The vehicle needs to be able to move forward, reverse, move straight up and down, and turn on the spot. Thus the vehicle needs to be actuated with three degrees of freedom.

Endurance: The vehicle needs to have a long enough battery life to support at least 1 hour of continuous mission time.

Buoyancy: The vehicle needs to be able to change its buoyancy by filling internal ballast tanks with water. The ballast tanks need to have a water fillable-volume of at least 1.5 litres.

Vehicle speed: The vehicle needs to be able to move forward at a maximum speed of at least 1 m/s.

Vehicle pose tracking: The vehicle's position needs to be tracked in six degrees of freedom which include roll, pitch, yaw, vertical, sideways and forward motion. The vehicle's x and y position need to be tracked with an accuracy of 0.25 m, depth or vertical position with an accuracy of 0.1 m and roll, pitch and yaw measured with an accuracy of 10 degrees or 0.175 radians.

Vehicle depth control: The vehicle's control system needs to be able to control the vehicles vertical position in the water with a steady state error of less than 0.2 m and a settling time of less than 15 seconds for a step of 1 m in the set point.

Vehicle yaw control: The vehicle's control system needs to be able to control the yaw or heading of the vehicle with an error of less than 15 degrees or 0.262 radians and have a settling time of 10 seconds or less for a position set point change of 180 degrees or 3.1416 radians.

Vehicle x and y control: The vehicle's control system needs to be able to control the x and y position of the vehicle with an error of less than 0.5 m. This control system is only required to navigate to way points and doesn't need to keep its position. As soon as a way point is reached the AUV must proceed to the next way point.

1.4. Research Publications

The following articles were published by the author as either primary author or co-author in respect to this research study.

- 2nd Robotics and Mechatronics Symposium, 10 November 2008, Bloemfontein South Africa, "Autonomous Underwater Vehicle Development for Research and RescueOoperations", by S. Holtzhausen, O. Matsebe, Dr. N.S. Tlale and Prof. G. Bright.
- 15th International Conference on Mechatronics and Machine Vision in Practice, December 2008, Auckland New Zealand, "Autonomous Underwater Vehicle Motion Tracking using a Kalman Filter for Sensor Fusion", by S. Holtzhausen, O. Matsebe, Dr. N.S. Tlale and Prof. G. Bright.
- 15th International Conference on Mechatronics and Machine Vision in Practice, December 2008, Auckland New Zealand, "Robots for Search and Rescue Purposes in Urban and Underwater Environments A Survey and Comparison", S. Holtzhausen, R. Stopforth, Prof. G. Bright, Dr. N.S. Tlale and C.M. Kumile.
- 15th International Conference on Mechatronics and Machine Vision in Practice, December 2008, Auckland New Zealand, "Modelling the Dynamics of an Autonomous Underwater Vehicle (AUV) for Range-Bearing Simultaneous Localisation and Mapping (SLAM)", by O. Matsebe, S. Holtzhausen, Dr. N.S. Tlale and C.M. Kumile.
- 3rd Robotics and Mechatronics Symposium, 9 November 2009, Pretoria South Africa, "Autonomous Underwater Vehicle Development for Research and Rescue Operations" by S. Holtzhausen, P. Bosscha and Prof. G. Bright.

1.5. Definitions, Assumptions, Limitations and Delineation

For the purposes of this research study an underwater vehicle will be developed. The vehicle will only be designed for shallow waters, since testing will only be done to a maximum depth of 5 m. Vehicle dynamic and kinematic modelling will also not fall within the scope of this project, as that may be a study on its own because of the non-linearities involved in underwater systems which would complicate the current study too much if it were included.

The development of a beaconing or trilateration system will include some short cuts as the beacons are connected to the tethered system to trigger the sonar beacons. The reason for this is to cut down on the costs and time involved in the development of a complete trilateration system. But enough has still been done to prove that a trilateration system can be a viable navigation solution.

The testing environment will be tanks or swimming pools. The vehicle will be tested in the absence of strong water currents, but data concerning the effects of water currents might be very relevant to this study. Other tests will be devised to simulate the effect of water currents on the vehicle to see how the controllers react to such disturbances.

Throughout this dissertation the following terms will used and given here are their definitions as they will be used.

- Surge: Forward or backward movement of the AUV towards the front or rear of the vehicle.
- Sway: Sideways motion of the vehicle.
- Heave: Vertical movement of the vehicle.
- Wet components: Components placed on the outside of the hull that will operate in the water and needs to be in contact with the water.
- Dry components: Components placed inside the hull of the AUV that needs to be kept away from water.

1.6. Dissertation Outline and Chapter Overviews

1.6.1. Literature Review

This chapter will discuss the secondary literature studied for this research project. It will identify and review the literature that is relevant to this study. The literature study will firstly look at common applications of AUVs. The next section will discuss current AUV systems. The next few sections will study AUV subsystems which include mechanical design, electronic design, sensor systems, vehicle guidance, motion control, software systems and underwater communication. The last section will provide a conclusion on the literature studied.

1.6.2. Mechanical Design

This chapter will show the vehicle body design of the AUV. It will discuss the considerations in the body design and show which steps were followed and why. A discussion on the stability of the vehicle as well as the manoeuvrability of the vehicle will also be given. The section will end with a conclusion on the mechanical design.

1.6.3. Electronic Design

This chapter will discuss the design and implementation of all electronic components on the vehicle excluding the sensors as these are discussed in a later chapter. The electronic components include power distribution systems, an industrial on-board computer, an additional IO board for data capturing and actuator control, the actuators themselves as well as the communication system. It will also show the system integration between all the hardware. A conclusion will be provided on the electronic design and implementation.

1.6.4. Sensors

This chapter will show and discuss the sensors used for vehicle tracking and how they were implemented and used. It will start by discussing the reference frames, why they are important and how to do transitions between them. Next it will discuss the different sensors used, what each one of them measures and the interface to each sensor type. The section will end with a conclusion made from the sensor implementations.

1.6.5. Data Fusion

This chapter will discuss how and why sensor data are combined from different sensors. The first section will give the data fusion method and explain how it works and how to implement it. The following sections will show how it was implemented for each measured degree of freedom. Experiments with their results will be shown for the different degrees of freedom. A conclusion will then be given on the findings and results of this section.

1.6.6. Software Design

This chapter will cover the implementation of software to control all hardware and control the vehicle as a whole. The software is divided into three sections. The first is the embedded software that runs on the IO board which interfaces directly to all sensors and actuators. The second is the software running on the industrial on-board PC where the Player server is implemented. The third is the base station from where the vehicle is controlled through a Player client program. A section on the implementation of Player and how it was used is also included in this chapter. The chapter will finish with a conclusion on the software implementation.

1.6.7. Control System Design and Implementation

This chapter will discuss the control systems implemented for control of the vehicle's position. Four control systems will be discussed. The first is a simple controller for the ballast system position control. The second is on the PID controller which controls the vertical position or depth of the vehicle. The next is also a PID control system which controls the heading of the vehicle. The last is another PID controller which is responsible for controlling the X and Y position of the vehicle on a horizontal plane. Results on these control systems will also be given throughout this chapter. The conclusion will then discuss these results as well as the implementation of the controllers.

1.6.8. Validation and Conclusion

This chapter will end the research study. A validation will be done to test the vehicle's performance against the specifications given. It will measure whether the research study was successful in answering the research questions posed. Conclusions will be made on the implementation of the research study. A summary of contributions will be given and suggestions for further work will be discussed.

Chapter 2.

Literature Review

This chapter will discuss the literature studied for this research project. Relevant research studies have been identified and studied. The first section in this chapter will discuss common applications where AUVs are being used presently or may be used in the near future. The next section will start with a broad overview of the existing AUV systems currently in use as well as technologies that are still being developed. The following four sections will go into more details on specific areas of focus in AUV design. These include the mechanical design, electrical design, sensor systems and vehicle guidance, control, software and underwater communication systems.

2.1. Common Applications of AUVs

Applications of AUVs can be categorised into three groups according to [32]. These three groups are marine security and warfare, oceanography, and submerged structure inspection and maintenance. Oceanography is the study of the ocean and everything in it, including biological life forms living inside it. It also includes studies on the human impact on the ocean and life in the oceans.

In oceanographic studies, AUV-based surveys can use more sensor platforms and cover larger areas than manned platforms doing the same survey [26]. Using AUVs can therefore be much more efficient than manned systems. The maximum depth of most oceanographic sensors are limited to about 600 m which then limits the mission depth even though the vehicle has the ability to dive to more extreme depths according to [27]. Most AUV systems provide a side-scan sonar as an imaging sonar to provide three dimensional images of the sea floor or some underwater feature to be examined [26].

Ocean observation networks currently consists of drifting buoy systems called ARGO floats which are mostly found at the surface or near the surface of the ocean. These floats' current locations in the ocean observation network can be seen in figure 2.1 taken from [6]. There exists a need to extend these networks to much deeper depths into the water column below the surface so that much more information on the ocean can be harvested as described by [6]. According to [6] the use of AUVs in ocean observation networks will lead to increased density of real-time ocean data, which will enable higher resolution modelling and assessments of ocean conditions.

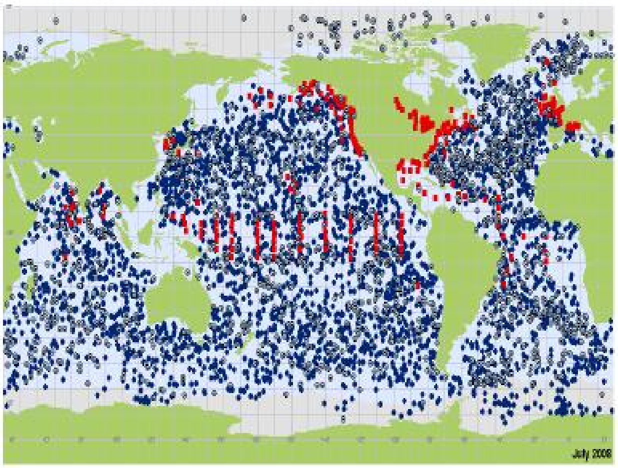

Figure 2.1.: Floats and drifting/moored buoy locations in existing ocean observation network

Installation and use of science nodes on the sea floor is also an option for collecting deep sea oceanographic data but can be very costly for deeper installations. AUVs can provide a cheaper alternative according to [6]. AUVs can also be used to collect data from sea-floor installed sensors instead of laying sea floor cables connecting the sensor node to land stations.

The use of AUVs for ocean surveys has become very common. According to [19] the Autonomous Benthic Explorer (ABE) vehicle has conducted 191 benthic surveys in the last decade at mid-ocean ridge sites at an average depth of 2000 m. These surveys have provided bathymetric and magnetic maps of the sea floor in these areas as well as photographic images of biological and geological features. It also provided detailed maps of hydrothermal plumes found at these sites.

Under-ice exploration as described by [22] has been conducted in the Arctic region to explore micro-organisms evolving in a relatively isolated environment. These areas have been relatively unexplored because of the dangers involved in manned missions in under-ice environments. In a different expedition described in [6] the REMUS AUV, which will be discussed in more detail later, has been used for shallow water oceanographic observations as part of the LEO-15 (Long term Ecosystem Observatory at 15 m) program. The program has also been expanded to mid Atlantic observations. Chemical traces of measurements made in such observation missions can be shown where the sensor traces are overlaid on the mission track of the vehicle. An example of such data can be seen in figure 2.2 taken from [22].

In another oceanographic study, AUVs are being used to map deep coral reefs for conservational purposes as shown by [28]. These deep coral reefs were not previously indicated on available published bathometric charts. Deep coral reefs differ from shallow coral in the fact that photosynthesis cannot take place in deep coral reefs due to the

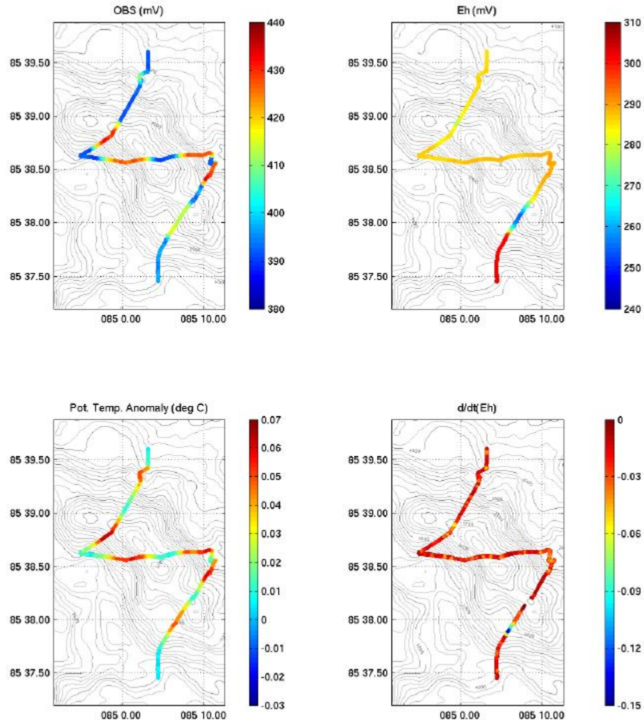

Figure 2.2.: Example of chemical sensor traces overlaid on the mission track of the AUV

absence of sunlight. This type of coral mostly relies on stingers to catch prey. They are being destroyed by bottom-trawling fishing methods. Ivory coral (*Oculina Varicosa*) is already protected and scientists are trying to get the same protection for *Lophelia* coral reefs which are found at a depth of between 300 m and 900 m. The REMUS vehicle was again used for this expedition in a joint operation by the Woods Hole Oceanographic Institute, the Waitt Institute of Discovery and the Harbour Branch Oceanographic Institute.

AUVs are also being used for undersea exploration for the oil and gas industry according to [26]. Previous systems made use of towed sensor platforms. The use of AUVs resulted in time savings in the order of 60 % compared to the towed systems. The savings in time and costs increase even more as the surveys move into deeper waters because the shallow water oil and gas production fields are becoming more and more depleted. Once the production fields have been established, AUVs are used to inspect the pipelines for maintenance purposes. AUVs are also used to do Environmental Effects Monitoring (EEM) in areas affected by the harvesting of petroleum resources as discussed by [27]. EEM consists of measuring the following:

- water temperature,
- salinity,
- turbidity,

- dissolved oxygen,
- chlorophyll,
- nutrients,
- particle matter,
- hydrocarbons,
- dissolved gases and other chemicals,
- and metals such as Fe, Mn, Al, Cu, Cr, Pb and Cd.

Another proposed application for AUVs by [23] is search and rescue operations. The motivation for the use of AUVs in search and rescue operations comes from the European Commission for Research and Technology Development funding program. The section on improving safety and security states that the objective is to develop new technologies and innovative solutions for the improvement of safety and security in transport operations and the protection of vulnerable persons. It outlines research into systems and tools to assist emergency personnel in emergency situations as well as autonomous or remote controlled mechanical systems to be used in rescue missions. Murphy [23] has identified suitable characteristics for AUVs to be used in search and rescue operations. These characteristics are listed below.

- The vehicle should have a low displacement and should be portable.
- The vehicle's mission endurance should be long enough for search and rescue operations.
- The speed capabilities of the vehicle should be in the order of 3 m/s.
- The maximum operational depth of the search and rescue vehicle should be 3000 m.

The advantages of using autonomous vehicles in search and rescue operations are firstly that the search capability is multiplied while using the same amount of manpower. Secondly there is a huge risk reduction to rescue workers and faster and more efficient recovery of casualties. It also provides additional search capabilities that was not previously available and more deployment versatility. Lastly it is usually more cost effective to use AUVs.

AUVs are also being used in shipping ports security, according to [26]. In this case the AUVs are being used for underwater hull inspection of cargo and other ships. The AUV searches for foreign and unwanted objects on the hull of the ship. AUVs have also been employed for military use in the form of mine hunting. REMUS 100 AUVs were used in Operation Iraqi Freedom in 2003 for shallow water mine hunting.

This section showed some of the applications where AUVs are currently being used. It described applications ranging from environmental studies to military use.

2.2. Review of Existing Systems

This section will take a look at current AUVs in operation. It will discuss their physical properties as well as their internal workings. The idea is to first know what is out there before starting a new design.

There are AUV competitions in which the vehicle has a specified mission to complete autonomously. These competitions are primarily for universities or other academic institutions. Some of the literature studied was mainly on the development of a vehicle for participation in these competitions. These include [1] and [9]. The European competition is called the Student Autonomous Underwater Challenge - Europe (SAUC-E). The literature studied in this case was on the participation in the 2007 competition held in July at Haslar Ocean Basin, Gosport, UK which is 5.5 m deep. The University of Southampton won the competition with their vehicle called SotonAUV which will be discussed in further detail later in this section. Second place was awarded to the University of Cambridge and third to the ENSIETA team. Another competition for AUVs is the International Autonomous Underwater Vehicle Competition (IAUVC). The objective in this competition is to demonstrate vehicle autonomy by locating a target on the floor, depositing markers onto the target and then proceeding to the recovery zone.

Murphy [23] describes existing technologies for search and rescue operations which include bad weather and night vision systems, radar, electronic location beacons, self-deploying life rafts and high-performance life boats. Acoustic sensors that can discriminate between surface swimmers, submerged divers and other biological lifeforms have also been developed and are already commercially available. These systems together with an AUV can be very useful in search and rescue situations as well as other operations.

A visual servo application has been developed in [30] with an AUV that uses stereo vision cameras to track and follow certain objects. This system could be extremely useful in certain applications of AUVs where the the vehicle needs to follow an object such as a certain fish.

In extended AUV missions it is preferred to make use of a different type of AUV according to [26]. These AUVs are called gliders. Gliders are low-power AUVs using wings and buoyancy changes for propulsion. Actuation is therefore only needed when the buoyancy of the vehicle needs to change and the vehicle follows a sinusoidal-type path going up and down continuously. Gliders have great potential in ocean observation networks due to their long endurance and they are becoming more popular to use in the research community according to [6]. New technology in gliders, as discussed in [26] have produced gliders that make use of the variation in ocean water temperature to change its buoyancy and thus reduce battery power requirements even more. Gliders have been used in oceanographic missions that lasted several months without having to recharge their batteries.

The rest of this section will discuss existing AUVs that are currently being used. The first AUV as shown in [1] is the SotonAUV develop at the University of Southampton. This AUV has been designed specifically for the SAUC-E competition as described above. The AUV is 1.31 m in length and uses two wing-mounted side thrusters for lateral propulsion. It also makes use of two vertical tunnel thrusters for vertical propulsion. The vehicle makes use of a 12 V 7 Ah battery pack containing sealed lead acid batteries which allows 20 minutes of operation. The sensor system of the vehicle consists of a magnetometer for yaw measurements, pressure sensor for depth measurements and an IMU which can measure all six degrees of freedom. The software runs on a Windows XP platform using Matlab for vehicle control. The control software consists of five software agents running in parallel. These five agents include the mission controller, two camera agents, the remote control agent and the monitoring agent.

The next AUV to be reviewed is the REMUS AUV. The REMUS is a very popular AUV and has been used in numerous studies including [6], [26], [27] and [28]. The vehicle was developed at the Woods Hole Oceanographic Institute. The REMUS is a lightweight, low-cost AUV developed for coastal water monitoring. There are different variations of the REMUS vehicle available but the standard vehicle has a maximum depth of 200 m. It is 1.5 m in length with a diameter of 20 cm. The vehicle's dry mass is 30 kg. The REMUS 6000 is described in [28]. It has a maximum depth of 6000 m and makes use of a side-scan sonar and multi-beam sonar for acoustic imaging.

The Puma and Jaguar are two very similar AUVs developed for under ice exploration described by [22]. The vehicles are each 2 m in length and 1.5m tall. It has an upper and lower hull spaced apart from each other. The vehicles weigh 250 kg each. It makes use of three thrusters for lateral and vertical propulsion. It contains a battery pack of 64 lithium ion batteries which gives it a mission time of more or less 24 hours. It has horizontal top speed of 35 cm/s and dives at 20 cm/s. Due to the double hull design the vehicle is naturally stable in pitch and roll. It has a maximum depth of 6000 m. The Puma AUV is shown in figure 2.3 taken from [22].

The Flaga is a hybrid-type AUV which combines features from normal AUVs and gliders as shown in [2]. Its name is taken from the Italian water-bird that dives into the water to catch fish. The vehicle is 2 m in length and a mere 14 cm in diameter. It has a mass of 30 kg and can vary its mass by 0.5 kg for buoyancy changes. It also has a moving mass inside to change the position of the vehicle's centre of mass. The moving mass has a displacement of 5 cm. The Flaga is powered by a 12 V 72 Ah lead acid battery pack. It has a maximum operating depth of 50 m. The maximum speed is 2 knots or 1.01 m/s and jet pumps are used for propulsion. The Flaga AUV is shown in figure 2.4.

The C-SCOUT was developed at the Memorial University of Newfoundland and is described by [8]. It is a modular AUV where the modules contain either electronics, fin actuators, sensors, ballast, through-body thrusters or body contours. The vehicle is designed for speed and long distance. The MUN Explorer AUV is described by [27]. It

Figure 2.3.: The Puma AUV hangs from a deployment crane off the side of a ship [22]

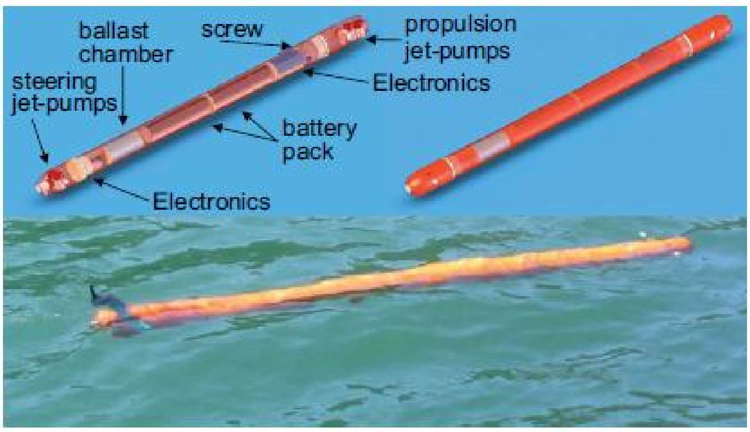

Figure 2.4.: The Flaga III AUV [2]

is 4.5 m in length with a maximum depth of 3000 m. The AUV can carry a scientific payload of 150 kg. The MUN explorer AUV is shown in figure 2.5.

Figure 2.5.: The MUN Explorer AUV surfaces during a mission [27]

The ARCS AUV also described by [27] is a 6.4 m vehicle with a 68.6 cm diameter. It has a range of 235 km and a maximum depth of 300 m. Its maximum speed is 2.8 m/s. The biggest AUV in the world is the URASHIMA AUV described in [14]. The URASHIMA was developed in Japan and has a length of 10.6 m. The vehicle width is 2.55 m and it weighs 10 tons. It has a maximum operating depth of 3500 m and a range of 300 km. The vehicle's maximum speed is 4 knots. It can change its buoyancy by up to 60 kg. The vehicle is powered by fuel cell technology. Sensors include INS, DVL, a homing sonar and an obstacle avoidance sonar. The AUV is shown in figure 2.6 and the vehicle layout is given in figure 2.7.

Figure 2.6.: URASHIMA AUV recovery after a mission [14]

The last AUV to be studied is the SLOCUM glider AUV described in [16]. This AUV differs from the other in the fact that it is a glider AUV. It therefore does not make use of thrusters but uses wings together with buoyancy changes for propulsion.

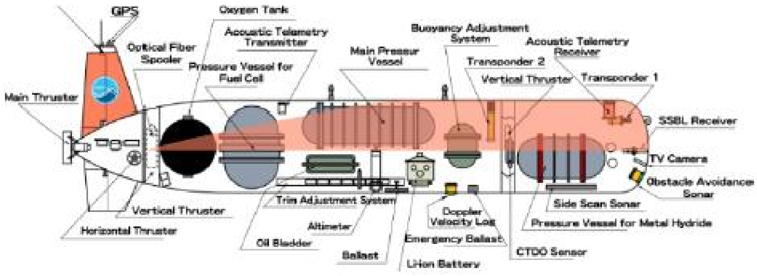

Figure 2.7.: URASHIMA AUV layout [14]

The vehicle is 1.8 m in length and has a cruising speed of 30 - 40 cm/s. The vehicle follows a saw-tooth vertical trajectory. The vehicle uses a tail rudder for steering. The batteries of the vehicle enable operation of anything between 20 and 50 days depending on the sensor payload being carried. The vehicle has a maximum operational depth of 200 m and the newer version of the SLOCUM glider will have an operation depth of 1000 m. Since the mission time is much longer than that of other AUVs, the gliders are programmed to surface at regular intervals to transmit position and sensor data and download new mission way points or specifications. The SLOCUM glider is shown in figure 2.8 taken from [16].

Many AUVs are currently in use all over the world and are being used for many different purposes. This section has shown and discussed a few of these AUVs and described their general method of operation.

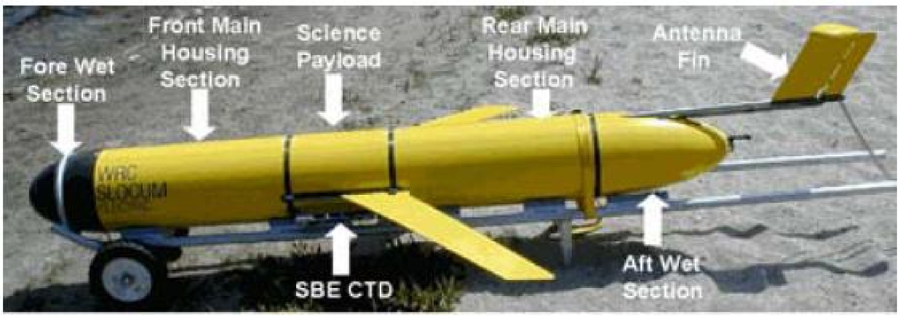

Figure 2.8.: The SLOCUM glider ready for deployment [16]

2.3. Mechanical and Electrical Design

Every AUV in its simplest form must consist of some sort of navigation system, propulsion system and a dry watertight compartment where the electronics are hosted, according to [9]. Mechanical design factors of an AUV include buoyancy, hydrodynamic damping, Coriolis forces, added mass, stability and water pressure. Nicholson [26] proposes a modular design for the AUV, where a single vehicle can carry one of many sensor packs or has many different configurations to perform a greater variety of missions. This then reduces the cost compared to multiple AUVs with each a single purpose.

To ensure roll and pitch stability, according to [9], the centre of buoyancy should always be directly above the centre of mass of the vehicle. The two should be vertically aligned to give a bottom heavy configuration. Batteries are usually the heaviest components of the AUV so it should be a good idea to place them as low as possible inside the hull of the AUV. The AUV should also be designed to have close to neutral buoyancy so as to minimise the force required to keep the vehicle submerged.

Many different materials can be used for the construction of the hull. Usually metals like aluminium are used, but the URASHIMA has a titanium frame, with titanium alloy vessels or compartments to withstand the water pressure. The URASHIMA's body is then covered with fibreglass reinforced plastic according to [14].

Many different propulsion systems have also been tested and investigated in the literature. Most AUVs use propeller-type thrusters but [20] shows a design for jet propulsion thrusters inspired by squids and other *Cephalopods*. Water is drawn into a large cavity and ejected with high momentum through a nozzle to propel the vehicle forward. This provides the AUV with the ability of low-speed manoeuvring forces without affecting forward drag on the vehicle body. Other studies have attempted to mimic fish propulsion methods. One of these are seen in [11] where a fish-like mechanical structure has been developed for the AUV. The biomimetic AUV is propelled by mimicking fish body and fin movement. The study also shows the modelling and control of the propulsion system. The vehicle body movements are then optimised using genetic algorithms. Another study given in [25] uses macro-fibre composite material to create a fin actuator for an AUV. It uses piezoelectric smart materials for actuation. The actuator mimics creatures with long and slender shapes like a sea snake. The actuator creates thrust by creating transformation waves generated by a meandering motion.

Some AUVs have the ability to vary their buoyancy. Buoyancy is changed by either changing the weight of the vehicle or changing the volume of the vehicle in the water, thereby changing the amount of water displaced by the vehicle. Hyakudome [14] presents a buoyancy control system that makes use of an oil tank and bladder system where oil is pumped between the tank and the bladder to vary the size of the bladder.

Hydrodynamic forces are the subject of many studies in underwater systems. According to [9] hydrodynamic forces are forces acting against the motion of the vehicle in the water. Hydrodynamic forces are the cause of most non-linearities when modelling the vehicle dynamics. Hydrodynamic forces are also very difficult to observe and measure. The hydrodynamic coefficients can be calculated using the component build-up method according to [8]. The study derived the hydrodynamic forces from empirical relations that only require the specification of vehicle geometry. Another study from [33] used Computational Fluid Dynamics software to estimate the hydrodynamic coefficients of an

AUV with a complex structure or a vehicle that is not streamlined. The study estimated 36 hydrodynamic coefficients.

According to [26] most AUVs use lithium ion battery systems. It is of great importance to use the latest battery technology since battery capacity limits the AUV endurance and battery size is also a constraint. The study also discusses the use of underwater docks with charging stations for AUVs. Charging can be done through induction where no electrical connection is needed. These underwater charging stations have not seen much use in present AUV systems.

In the electronic system implementation from [9], the author proposes the use of a leak detection system. The system uses a set of probes at the bottom of each hull connected to an ADC to check for water inside the hull.

This section described some of the mechanical and electronic considerations involved in the design process of an AUV. It also discussed some of the problems tackled by other researchers in the field of AUV development.

2.4. Typical Sensor Systems and Guidance

This section will look at typical sensors used on current AUV systems. It will mostly focus on the sensors AUVs in the literature use for navigational purposes. It will also have a look at how data from these sensors were used to track and guide the vehicle.

Before looking at the sensors used, one should first understand the concept of the two reference frames used in specifying the vehicle's state. The reference frames are described in [30]. The two reference frames are the world or global reference frame and the vehicle reference frame. The world reference frame is specified before hand and is set to the environment around the vehicle. It can be set so that the x axis in this frame always points north, the y axis always points east, and the z axis always points straight down. The origin of this reference frame can be set as the vehicle's starting position or anywhere else and doesn't change through the course of the mission. The vehicle's reference frame is always centred at the vehicle's centre of mass and turns and moves with the vehicle. These two reference frames are used because some sensors' measurements are taken in the world reference frame, for example GPS, and some sensors' measurements in the vehicle's reference frame, for example IMU. To be able to use all these sensor data for vehicle navigation one needs to be able to convert measurement vectors from one reference frame to the other. A vector transformation matrix is set up to do the translation between the two reference frames.

According to [19] GPS can provide superior three dimensional navigational capability. The problem with underwater environments is that the GPS radio signals are blocked by the water and GPS can therefore only be used when the vehicle is surfaced. This means other sensors are required for underwater vehicle tracking and navigation. Other navigation systems include sensors such as LBL, DVL and a magnetometer or compass, according to [22]. These sensors are then used together with a differential GPS which is used to update the vehicle's position every time the vehicle surfaces. The Kambara AUV in [3] utilises the following sensors for navigation: a compass module, an inclinometer, pressure sensor and a motion pack which contains an IMU.

An LBL system is basically a form of triangulation or trilateration. This system is described in [19]. The system makes use of beacons usually deployed on the sea floor but sometimes also on the surface in the form of GPS-equipped buoys. The beacon positions are known to the vehicle. The beacons transmit an acoustic pulse to the vehicle which the vehicle then uses to calculate its position. These systems usually operate with an acoustic ping at about 12 kHz. The higher the frequency the more accurate the positioning system but the lower the range. An accuracy of anything between 0.1 to 10 m can be achieved, depending on the frequency used as well as other system factors. Another system very similar to LBL is USBL also described in [19]. This system makes use of a single sonar array usually mounted on a ship hull to calculate the range and bearing to the vehicle to get its position. The advantage of this system is that it requires less infrastructure before the mission starts.

A DVL is a sensor that makes use of Doppler navigation as described in [19]. A DVL employs Doppler sonars to provide bottom-velocity measurements. These measurements can then be used to calculate the relative position of the vehicle. This method of vehicle tracking is only useful in near-bottom navigation, where the vehicle is less than 100 m from the sea floor. This system is usually implemented together with an INS navigation system that will be discussed later in the section. According to [26], navigational accuracy of 0.05 % of the total distance travelled has been achieved with a DVL navigation system while bottom-lock was maintained during the mission.

The sensor used for vehicle depth measurement is usually a water pressure sensor that can calculate the depth from the water pressure, but [9] also describes the use of an echo sounder to measure the vertical position (depth) of the vehicle. An echo sounder bounces an acoustic pulse from the bottom to find the distance and, if the depth of the environment is known at that point, one can calculate the vertical position (depth) of the vehicle. The system can also be used facing upwards, as the acoustic pulse will also be reflected from the water surface.

Magnetic heading sensors or compasses can be found on almost all AUVs. According to [19] the accuracy of a magnetic heading sensor can be the main source of error in the performance of the overall navigation system. Sources for errors in magnetic heading sensor measurements can be one or more of the following:

- the vehicle's own magnetic signature due to metals used in the construction of the body,
- gravity-based roll and pitch compensation affected by vehicle acceleration,
- geographic or local magnetic anomalies in the nearby vicinity of the vehicle, and
- orientation of the compass mounting inside the vehicle.

Inertial-based systems like IMU or INS have become very popular navigation sensors for AUVs according to [19]. These systems provide very accurate navigation in short missions. These systems can be very costly. Low-cost IMUs are usually not accurate enough for AUV navigation. IMUs contain gyroscopes and accelerometers, one of each installed on the three axes. Because these sensors measure velocity and acceleration, one needs to calculate the integral of the measurements to be able to find the vehicle's position. The errors in measurements causes sensor drift in the integral calculations since all the errors add up and the error in position will grow with time.

Some of the best solutions achieved so far were when two or more of the above systems were combined to form an AUV navigation system. The feasibility of INS and DVL combined with GPS for AUV navigation has been confirmed by a study done by the Monterey Bay Aquarium Research Institute [31]. This study also provides a guide for sensor and navigation systems depending on the length of the mission. For mission distances less than 10 km a calibrated INS system together with a DVL or some other acoustic navigation system should suffice. For longer range missions up to 100 km a large network of beacons or landmark-based navigation systems, which will be discussed later in this section, are required. Missions with a range greater than 100 km are problematic. IMU-based systems will show too much sensor drift, a beacon network is impractical due to the size of the network and SLAM or landmark-based systems will use too many landmarks and the processing time will become impractical. Such missions can be navigated using a method called Fast-SLAM or Constant Time SLAM where less computation time is needed.

A study by [15] proposes a method to improve the accuracy of an INS navigation system. The idea is to rotate the IMU on a turntable inside the AUV at a constant rate about the Z axis. This will then reduce the error on the gyroscope measurements from the IMU. More processing is required due to the fact that an extra reference frame is introduced for the rotating IMU. Another study [13] shows a method to model the error of an INS/DVL navigation system. The model is then used to predict the navigational error of the AUV and promote its accuracy. The study uses time-series models to describe the error and the model coefficients are then estimated. It uses the 53H method to generate a smooth estimate of the data.

The study done by [19] proposes the use of deterministic state estimators where the knowledge of the vehicle's dynamics are used to derive diffusion based trajectory estimators. These navigation state estimators supplement sensor measurements with information from a kinematic or dynamic model. These state estimators can be implemented as a form of sensor data fusion where data from more than one sensor is used to improve on the accuracy of a single sensor. According to [26] data fusion of several navigation sensors can minimise navigation errors. A good example of such a system is a GPS-INS-DVL navigation system. Techniques used for AUV position estimation and data fusion are described in [31]. They include:

- Kalman filters and extended Kalman filters,
- particle filters,

- SLAM as well as Concurrent Mapping and Localisation.

According to [19] Kalman filtering as well as the extended Kalman filter are very popular for implementation of AUV state estimation. It presents a form of unbiased estimation. The idea is to use data from many sensors to estimate the vehicle's state. In a study by [12] the use of a low-cost IMU for vehicle orientation tracking is proposed. Sensor drift is discussed here to be an offset in the sensor measurement. The study uses a Kalman filter to estimate the orientation or heading of the vehicle. An experiment was performed where the IMU was placed on a turntable together with a magnetometer. State estimation was done using a Kalman filter and gave very promising results.

Particle filters are also an option for AUV state estimation according to [31]. They are not subject to the restrictions of a Kalman filter and can accurately model highly non-linear functions where the uncertainties are non Gaussian. The problem with particle filters is that they are much more computationally intensive than Kalman filters.

SLAM is a navigation technique where no infrastructure or knowledge about the environment is needed as shown in [19]. The vehicle exploits its sensing abilities and uses range and bearing data to landmarks to correct the odometric error. The vehicle builds a map of landmarks as it moves about its environment and at the same time localises itself in the map. The major challenges of SLAM is firstly defining features from raw sensor data and secondly to establish measurement to feature correspondence or data association. The fact that the sea floor is very unstructured makes SLAM in underwater environments much more difficult than in other environments.

There is a need for more accurate near-bottom navigation in AUVs according to [19]. Improvements in this area will allow scientists to more fully exploit scientific data collected in near-bottom AUV missions. The study done by [2] also proposes an adaptive sampling system where oceanographic data are analysed on the vehicle itself and the next sampling location is established on-line. The study also discusses the use of a team of AUVs working together and communicating with each other to achieve a common goal more efficiently.

Many different sensors and their suitability to different situations have been discussed in this section. Vehicle state estimation has also been shown to be a successful method for data fusion to improve on the errors and shortcomings of a single sensor.

2.5. Vehicle Control

Many different techniques for AUV control are presently being implemented. Control systems from PID controllers to Fuzzy Logic controllers have been used on AUVs. This section will look at the systems used on present day AUVs.

The URASHIMA AUV employs nine independent control systems as described by [14]. The controllers are used for different degrees of freedom or for different mission objectives and are not all in use at once. The controllers include control for vehicle speed, pitch, depth and heading, also heading rate, fixed-point keeping, an altitude controller, trim controller and a buoyancy force controller. The system generally makes use of PI controllers as they use a simple structure and are robust.

A method called computed torque control is discussed by [30]. This is actually not a control system in itself but is used to linearise the output of the thrusters used so that the implemented control system can be more efficient. The thruster input voltage to output torque is measured so that the relation is known. The thruster torque is then controlled instead of the thruster input voltage. The control system used in this study is a PID controller.

According to [9], simple PID controllers have been successfully used for AUV motion control. They are relatively easy to implement and are robust. Other control techniques used in AUV motion control are Simple Linear Quadratic Gaussian controllers as well as Fuzzy Logic controllers. Fuzzy Logic controllers avoid the need for complex hydrodynamic modelling but the controller itself can become very complex to implement. The study by [30] also discusses the common use of PID control for AUV motion control due to its simplicity of implementation. The study has shown that a PID controller can yield satisfactory results in small operating environments. In [2] a PID controller is used where the integral part is removed and control is only performed through the proportional and derivative part. The P and D gains are tuned through a process of trial and error and by understanding the effects of the different gains of the controller until acceptable performance has been achieved.

Other systems like the one implemented in [21] shows how a discrete-time-delay controller can be used to control yaw and depth position of the AUV. The dynamic model of the AUV is also analysed in the study. Another system discussed in [4] seeks to compute the optimal kinematic controls and corresponding curvature and torsion of the AUV path. The tool used to do this is the coordinate free Maximum Principle of optimal control. It first establishes the kinematics and geometry of the AUV. The study by [8] makes use of a cross-track controller to direct the vehicle to a target point and attempts to minimise the distance between the vehicle and a desired path. The system discussed in [24] makes use of model predictive control for AUV heading control. The AUV in this case is a torpedo shaped AUV using rudders for yaw actuation. The controller is optimised using a genetic algorithm. The controller in this case uses a class of algorithms to compute a sequence of manipulated adjustments to optimise future behaviour of the plant or in this case the AUV.

As can be seen in the literature studied on AUV control many different control techniques have been successfully implemented for AUV motion control. The most popular controller used is probably PID control, due to its simplicity and robustness.

2.6. Vehicle Software and Underwater Communication

This section will discuss the software implementations of existing AUV systems as well as underwater communication systems used presently.

Vehicle autonomy can be defined or implemented in many different ways according to [26]. It can be a set of way points that the vehicle needs to follow by itself in order to complete its mission. Obstacle avoidance can also be included in the navigation strategy. The navigation strategy is what defines the autonomy level of the AUV. This strategy is implemented in the software, and the vehicle navigation decisions are based on it.

In the AUV software implementation in [32] the software is broken up into modules. Each module runs in its own thread independently of the others. Data passes between the modules for processing. The modules implemented in this study are the command module, communication module, navigation module, instrumentation module and vision module. In the implementation of the URASHIMA AUV software discussed in [14], the software has three navigation modes. These are autonomous navigation mode where the vehicle follows its programmed instructions without any external control, acoustic remote control mode where the vehicle is controlled through limited acoustic signals from the control ship and tethered remote control mode where the AUV are much more precisely controlled through a tether connecting the AUV to the control ship. In the software implementation by [32] the AUV software has three modes of operation. These include mission staging where the instructions to complete the mission are loaded on the AUV and everything is set up for the mission at hand, mission execution where the mission instructions are executed by the AUV and data reporting mode where the data recorded during the mission are fed back to the operators.

Safety features in the software are also necessary for vehicle preservation. These are described in [22]. The safety measures ensure that the vehicle is not damaged when something goes wrong and that the vehicle will return to the surface to be recovered in case of an emergency. In the case of the implementation by [22], the vehicle will abort its mission and automatically surface if:

- the on-board computer reboots,
- the control process exits,
- an abort signal is received from the control ship,
- an internal mission abort is triggered by a set of internal rules, for example a maximum depth reached.

This safe mode will ensure a controlled surface procedure by the AUV.

Since underwater communication cannot be done using standard radio signals, acoustic pulses are used to transmit data wirelessly through the water. The data rate and range limitations on acoustic systems are far greater than that of radio systems. Acoustic communication systems exist and have been successfully employed on AUVs. The study by [26] discusses some of the most commonly used acoustic communication systems used for underwater data transmission. The first system discussed is the Benthos Telesonar. It has a data rate of 1 kilobit per second and ranges in the order of a kilometre. Another system commonly used by the offshore petroleum industry is the LinkQuest modem, which shows very similar performance to the previous system. The most popular system used in AUVs is the Woods Hole Oceanographic Institute acoustic modem or short, the WHOI micro modem. This modem has been successfully implemented in many AUVs used for underwater research. The system implemented in [22] also employs the WHOI micro modem. It uses a base signal of between 8 and 12 kHz and has an effective range of 7 to 10 km. The data transfer rate is 80 bits per second. The slow transfer rate in these acoustic systems limits communication to the bare minimum and is usually not used for sensor data transfers from the AUV but only for simple commands and AUV status messages. The study by [19] shows that acoustic modems can be used in a team of AUVs to share range measurements and telemetry data for more accurate navigation.

This section has shown important software considerations and methods for software implementations. It also discussed how underwater communication between the control ship and the AUV can be achieved.

2.7. Conclusion

This section has discussed the secondary literature on previous work undertaken by other players in the field of autonomous underwater vehicles. It discusses the initiatives of other researchers to overcome the problems found in the design and development of an AUV. Many of the studies were shown to be very relevant to this study and much has been learnt from them. Other studies simply show and discuss the current situation in the AUV world.

Chapter 3.

Mechanical Design

This chapter will discuss the mechanical issues in the design and development of an AUV. The first section will show the vehicle body design and also discuss the design steps. The following section will discuss the component layout inside the vehicle and how the layout as well as the vehicle shape affects the vehicle stability. The next section will discuss the vehicle's manoeuvrability and controllability due to its shape and thruster positioning followed by a discussion on thruster torque output. The chapter will end with a conclusion on the mechanical considerations in the design process.

3.1. Vehicle Body Design

It was decided to make the vehicle body design a simple design using easy and quick construction processes. For the final design a simple rectangular box was used as a watertight compartment to house the dry components of the AUV. A protective frame was then designed and placed around the rectangular box to provide protection to the AUV as well as the sensors mounted on the outside of the AUV. The material used for the construction of the rectangular box was aluminium, as it is relatively inexpensive, easy to acquire and easy to work with. Aluminium plates were welded together to form the water tight container.

The size of the watertight container had to be kept as small as possible to limit the amount of water being displaced by the AUV and to achieve close to neutral buoyancy. The minimum space possible for the container was restricted by the components to be placed inside. The length of the container had to be at least the length of the ballast tank which with a fully extended piston rod requires 520 mm. The width of the container was determined by the combined width of the two ballast tanks as well as a battery between them. These added up to 240 mm. The height of the container was limited by the combined height of the batteries and the on-board computer which came to 160 mm. The container size was decided on to give a little extra play on these minimum measurements. The final dimensions are 530 mm by 304 mm by 186 mm. This gives the container a total volume of close to 30 cm^3.

The vehicle design was done in SolidWorks and the extra components that would be mounted on the outside were also added. With the extra components the calculated volume given by SolidWorks was 34.4 cm^3. This means that to achieve neutral buoyancy the vehicle needs to have a mass of around 34 kg. From the SolidWorks analysis together with knowledge on the weight of the thrusters mounted on the outside, the calculated weight of the empty vehicle would be 13.22 kg. This meant that more than 20 kg still needed to be added inside the vehicle for neutral buoyancy. The Solidworks design is shown in figure 3.1. Thruster mountings were designed in such a way that the holes for the bolts go through the protective frame instead of the hull.

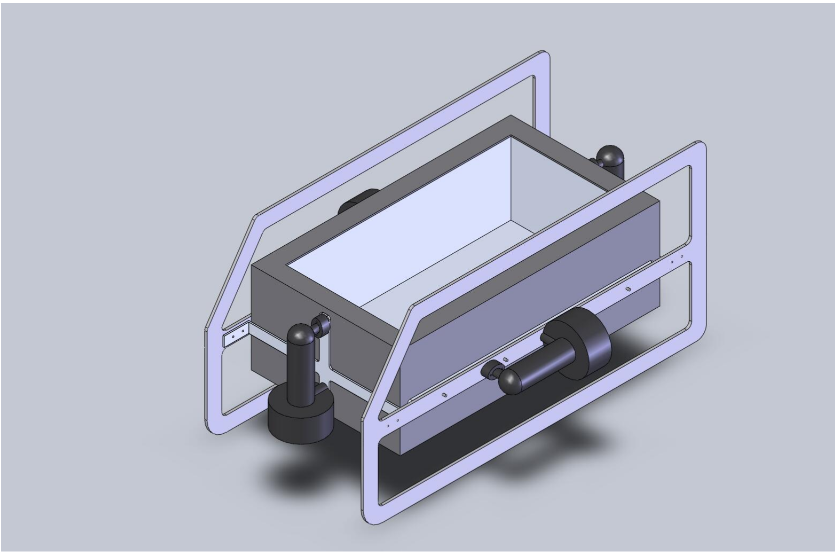

Figure 3.1.: SolidWorks design of the AUV hull, protective frame and thrusters

The opening in the watertight container had to be sealed in such a way that it can be easily opened and closed again and still remain watertight. A lid with a rubber o-ring was designed for this purpose. The idea was to make as few as possible holes through the body of the AUV as these can potentially be a source of leaks in the hull. An extra plate with bolts was glued to the upper lip of the container around the opening. Bolts were counter sunk and tapped into this plate pointing upwards. The upper lid was then bolted to the lower lid. The o-ring was installed on the inside of the bolts so that the bolts are on the wet side of the o-ring. The o-ring was placed inside a groove in the lower plate of the lid where the depth of the groove is about a third of the o-ring diameter. This ensures that the o-ring is compressed and shaped to its surroundings to create a proper seal. The lid design is shown in figure 3.2.

The completed vehicle with all components installed weighed 23 kg. This meant that more weight was needed. Lead shot was placed in bags and evenly distributed inside the vehicle. This added about 11 kg to get the vehicle closer to the required weight for neutral buoyancy. Lead can be added or removed in case the vehicle weight needs to be adjusted or more components are installed inside.

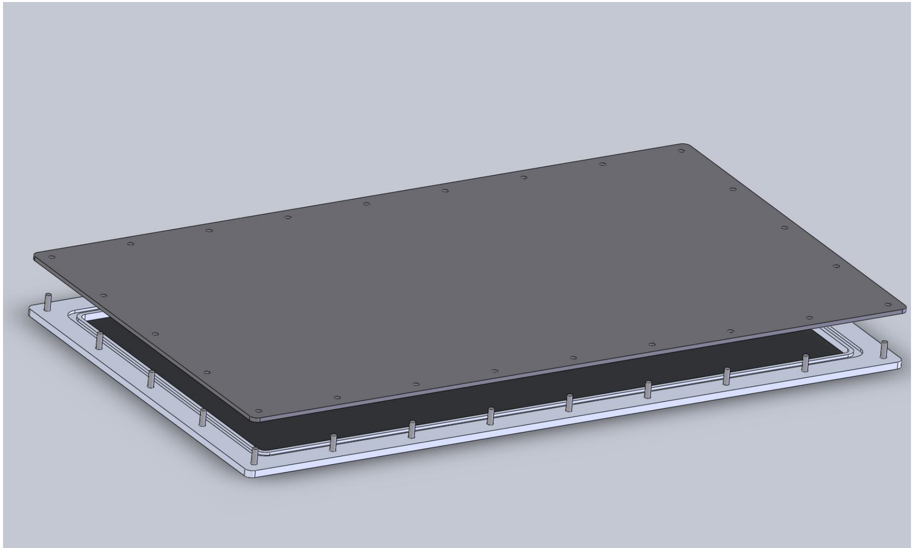

Figure 3.2.: AUV watertight lid design

The aluminium lid was replaced with a transparent perspex lid. The purpose of this is that the operator can see what is going on inside the AUV without having to remove the lid. When the vehicle is surfaced the operator can check for water inside the vehicle or make sure everything is still running as it should. Blinking LEDs used on the electronics of the AUV could now be used to display the status of some of the hardware. The transparent lid also helps to ensure that the o-ring was compressed evenly and that it seals everywhere.

The protective frame was connected to the sides of the watertight container. The frame was fastened to the side using bolts that are glued to an aluminium strip. This was done to minimise the holes in the hull of the AUV.

Holes were only drilled for cables that were absolutely necessary. These cables include the four thruster cables, water-pressure sensor cable, the acoustic transducer cable and the tether cable. Stainless-steel glands were used to ensure a watertight seal where the cable goes through the hull. All the glands used for this purpose had an IP68 rating which meant it could be submerged in water and still remain watertight.

Experiments were performed to ensure that the AUV is completely watertight before any electronics were installed inside. The empty vehicle was filled up with weights to enable it to sink. The lid was fastened and the vehicle was lowered to the bottom of the testing tank at the CSIR, which is 5 m deep. The vehicle was left at that depth for a couple of hours. After the experiment the AUV was opened up to check for water inside the watertight compartment. Leaks were fixed and the experiment was repeated until the vehicle was found to be completely watertight at this depth.

The complete AUV is shown in the photo in figure 3.3.

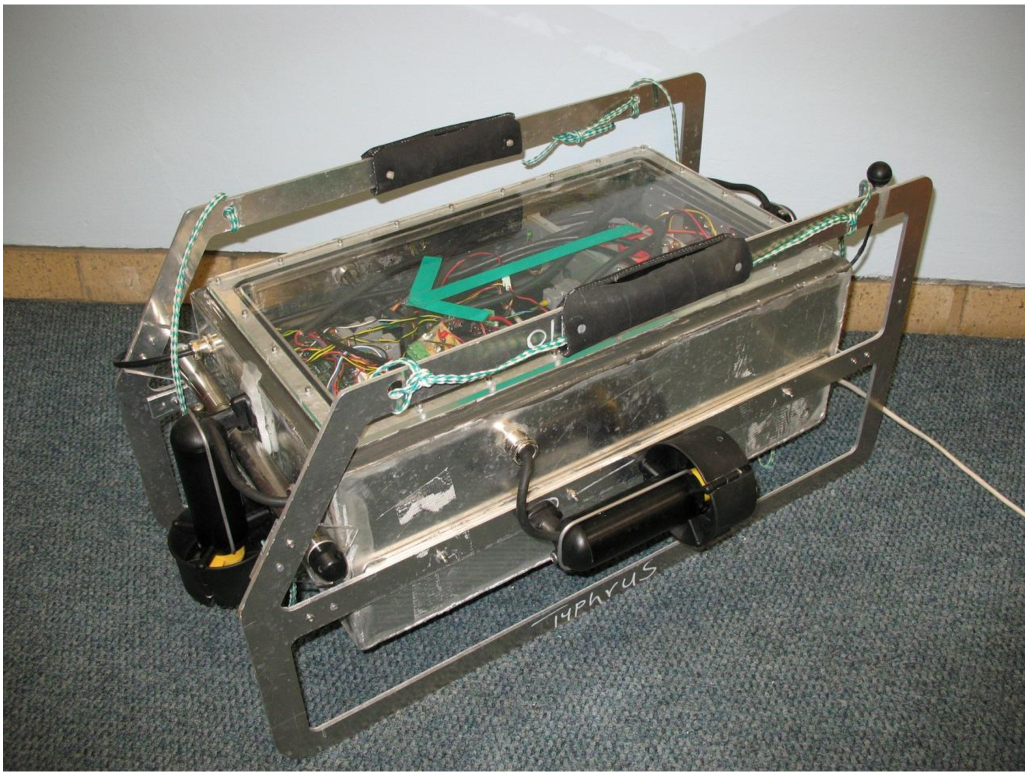

Figure 3.3.: A photo of the complete AUV

3.2. Vehicle Manoeuvrability and Controllability

The AUV utilises four thrusters. Two thrusters are mounted on the side of the AUV facing forward, facilitating forward and reverse motion as well as differential turning. This means the vehicle can turn on the spot without having to move forward or backwards to be able to turn. This is unlike AUVs making use of a rudder system were a minimum speed is required to be able to turn and manoeuvre. A rudder controlled AUV is also limited in manoeuvring space as it usually requires a large circle to complete a full turn. The AUV designed for this project has the ability to turn and manoeuvre in small confined spaces.

The thrusters can provide up to 28 N of thrust in the water which is more than enough to accelerate and drive the AUV at comfortable velocities. The section on control systems will show that the thrusters provide more than enough torque to control the vehicle's position in a three dimensional space even though the AUV shape is not optimally streamlined.

The AUV is under-actuated due to the fact that it does not provide actuation abilities in roll and sway movements.

3.3. Vehicle Layout and Stability

To ensure vehicle stability in pitch and roll, the layout of components inside the vehicle had to be carefully designed. The hull of the vehicle was split up to form two levels, one at the bottom and one at the top. The heavy components were placed on the bottom level. The reason for this was to ensure that the centre of mass will be lower than the centre of buoyancy. The heavy components placed in the bottom included the two batteries, the ballast system and the lead shot. Also, the electronic components were placed on the top level as water leaking into the vehicle would flow down the sides to the lower level first and the electronics would be unharmed if only a little water got in. Measures were taken to detect water inside the hull of the AUV. The top level of the hull contains the on-board computer, the IO board, the dry sensors, the motor controllers and the power supply for the ballast system.

The bottom and top level layout is shown in figure 3.4 and 3.5.

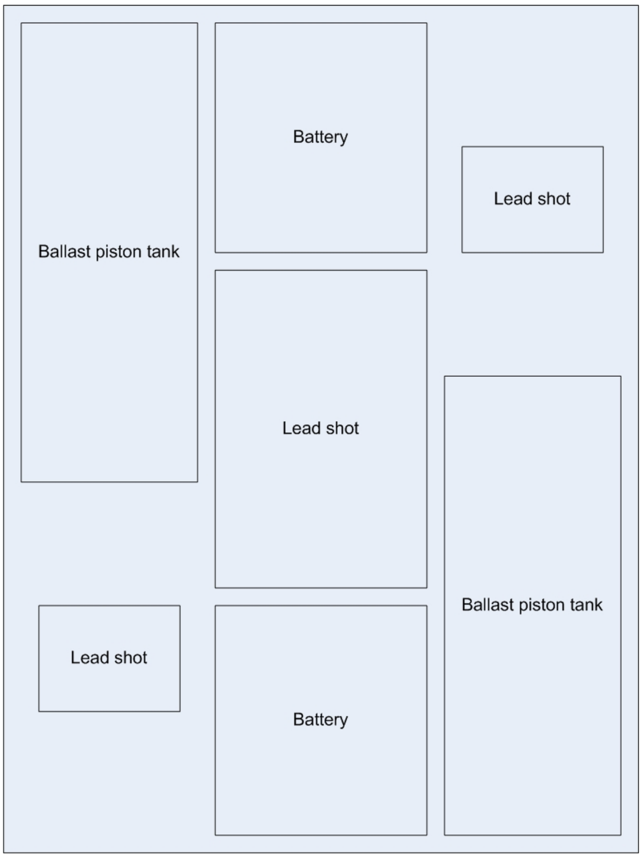

Figure 3.4.: Component layout of the bottom level of the AUV

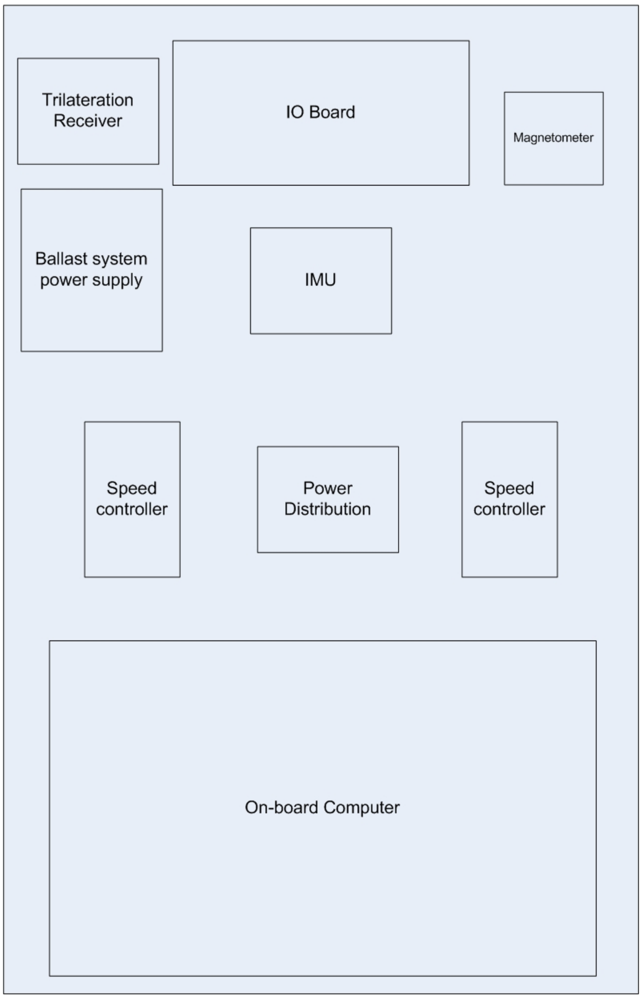

Figure 3.5.: Component layout of the top level of the AUV

Because the AUV is naturally stable in roll and pitch, no actuation or control were implemented in these degrees of freedom. Even though the front and rear thrusters can provide the ability for pitch actuation, it was not implemented in this project.

3.4. Thruster Torque Output

The thruster input signal to output torque relation were found to be non-linear. This non-linearity can cause undesired effects in vehicle control. This meant that the relation between the input signal to the speed controller had to be modelled to the output torque created by the thruster. An experiment was conducted to measure this input to output relation. One of the thrusters was mounted on the end of an aluminium arm that can be placed in the water. The middle of the arm was placed on a pivot. The top end of the arm was connected to a load cell. The experimental set-up is shown in figure 3.6.

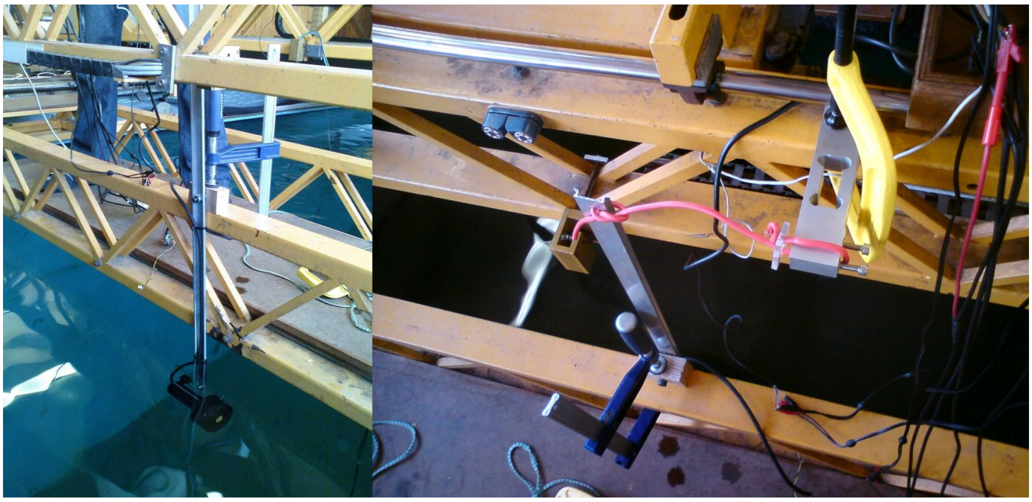

Figure 3.6.: Experimental set-up for thruster torque measurements

The load cell could then measure the torque output of the thruster. The load cell first had to be calibrated using known loads to relate the output voltage to a force. Thruster input values were recorded against the measured output torque from the load cell. The experiment was conducted for forward and reverse thrust. The experiment results are shown in figure 3.7.

The figure shows the non-linearity of the relation between thruster input and output. The data shows that the thruster output torque only starts increasing at about a 25 % input signal and then increases more or less linearly until close to the maximum output. The maximum output torque measured in the experiment is less than the rated maximum. This is because of a lower input voltage from the power supply. At 30 V the thruster can supply 28.4 N of torque but the experiment was conducted using only 24 V as will be supplied in the AUV.

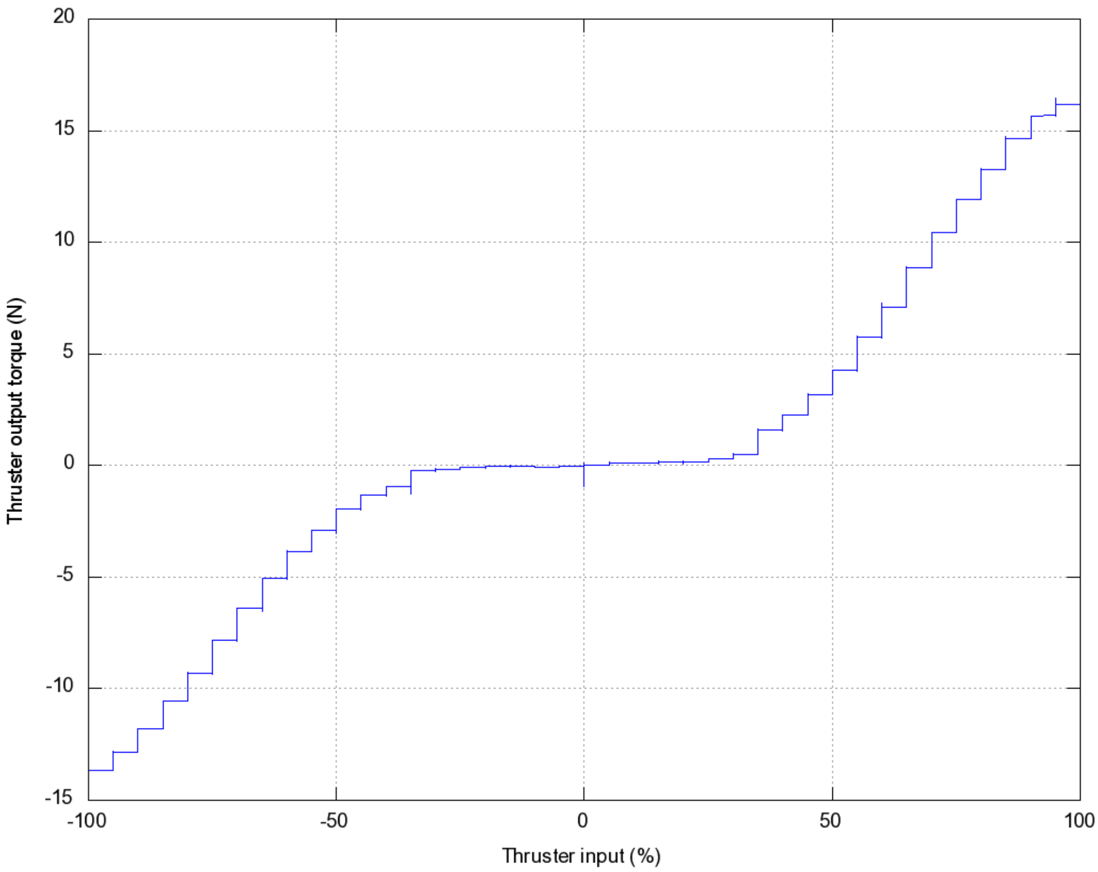

Figure 3.7.: Thruster output torque measured against the input of the speed controllers

3.5. Conclusion

This chapter discussed the mechanical issues considered in the design process of the AUV. It showed the physical body design, weight considerations, component layout inside the vehicle, vehicle manoeuvrability due to thruster placement and the modelling of thruster output so that the vehicle can be controlled more accurately. The issues encountered were discussed and the implemented solutions were given.

Chapter 4.

Electronic Design

This chapter will focus on all electronic systems implemented on the AUV as well as their designs and integration into the system. The chapter will start of with the on-board computer which is responsible for the main control functions and decisions. The next section will look at the low-level IO interface board which interfaces to all sensors and actuators. The following section will discuss the actuators used in the implementation of the AUV. The subsequent section will examine the power distribution and battery system. The next section will show details on communication between the base station and the AUV followed by a section on system integration of all these subsystems. The chapter will finish with a conclusion on what has been found.

4.1. Onboard Single-Board Computer

The vehicle will be controlled through an on-board computer. The computer system used for this project is a Wafer-Luke single-board industrial type computer. The computer uses a VIA Luke processor running at 1 GHz. The system utilises 500 MB of RAM and was installed with a 40 GB hard drive. It has two USB ports, two ethernet ports, two serial comm ports, one of which is only RS-232 and the other RS-232 or RS-485 selected through jumpers on the motherboard. Other interfaces include a VGA graphics connector and a LPT parallel port. The other interfaces are shown in figure 4.1 taken from the data sheet.

The Wafer Luke industrial computer motherboard is 146 mm by 102 mm in size. The board is installed into a slightly bigger case with space for a hard drive and small power supply. The hard drive is a small hard drive like the ones used in laptops. The power supply takes 15 to 30 V DC input and converts it to 12 V and 5 V for the motherboard and hard drive. The mother board does not make use of fans for cooling but instead uses heat pipes conducting the heat generated by the processor to the case where a large heat sink is installed on one side.

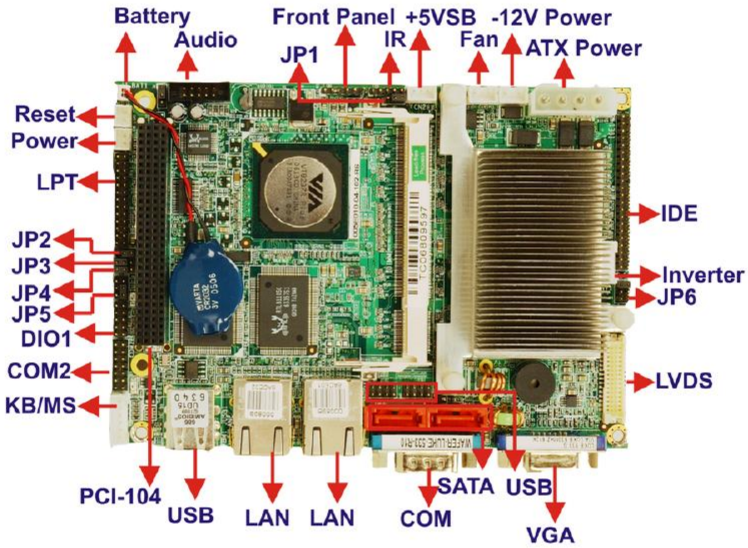

Figure 4.1.: Motherboard layout of the Wafer Luke single-board computer

4.2. IO Board

An IO board was developed to handle all the lower level interfacing to the actuators and sensors. These interfaces include SPI, PWM, I2C, ADC, general digital IO pins and more. The board was developed by the robotics group at the CSIR specifically for these types of applications. It was developed as a generic CPU board to provide lower level interfaces. The board also has two RS-232 as well as RS-485 serial ports for communication to a computer or other devices. The ports are configured so that RS-232 and RS-485 can be used on the same port at the same time utilizing different pins on the port. The board makes use of an 8 bit AVR ATMega 128 processor from Atmel.

The board has six PWM interfaces which can be used to control servos or DC motor speed controllers. The SPI and I2C interfaces can be used to drive a serial bus and more than one device can be connected to each of these. It also contains eight analogue channels which can be used for analogue to digital conversion. These inputs can also be used as digital input pins if needed. There are also eight more generic output pins which are open collector outputs to be used as switches for certain devices. The board has four more digital input pins with external interrupt capabilities. It also has a connector for an LCD display in case this is required by the user. The rest of the available pins are routed to a bread boarding area on the side of the board.

4.3. Actuators

The AUV makes use of two types of actuators. Both these actuators will be discussed in detail in this section.

4.3.1. Thrusters

The main form of actuation on the AUV is the thrusters. The thrusters makes use of propeller systems and use a small DC motor encased in a watertight enclosure to turn the propeller. The thrusters create torque of up to 28.4 N in the water. They were acquired from a company called Seabotix. They are BTD-150 thrusters and are shown in figure 4.2.

Figure 4.2.: The Seabotix BTD-150 thruster

The DC motor requires a speed controller to supply the correct input voltage for the thrusters to turn at the correct speed. The speed controllers used in this case are Scorpion XL speed controllers from a company called Robot Power. The speed controllers are supplied with 24 V from the battery system and can supply whatever the thrusters need to turn at the required speed. The speed controllers are then controlled using the PWM signals generated by the IO board discussed in the previous section. The signals required are general RC signals where pulses are sent at about 50 Hz and the pulse width determines the speed or the output voltage of the speed controller. The pulses need to be between 1 and 2 ms wide where 1.5 ms are the centre or zero position for the speed controller.

4.3.2. Ballast System

The buoyancy of the vehicle can be varied through the ballast system. The ballast system consists of two piston tanks which can be filled with water from the surrounding environment of the vehicle. The water enters through two openings on the side of the AUV. The ballast system was acquired as a complete system and is controlled through simple digital signals. It takes four signals as input so that each piston tank can be controlled independently of the other. Each piston tank therefore uses two digital input signals and the two signals determine the direction of the piston. Micro switches are used to limit the piston rods and stop them from moving out of certain boundaries and damaging the ballast systems. The digital input signals for the ballast system is generated by the IO board discussed in the previous section. The two piston tanks have a fillable volume of 800 ml each which gives the vehicle a total mass variation of up to 1.6 kg. One of the piston tanks is shown in figure 4.3.

Figure 4.3.: A piston tank from the implemented ballast system of the AUV

4.4. Power Distribution

The battery system of the AUV consists of two 12 V 12 Ah batteries placed in series to supply 24 V. The power requirements of all modules are below this level. Most of these modules utilise their own power supply to convert the 24 V input voltage to whatever they require. The power requirements of on-board modules are as follows: the thrusters require 24 V and connects directly to the battery system, the on-board single-board computer requires 12 V as well as 5 V but has its own power supply to supply these levels from the 24 V input as previously discussed. The IO board requires 5 V for the processor and also has a built in power supply to bring the input voltage down to this level. Some other systems or sensors get their power directly from the IO board power supply which delivers 5 V DC. This includes the water pressure sensor, the IMU, the magnetometer and the wheel encoding sensors. The ballast system requires 5 V but also requires a power supply that can deliver up to 5 A of current, even though it is just for a very short period at a time, to get the system moving. A separate power supply was acquired for this system. The power supply connects directly to the battery system which can deliver the current when needed. The power supply used for the ballast system is an SDM30-24S5 DC-DC converter supplying up to 25 W of power.

A simple power distribution board was developed which connects directly to the battery system. Connectors were installed for all devices supplying the 24 V from the batteries to all devices. A main power switch was added to the board to disconnect all power to the hardware if necessary. A power indication LED was also added, together with a rather large current limiting resistor, to indicate whether power is applied to the system. This power distribution board makes for easy installation and removal of system hardware.

4.5. Communication System

An underwater communication system was acquired for this project as well as other underwater projects that will be undertaken be the group at the CSIR. The underwater modems acquired are Aquacomm underwater acoustic modems from DSPcomm. The modems have a data transfer rate of up to 480 bps. They utilise the frequency band from 16 kHz to 30 kHz with an effective range of 3 km. The modems themselves are very small; 78.7 mm by 69.8 mm. They were supplied with two transducers which are cylindrical in shape with a diameter of 70 mm. The transducers are made of plastic and have an operating depth of up to 100 m. Transducers that can be taken to a depth of 2 km are also available.

The system has not been used thus far because the environments where the vehicle was tested were too small for the acoustic communication system. There were too many echoes off the sides of the tank or swimming pool. A tether cable was used instead for communication between the AUV and base station in these cases. The software drivers to implement the acoustic communication system were developed as only data encapsulation is required for the modem to interpret the information to be sent. The acoustic system will be employed when the AUV is ready to move to bigger bodies of water like a dam or the ocean.

4.6. System Integration

The complete system and integration is shown in figure 4.4. The figure shows all interfaces between the hardware in the AUV and shows which components connect to which. The on-board computer is where all the main control tasks are performed. This then is connected to the IO board which provides low-level interfaces to all sensors and actuators. The on-board computer also connects to a remote station through an ethernet tether. The base station will provide remote control and vehicle status monitoring capabilities. This will however be discussed later. The tether cable is a standard unshielded twisted pair cable as used in standard networks. It contains eight wires inside of which four is used for the ethernet link and the other four for the RS-232 connection to the trilateration system. These four wires include the ground connection, the transmit and receive signals for the RS-232 and a digital trigger line for the trilateration system as discussed in the chapter on sensor systems. The sensors will not be discussed in this chapter as a complete chapter has been reserved for this.

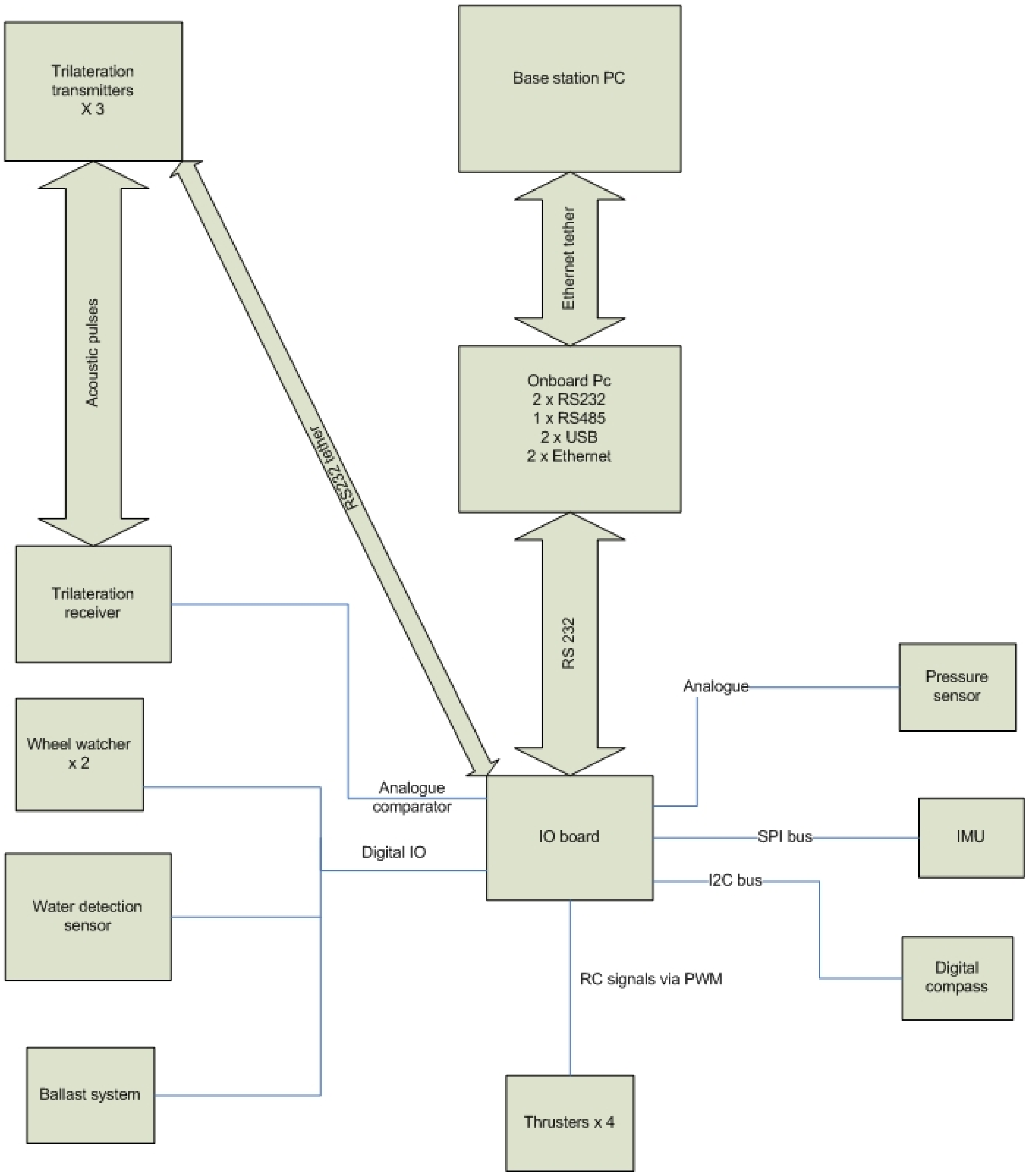

Figure 4.4.: The complete hardware diagram of the AUV

4.7. Conclusion

This chapter showed and discussed the electronic design steps taken in implementing an AUV. It showed the different interfaces between all hardware and how they work together. It discussed how power was distributed to all hardware and converted to the correct voltage levels according to hardware requirements.

Chapter 5.

Sensors

This chapter deals with the sensors used on the AUV. Only the sensors used for navigational purposes will be discussed here. Other sensors that may also be used on the AUV are mission specific sensors. These might include water temperature sensors, side-scan sonars and many more. These sensors will be determined by the mission and will not be used for navigational purposes. Most of the sensors used in this project are relatively inaccurate and low-cost sensors. The sensors required to track the position of the vehicle track its movement or position in six degrees of freedom. These six degrees of freedom are roll, pitch, yaw, thrust, heave and sway and are shown in figure 5.1 as taken from [9].

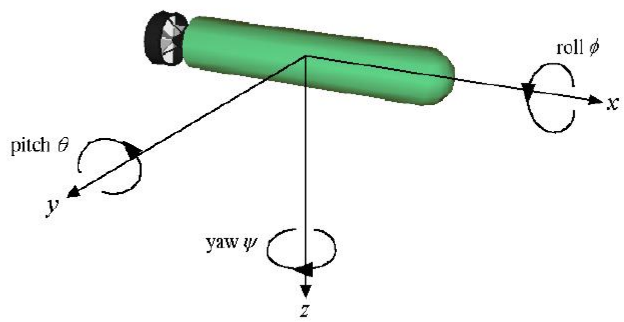

Figure 5.1.: Six degrees of freedom of an AUV

The sensors used to track the vehicle's position include an IMU, magnetometer or compass, water pressure sensor and an acoustic trilateration system. Two wheel watcher sensors are also used to measure the position of the ballast system.

5.1. Reference Frames

Before looking at the sensors being used for vehicle navigation one needs to understand the correlation between the world or global reference frame and the local reference frame of the vehicle. Two Cartesian reference frames are defined according to [30]. The first is the world reference frame which is a global-fixed reference frame. This reference frame is used for tracking the vehicle's position and its orientation or pose with respect to the world around it. The second is the local reference frame which is attached to the vehicle's body. This reference frame is defined as an instantaneous reference frame at any time t. Thus the local reference frame moves relative to the world reference frame as the vehicle moves and manoeuvres. Figure 5.2 shows an example of two such reference frames as taken from [30].

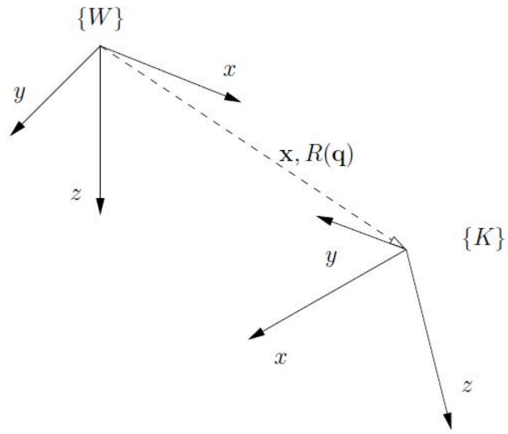

Figure 5.2.: Illustration of two reference frames $\{W\}$ and $\{K\}$

The world reference frame in this case is defined as follows. The positive X axis is defined as pointing directly north, the positive Y axis would then point directly east and the positive Z axis would point upwards. The local reference frame is defined so that the positive X axis points to the front of the vehicle, the positive Y axis points to the right of the vehicle and the positive Z axis points to the top of the vehicle. Sensors used to track the vehicle's position or movement may take its measurements in any of these two reference frames and a transformation may be done to transform them to the other reference frame. To track the vehicle's movement one would want to use the world reference frame and therefore all measurements taken in the local reference frame should be transformed to the world reference frame.

5.1.1. Vector Transformation between Reference Frames

It is often required to represent a vector in two different reference frames. To achieve this a transformation needs to be done on the vector to get the vector's representation in a different reference frame. A vector and a rotation matrix are defined, as both are needed for the transformation. A vector ${}^{A}P$ is defined as vector P in reference frame $\{A\}$ where ${}^{A}P \in \mathbb{R}^3$ and ${}^{A}_{B}R$ is defined as a 3×3 rotation matrix in reference frame $\{B\}$ relative to reference frame $\{A\}$ where ${}^{A}_{B}R \in \mathbb{R}^{3\times3}$. The translation of vector P from reference frame A to reference frame B is shown in equation 5.1 where ${}^{A}P_{B_{org}}$ denotes to the origin of reference frame B relative to reference frame A.

$$ {}^{A}P \;=\; {}^{B}P \;+\; {}^{A}P_{B_{org}} \tag{5.1} $$

The rotation of the vector P in reference frames A and B is shown in equation 5.2.

$$ {}^{A}P = {}^{A}_{B}R\,{}^{B}P \tag{5.2} $$

The rotation matrix is used to represent the attitude of the vehicle as described in [30]. The rotation matrix is a 3×3. The rotation matrix is an orthogonal matrix of order 3 where $R \in \mathbb{R}^{3\times3}$ and $RR^{T} = I_{3\times3}$. A rotation matrix contains nine parameters but since there are six constraints due to the orthogonality of the matrix, only three parameters can be used to represent the rotation matrix. There are several ways to represent a rotation matrix, all of which are discussed in robotics texts like [29]. These methods include Euler angles, equivalent angle-axis parameters and Euler parameters. Euler angles are the most commonly used representation of vehicle attitude. A set of Euler angles is defined as a set of three successive rotations around three axes, like $Z - Y - X$ where the frame is first rotated around the X axis, then around the Y axis and then around the X axis. Define α, β and γ as the rotation angles around the X, Y and Z axes respectively. The rotation matrix between the world reference frame and the local reference frame are the defined as shown in equation 5.3 to 5.6 according to [30].

$$ R = R_z(\alpha)R_y(\beta)R_x(\gamma) \tag{5.3} $$

$$ R_z(\alpha) = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{5.4} $$

$$ R_y(\beta) = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \tag{5.5} $$

$$ R_z(\gamma) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{bmatrix} \tag{5.6} $$

These reference frames can now be used to track the vehicle's position or movement in a three-dimensional space and transformations can be made between the two defined reference frames.

5.2. Inertial Measurement Unit

The main sensor used for the navigational purposes of the AUV is the IMU. This sensor contains three gyroscopes and three accelerometers. The three gyroscopes are placed on the X, Y and Z axes to measure rotational velocity around these axes. The three accelerometers are also placed on the three axes to measure linear acceleration in these three directions. The gyroscope data are then used to determine the rotation of the vehicle around the three axes. Roll, pitch and yaw represent the rotation around the X, Y and Z axes of the vehicle respectively. The rotational position of the vehicle in terms of these three degrees of freedom is determined at this stage by calculating the integral of the rotational velocity over the time period of the measurement. The accelerometer data can be used to calculate the linear movement of the vehicle. This can be determined by calculating the double integral of the accelerometer data over the time period of the measurement. To calculate the position of the vehicle in a three-dimensional space one constantly needs to make the translation between the vehicle's local coordinate system and the world coordinate system as described in section 5.1. The IMU can therefore be used to measure all six degrees of freedom of the AUV.

The measurements from the accelerometers can also be used to calculate the vehicle's pitch and roll. Since the three accelerometers will always measure the gravity vector, which is always straight downwards, it can be used to calculate the pitch and roll angles of the vehicle as shown in equations 5.7 and 5.8 derived from first principles. In the equations θ gives the roll or pitch angle, a denotes to the X or Y value taken from the magnetometer for calculation of pitch or roll respectively, and z denotes to the vertical measurement of the magnetometer. The problem is that this measurement can be affected by linear acceleration and it is therefore not perfect.

$$r = \sqrt{z^2 + a^2} \tag{5.7}$$

$$\theta = \frac{\pi}{2} - \arccos\frac{a}{r} \tag{5.8}$$

The specific IMU used in this case is the ADIS16350 Tri Axis Gyroscope and Accelerometer from Analog Devices. This is a relatively low-cost device. The problem with IMUs is that they are very sensitive to sensor drift due to the noise in gyroscope and accelerometer measurements. There are IMUs available on the market that are much more accurate. These IMUs are typically used for guidance systems on missiles and are very expensive and difficult to obtain.

The IMU uses an SPI interface. The interface consists of six lines of which two are power and ground respectively. The other four are for data transmission. The first is the D_{out} line normally referred to as MISO which is the device's data output line. The next is the D_{in} line or MOSI line which is used for data input to the device. As both these data lines are used for serial transmission of data, a third line is included as a clock line to ensure synchronous data transmission. The last line is the chip select line or CS line. This line is used to enable the SPI interface of the device. If this signal is high the device will not react to any activity on the SPI bus. This feature enables the developer to use more than one device on the SPI bus as each device uses an independent CS line.

The SPI bus operates in full duplex mode which means it supports simultaneous transmit and receive functions. A complete data frame for this device consists of 16 bits. The data frame consists of a read or write bit followed by a 0, followed by a six bit address and then an 8 bit command. The six bit address is always a register address in the IMU's memory bank which will be written to or read from. Since all registers are 16 bits, two data frames are required to write a register. In case of a read operation any one of the two addresses of the register can be used to read the complete 16 bit register and again this will require two data frames. Also in a read operation the second byte or command section of the data frame will be ignored by the device.

Data is read from the IMU in 14 bit two's complement. The MSB holds a new data indicator so that when the register is updated with new data this bit is set and when the data are being read this bit is cleared. The next bit is used to indicate a system error or an alarm condition. The received data then needs to be multiplied by a scaling factor of 0.018315 °/sec for the gyroscope data or 2.522 mg for the accelerometer data.

To overcome the problem of sensor drift other sensors were added to improve on the measurements from the IMU. Another sensor was added for each measured degree of freedom. These sensors will be discussed in the sections that follow.

5.3. Magnetometer

Another sensor used for AUV navigation is a magnetometer or electronic compass. The magnetometer measures the earth's magnetic field in the directions of the X, Y and Z axes. It returns the three measurements separately to give the vector values of the magnetic field. This can then be used to calculate the vehicle's heading. The heading measurement is taken in the global reference frame or coordinates and therefore does not need to be converted. An example of the measured magnetic field of the earth is illustrated in figure 5.3, taken from [5], where the heading is given by α.

One also needs to compensate for vehicle tilt. This is shown in equations 5.9 and 5.10 by taking roll and pitch measurements as ϕ and θ together with the magnetometer readings x, y and z as shown in [5]. The heading or azimuth of the vehicle can then be calculated as in equation 5.11.

$$x_H = x\cos(\theta) + y\sin(\phi)\sin(\theta) - z\cos(\phi)\sin(\theta) \tag{5.9}$$

$$y_H = y\cos(\phi) + z\sin(\phi) \tag{5.10}$$

$$Azimuth = \arctan(y_H/x_H) \tag{5.11}$$

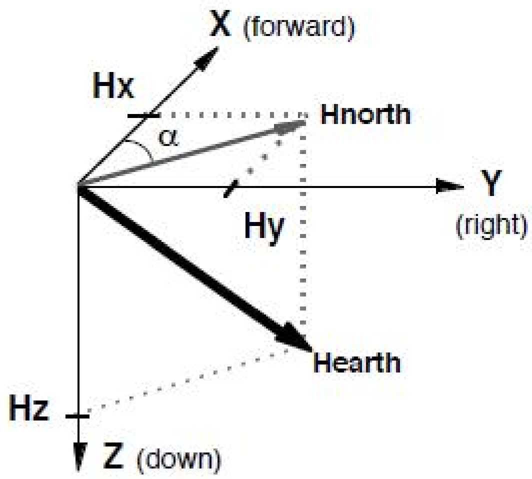

Figure 5.3.: Example of the earth's magnetic field vector

A major drawback when using a magnetometer for navigation is the fact that it is very sensitive to other disturbances in the earth's magnetic field. These disturbances can be introduced by other magnetic objects in close vicinity of the sensor as discussed in [29]. These include metallic objects used in the construction of the vehicle as well as objects in the environment around the vehicle. One way to get around this is to recalibrate the sensor whenever it is introduced to a new environment or even before every dive.

Calibration of the magnetometer is done as follows. The first step is to collect the data of all three sensors of the magnetometer while a full rotation in the XY plane is being done. The recorded data for such a rotation is shown in figure 5.4. In the figure the Y axis shows the individual sensor measurements of the magnetic field in μT and the X axis shows the sample number. Measurements were recorded at a frequency of 4 Hz for this experiment. Since a full rotation has been done the X and Y measurements should both have some maximum and minimum values which are both equally distanced from zero. This means that to calibrate the magnetometer a value needs to be subtracted or added to the X and Y values respectively to move them to be centred around zero. In this case the Z value could not be calibrated since the rotation is only done around the vertical axis. The calibration values are calculated as the centre of the maximum and minimum of the measured sensor values. The result is shown in figure 5.5 and figure 5.6 then shows the calculated heading of the vehicle against time. In figure 5.5 the Y axis shows the individual sensor measurements of the magnetic field in μT and the X axis shows the sample number taken at the same sample rate as before. In figure 5.6 the Y axis gives the calculated azimuth or angle from north and the X axis again gives the sample number.

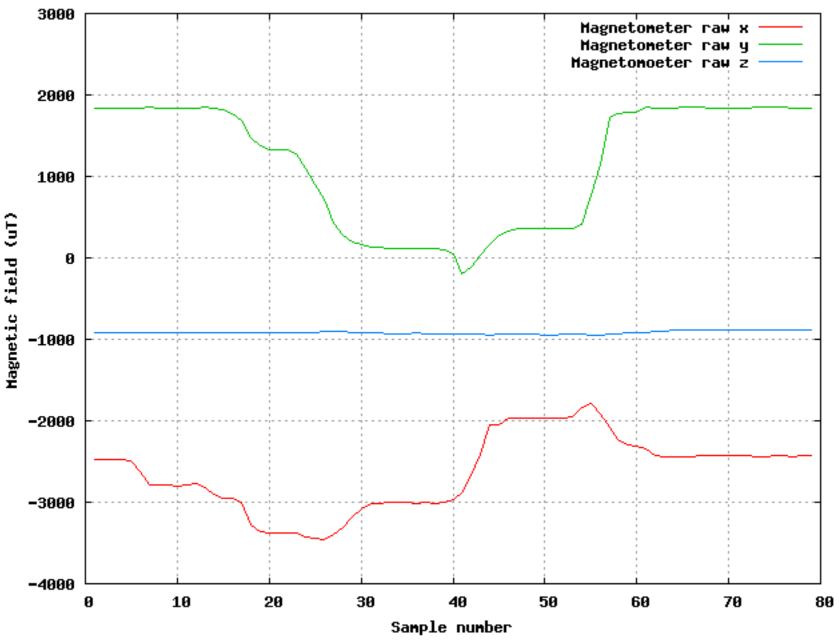

Figure 5.4.: Raw data from the magnetometer

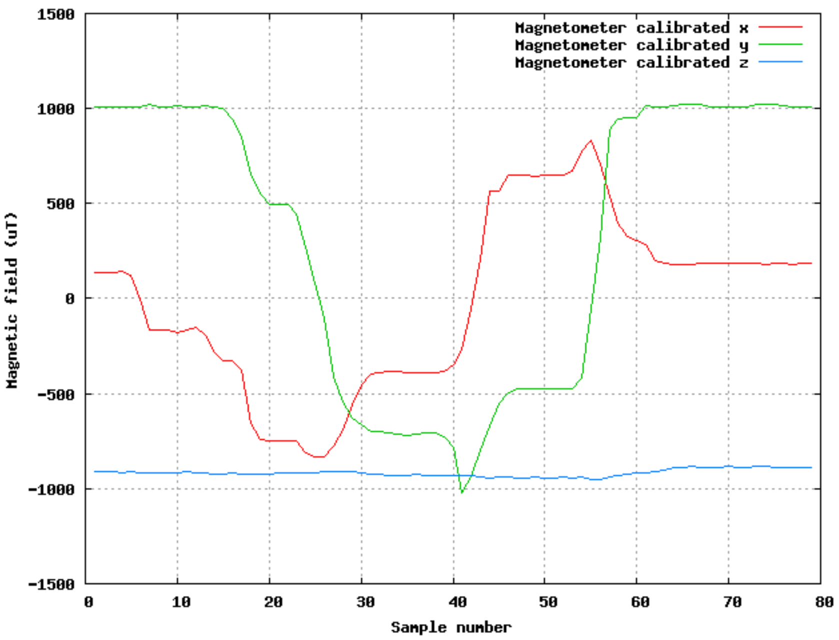

Figure 5.5.: Calibrated data from the magnetometer

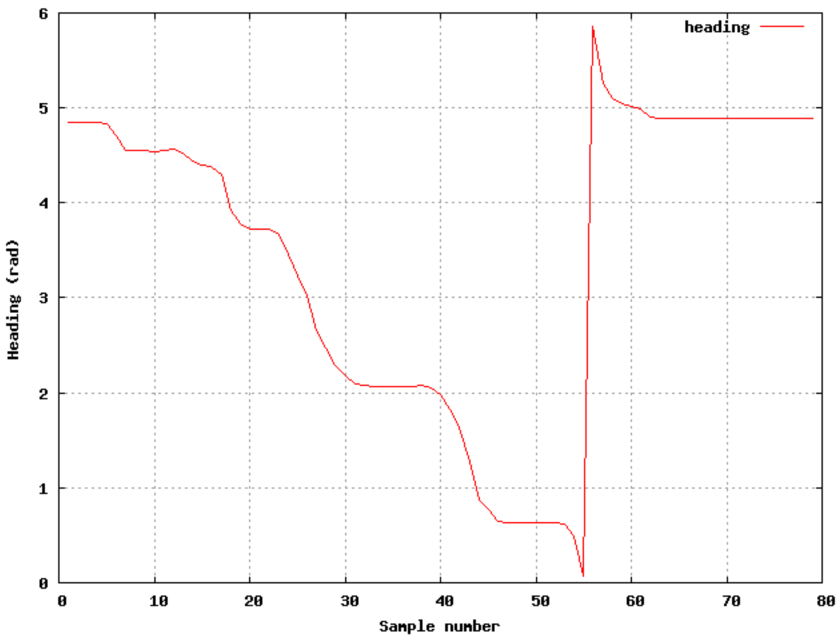

Figure 5.6.: Calculated heading from calibrated magnetometer data

The specific compass used in this case was the HMC6343 from Honeywell. The magnetometer is interfaced using an I2C interface which makes use of two lines for data transfers. These two lines include a data line and a clock line. The data line is bi-directional. The master unit first sends a command and then gives the slave device a turn to reply on the command while still supplying a clock signal for transmission. Communication is started through a start condition and ended with a stop condition. The slave device will only react if the first byte sent corresponds to its own address. The magnetometer requires 5 V for operation. Measurement data is sent back in 16 bit twos compliment format. The compass also contains three accelerometers for tilt measurements and can calculate a tilt compensated heading. This was however not used, as the compass needs to be calibrated and the built in calibration required rotation around the Z and X axes. The AUV would however be damaged if it was turned upside down. Therefore it was decided to rather use the raw magnetometer data and only calibrate the X and Y axes. The results proved to be acceptable as will be seen in later chapters.

5.4. Water Pressure Sensor

The next sensor to be implemented was the water pressure sensor. The purpose of this sensor is to measure the water pressure on the outside of the vehicle and calculate the depth of the vehicle or the vertical position in the water. Since a linear relation exists between the water pressure and the depth of the vehicle, it can easily be computed.

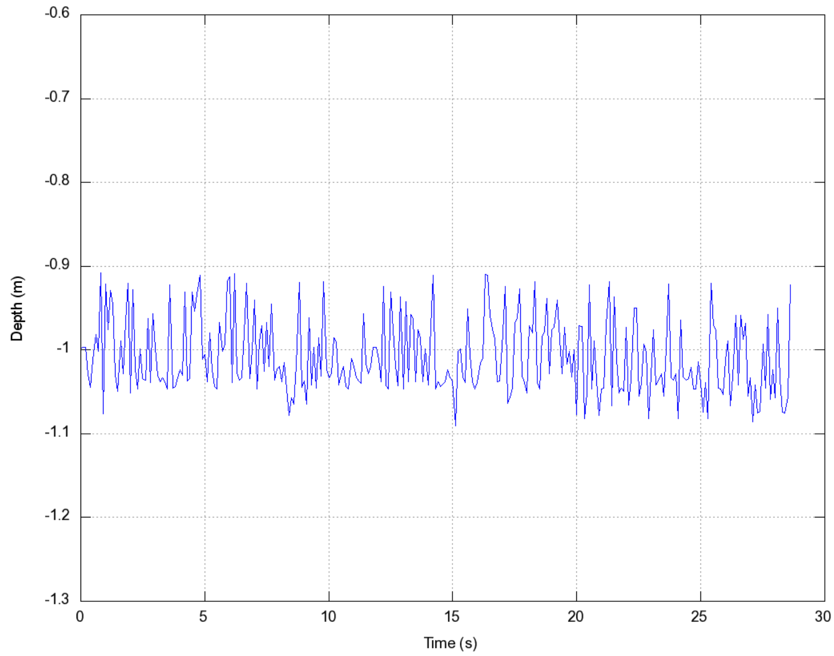

Figure 5.7.: Depth measurement accuracy from water pressure sensor

This relation is taken from Pascal's law as given in equation 5.12 where ρ denotes to the water density in kg/m^3, Δh denotes to the depth of the vehicle in meters and g denotes to the gravitational acceleration which is always 9.8m/s. The water pressure here is the change in pressure from the surface and is measured in Pascals (Pa).

$$\Delta P = \rho g(\Delta h) \tag{5.12}$$

The water pressure sensor used in this project is an LM series low-pressure media-isolated pressure sensor. The sensor is interfaced through an analogue interface. It uses three wires of which two are power and ground respectively. The third is the signal wire which gives an output signal between 0.5V and 4.5V depending on the pressure. The relation between the measured voltage and the water pressure is again a linear one. The pressure sensor has a range of zero to 600 mbar which means it can be used to measure depth up to 6 meters. The sensor has an accuracy rating of ± 0.1% of its range which gives an accuracy of ± 6 mm. This error will however be increased due to ADC sampling noise and accuracy. The acquired accuracy in depth measurement is shown in figure 5.7. The depth measurement error is shown to be less than 0.092 m. To measure this accuracy the vehicle was lowered to a depth of 1 m measured with a tape measure. The vehicle was kept at that depth, using ropes, while the measurements were taken from the pressure sensor.

5.5. Acoustic Transducers for Trilateration System

A trilateration system was implemented to determine the position of the vehicle. This is implemented using beacons at known positions which transmit an acoustic pulse at specified intervals. The vehicle can then calculate the distance to each beacon by measuring the time it took to reach the vehicle and multiplying it with the speed of sound in water. The distances to known positions can subsequently be used to calculate the position of the vehicle. The equations to calculate the position has been derived from first principles. Through utilising the distance equation, one can construct a distance equation to every known beacon position. The beacon position is known and the distance to each beacon has been calculated as discussed before. The only unknowns are the X, Y and Z values of the vehicle's current position. The distance equation is shown in equation 5.13 for n number of beacons. By subtracting the difference equations from each other one can now find three linear equations to solve the three unknown variables. To find three unique linear equations one will need four distance equations which also means four beacons are necessary.

$$r_n^2 = (x_n - x)^2 + (y_n - y)^2 + (z_n - z)^2 \tag{5.13}$$

To get the position of the vehicle one needs to solve these three equations simultaneously. This can be done using matrix algebra. All constants are placed on the right-hand side in the matrix K, and the coefficients of X, Y and Z are placed in the matrix A which is a 3×3 matrix. The matrices are constructed as shown in equation 5.14 and 5.15. The position of the vehicle can then be determined through equation 5.16.

$$K = \begin{bmatrix} -x_1^2 + x_2^2 - y_1^2 + y_2^2 - z_1^2 + z_2^2 + r_1^2 - r_2^2 \\ -x_2^2 + x_3^2 - y_2^2 + y_3^2 - z_2^2 + z_3^2 + r_2^2 - r_3^2 \\ -x_3^2 + x_4^2 - y_3^2 + y_4^2 - z_3^2 + z_4^2 + r_3^2 - r_4^2 \end{bmatrix} \tag{5.14}$$

$$A = \begin{bmatrix} -2x_1 + 2x_2 & -2y_1 + 2y_2 & -2z_1 + 2z_2 \\ -2x_2 + 2x_3 & -2y_2 + 2y_3 & -2z_2 + 2z_3 \\ -2x_3 + 2x_4 & -2y_3 + 2y_4 & -2z_3 + 2z_4 \end{bmatrix} \tag{5.15}$$

$$K = A \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{5.16}$$

The system above was first tested through simulation to prove that it works. Noise was added to the simulated distance measurement to test how it affects the system's accuracy. It was noted that the effect of the noise was significantly larger on the vertical or Z position than the horizontal or X and Y. The noise or error that was introduced to the distance measurement had a maximum amplitude of 0.05 m and contributed to a horizontal error of around 0.3 m and a vertical error of sometimes more than 5 m. This is due to the fact that the beacon positions are all at the surface because of practical reasons. As the vehicle moves deeper, or further away from the surface the vertical error grows even more. The vertical measurement was therefore left out and only the horizontal X and Y values of the calculated position were used. Since only two variables are now calculated the system can be reduced to utilise only three beacons and instead of using the direct distance, one should calculate the horizontal component of the distance and use that instead. The matrices in equations 5.14 and 5.15 are then reduced to a 2×1 matrix and a 2×2 matrix as the z components are not used and the equations using the fourth beacon falls away.

The simulation results are shown in figure 5.8. The blue line shows the actual movement of the vehicle, the red line shows the trilateration results and the blue circular markers shows the positions of the three beacons. The graph only shows the horizontal results or the XY plane. The depth of the vehicle was kept constant at a depth of 1 m and it was assumed that this depth was known or perfectly measured with some other sensor. The simulation also incorporates movements between each distance measurement which also adds to the error in position calculation. The horizontal and vertical axes in the graph are the X and Y positions of the vehicle.

The accuracy of the trilateration system also depends on the vehicle speed. This is due to the fact that the vehicle moves a short distance between each pulse received. The further this distance, the bigger the position error. The calculated positions forms a triangular type shape around the actual position. Therefore the higher the vehicle's velocity, the bigger the positional error and the bigger the triangles around the vehicle's position.

The trilateration system uses four sonar transducers, three to transmit and one to receive. The receiving transducer is mounted on top of the vehicle and the three transmitting transducers will be used as the beacons. The three transmitting transducers will be driven by a single micro controller. The micro controller generates an oscillating signal at 100 kHz. This frequency is used as the acquired transducers are optimised for this frequency. This signal is amplified by the transducer driver to a much higher voltage and sent to the transducer itself. The transducer driver is a simple circuit that amplifies the input signal using a transformer and a large capacitor to deliver the needed power. Since the input signal is generated from the micro controller which can't deliver much current, it is only used to switch a FET which connects the power supply to the transformer. The transformer then amplifies the signal. The signals for the three transducers amplifiers are all produced from a single controller board using an ATMega128 processor using the PWM functionality of the micro processor. Since the vehicle is only developed to be used in a small tank or swimming pool this controller board can be connected directly to the vehicle through the tether cable to the vehicle. A trigger signal is then sent directly from the vehicle to this controller board using a simple digital trigger signal.

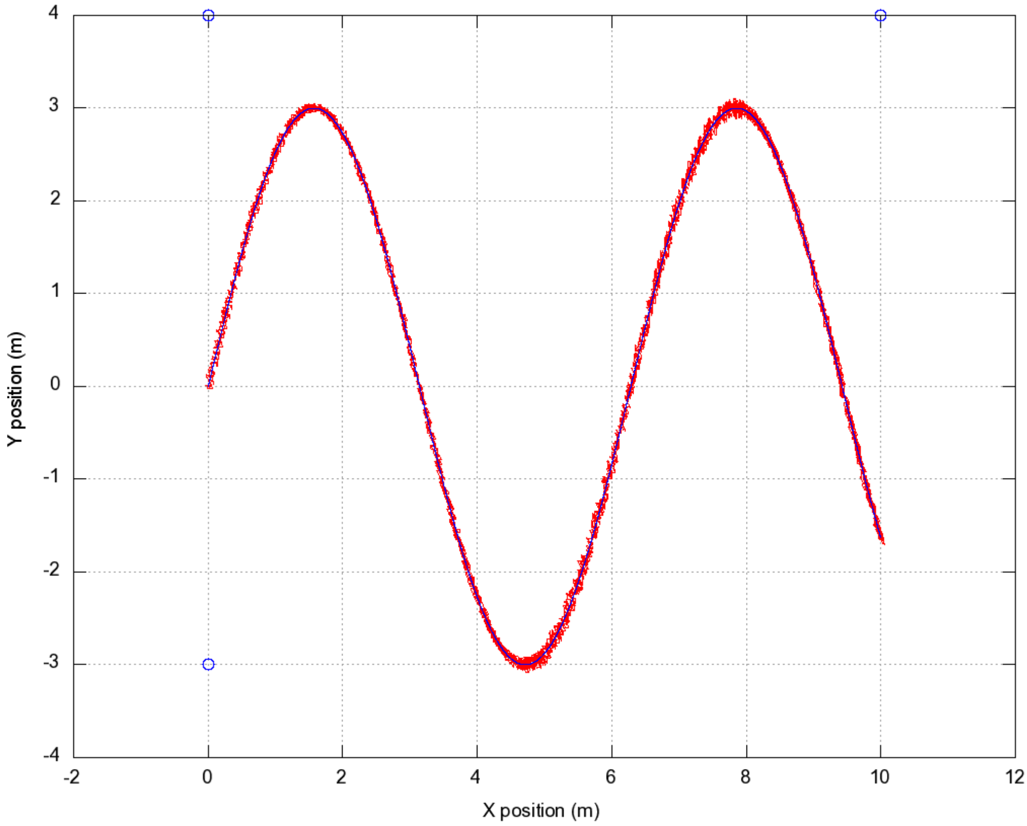

Figure 5.8.: Trilateration simulation results

Although this would not be feasible in longer ranges it was implemented in this way to prove that such a trilateration system can be used in underwater navigation. Because the trigger signal is sent directly from the vehicle through the tether cable the problem of clock synchronisation between the beacons and the vehicle is avoided. The signal sent is a simple pulse containing no information on the beacon position and timing details as are normally required in such systems. Since the timing of the pulse is known locally on the vehicle it can be used to determine the time the acoustic pulse took to reach the vehicle's receiving transducer. The controller board uses an RS232 interface to select which beacon should be fired next and then uses the digital line to send the trigger signal. An interrupt signal is sent as soon as the voltage on the trigger line drops to zero and the signal is immediately sent to the transducer driver. This minimises any timing errors in the system.

The receiving transducer on the vehicle uses an off the shelf receiving amplifier developed by the CSIR for another sonar project. The receiver board contains a band pass filter to filter out all unwanted frequencies and provides an output impulse type signal if a signal inside the required band has been received. The receiver is connected to the IO board. The analogue comparator functionality on the IO board is used to determine when a signal is supplied by the receiver board. The received signal is connected to the positive input of the comparator and a voltage divider with a potentiometer is connected to the negative input. The voltage divider output voltage level can then be set by changing the resistance of the potentiometer, which then sets the sensitivity of the analogue comparator. The analogue comparator's interrupt signal is then used to determine the time difference since the signal has been sent. The vehicle position can subsequently be determined as discussed above. The transducers used in this trilateration system were acquired from another group within the CSIR which specialises in sonar systems for the South African Navy.

The accuracy of the trilateration system was verified through the use of a laser range finder. A vertical pole was attached to the top of the AUV. When the AUV is submerged to a depth where the trilateration system became effective the top end of the pole would emerge from the water surface. At the top of the pole a square plate was attached to give a large enough target for the laser range finder. The X and Y positions of the pole was then tracked using the laser range finder. The experimental set-up is shown in figure 5.9.

The laser range finder was placed on the side of the testing pool at a known X and Y position and heading. The data could therefore be used to very accurately track the position of the vehicle and compare this to the trilateration system results. The results of the experiment is shown in figure 5.10. The laser range finder scanned at a rate of almost 0.5 Hz. The position point was compared to the corresponding position calculated by the trilateration system. The maximum horizontal position error was calculated at 0.21 m. In this experiment the motor output thrust was limited to 1 % of the maximum output to limit the vehicle velocity.

Figure 5.9.: Experimental set-up showing the pole with a target attached to the AUV

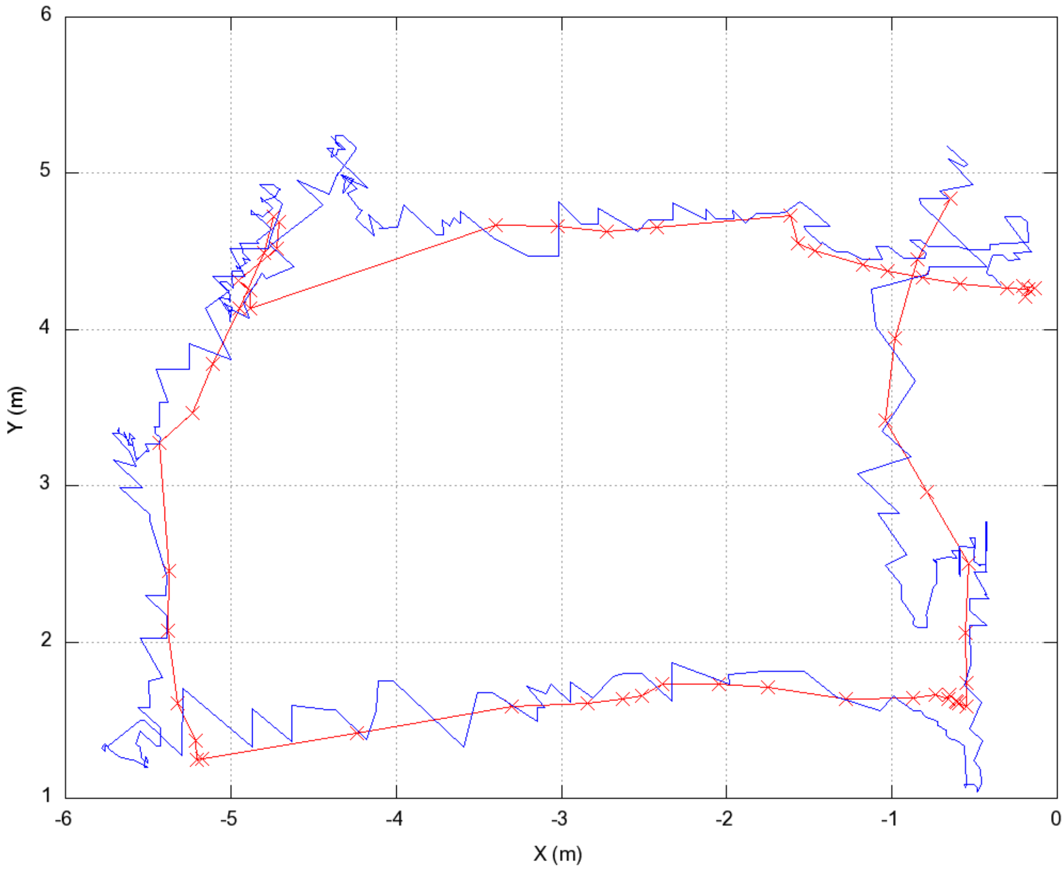

Figure 5.10.: Trilateration validation results using a laser range finder

5.6. Wheel Encoders for Ballast System

The wheel encoders installed on the ballast system is used to control the position of the ballast piston. The encoder disc is placed on the gear of the piston's drive system. The wheel encoders can then be used to measure the rotation of the gear. Since the middle gear rotates much faster than the last gear the resolution of the measurement is very high which gives for very accurate control of the piston position. The measurement resolution in this case is around 24 300 measurement points in the full positional range of the piston which is close to 30 cm. This might be a bit of an overkill as it gives a resolution of 1.2×10^{-5} m, but it was the most accessible place to put the wheel encoder. Since the wheel encoders only gives a relative position some other sensor or a known starting point was needed. To solve this problem a micro switch was installed on the drive shaft of the piston. When the switch is triggered the absolute position of the piston can be updated. The piston position was then fed back to the rest of the system as a percentage of the total range.

These sensors are interfaced through general purpose IO pins. The specific sensors used are Wheel Watcher sensors from Nubotics designed to be used for servo position tracking. The code wheel is a 32 stripe disc with a 50% silver and 50% black radial stripe pattern. These sensors provide two different ways of interfacing to them, each interface consisting of four wires, of which two are ground and power. The first interface provides a channel A and channel B signal. These signals' pulses have a 50% duty cycle and are 90° out of phase. The signals can be measured to determine the direction by looking at the order in which the two signals have been toggled. The distance of travel can be determined by counting the pulses on one or both signals. The other interface uses a clock and direction signal. The clock signal pulses low for 25 μs on each transition of channel A or B. The direction line is high when the disc rotates one way or low the other way. To determine the distance of travel one needs to count the clock pulses and get the direction of travel from the direction signal. Any of these four signals can be used together to measure the rotation of a wheel.

In this project only the channel A line was used. Since the direction of drive of the piston is known only one signal was needed. The encoder disc was also installed on the middle gear which means it rotates at a much higher speed than the last gear. Only low to high transitions on the channel A signal was counted to reduce the measurement resolution of the piston position as it was already very high.

5.7. Conclusion

Using the sensors discussed in this chapter one should be able to successfully track a vehicle's position and movement in all six degrees of freedom. The chosen sensors are not perfect, as has been shown in this chapter. Problems with specific sensors have been pointed out and the influence of these problems on the tracking of the vehicle position were discussed. This chapter showed which sensors were used for this project, how they were interfaced to and how the data was interpreted to make sense. Many sensors measure the same degree of freedom and the next chapter will show how this fact can be used to improve on the problems found in sensor measurements. This chapter also showed how to use sensor data to represent the vehicle position and attitude in a reference frame and how to translate between reference frames as some sensor measurements may be taken from different reference frames.

Chapter 6.

Data Fusion

In this chapter it will be shown how data from multiple sensors, that measures more or less the same thing or the same degree of freedom, will be combined through data fusion to improve on the measurements of the individual sensors. Once the data from all sensors have been collected they must be combined to estimate the position of the vehicle. Since many sensors measure more or less the same thing or the same degree of freedom, we use some form of sensor fusion to combine the data obtained from these sensors to calculate an estimate of the vehicle's position or orientation. In this project a Kalman-Bucy filter was implemented to combine sensor data and estimate the vehicle's current position. The prospect of sensor fusion also improves on the measurement of vehicle position by using data from more than one sensor to calculate a more exact estimate of the vehicle position than that obtained with a single sensor. The Kalman filter can deliver the required estimates in an optimal way.

The Kalman filter was developed by Rudolph E. Kalman in 1960 [17] and the Kalman-Bucy filter which is implemented for a continuous time process in 1973 [18]. The filter is based on a stochastic noise model according to [10]. The filter uses differential equations to define the state estimates and filter gains. The Kalman-Bucy filter will be implemented for the purposes discussed here.

6.1. Filter Model and Estimation

To be able to use the Kalman-Bucy filter one needs to have a system model in the form of differential equations as shown in equations 6.1 and 6.2 as taken from [7].

$$\dot{\boldsymbol{x}} = \boldsymbol{A}(t)x + \boldsymbol{B}(t)\boldsymbol{u} + v \tag{6.1}$$

$$\boldsymbol{y} = \boldsymbol{C}(t)x + \boldsymbol{D}(t)\boldsymbol{u} + w \tag{6.2}$$

In these equations x represents the state vector to be estimated, y is the measured output for u the measured input. $\dot{x}$ denotes to the derivative of x and v and w denotes the state and measurement noises respectively where both needs to be zero mean and white. Values for A, B, C and D must be chosen for the specific system in question to complete the model which will differ for each degree of freedom estimated. The estimate will then be calculated using the Kalman-Bucy estimation as shown in equations 6.3 to 6.5 as described in [7].

$$\dot{\boldsymbol{P}}(t) = \boldsymbol{A}(t)\boldsymbol{P}(t) + \boldsymbol{P}(t)\boldsymbol{A}^T(t) - \boldsymbol{P}(t)\boldsymbol{C}^T(t)\boldsymbol{R}^{-1}(t)\boldsymbol{C}(t)\boldsymbol{P}(t) + \boldsymbol{Q}(t) \tag{6.3}$$

$$\boldsymbol{K}(t) = \boldsymbol{P}(t)\boldsymbol{C}^T(t)\boldsymbol{R}^{-1}(t) \tag{6.4}$$

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}(t)\boldsymbol{x} + \boldsymbol{B}(t)\boldsymbol{u}(t) + \boldsymbol{K}(t)[\boldsymbol{y}(t) - \boldsymbol{D}(t)\boldsymbol{u}(t) - \boldsymbol{C}(t)\boldsymbol{x}(t)] \tag{6.5}$$

Equation 6.3 first calculates the error co-variance $\boldsymbol{P}(t)$ where $\boldsymbol{Q}(t)$ is the co-variance of v given in equation 6.1 and $\boldsymbol{R}(t)$ is the co-variance of the measurement noise given in equation 6.2. Equation 6.4 then calculates the filter gain given the new value for $\boldsymbol{P}(t)$. The next step is to calculate the estimate in equation 6.5, where $\boldsymbol{y}(t)$ is the measured output and $\boldsymbol{u}(t)$ is the measured input. One also needs to choose reasonable starting values for the state variable $\boldsymbol{x}(t)$ and for the error co-variance $\boldsymbol{P}(t)$. The reasonable starting values will depend on the system it is implemented on and its characteristics. All three of these calculations need to be done for every iteration of the process. $\boldsymbol{x}(t)$ can be found from $\dot{\boldsymbol{x}}(t)$ by calculating its integral and the same goes for $\boldsymbol{P}(t)$. The values of $\boldsymbol{R}(t)$ and $\boldsymbol{Q}(t)$ can now be adjusted until suitable results are obtained.

6.2. Vehicle Yaw Estimation

The sensor data used for the estimation of vehicle yaw includes the magnetometer measurements as well as the Z-axis gyroscope. The magnetometer measures the direct yaw position and the gyroscope measures the yaw rate. Both sensors therefore measure the same degree of freedom and thus a Kalman-Bucy filter can be applied to estimate the vehicle yaw. The filter model is then developed so that $\dot{\boldsymbol{x}}$ is given as in equation 6.6.

$$\dot{\boldsymbol{x}} = \begin{bmatrix} velocity \\ position \end{bmatrix} \tag{6.6}$$

The values chosen for A, B, C and D, to complete the model, is shown in equations 6.7 to 6.10.

$$\boldsymbol{A} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \tag{6.7}$$

$$\boldsymbol{B} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{6.8}$$

$$\boldsymbol{C} = \begin{bmatrix} 1 & 0 \end{bmatrix} \tag{6.9}$$

$$\boldsymbol{D} = 0 \tag{6.10}$$

An experiment was conducted to determine the optimal estimation parameters. For this purpose the two sensors were mounted together onto a potentiometer so that the actual rotation could be measured as well. Data from the three sensors was captured together with a time stamp for each measurement. The data was processed afterwards to determine the optimal estimation. The sensor pack was then rotated on top of the potentiometer while data was being collected. The data collected are thus from real sensors and not only simulated data.

The starting value for $\dot{\boldsymbol{x}}$ was taken as 0 for velocity and the first compass reading as the starting position. The starting value for $\boldsymbol{P}$ is shown in equation 6.11.

$$\boldsymbol{P} = \begin{bmatrix} 100 & 0 \\ 0 & 100 \end{bmatrix} \tag{6.11}$$

After running the estimation steps in equations 6.3 to 6.5 a substantial amount of times it was determined that values shown in equations 6.12 and 6.13 for R and Q delivered satisfactory results. To find the optimal values for R and Q the simulation results need to be analysed and one should decide which sensor's data is to be trusted over the other. R and Q are then adjusted to move the estimation result closer to either of the sensor readings until a suitable result has been found. In this implementation u is taken as the gyroscope measurement and y as the compass or magnetometer reading.

$$\boldsymbol{R} = \begin{bmatrix} 10 \end{bmatrix} \tag{6.12}$$

$$\boldsymbol{Q} = \begin{bmatrix} 0.3 & 0 \\ 0 & 0.3 \end{bmatrix} \tag{6.13}$$

The values given in equations 6.7 to 6.13 were then used in equations 6.3, 6.4 and 6.5 to calculate the estimate for the yaw of the vehicle iteratively as new data was collected from the sensors.

The experimentation results can be seen in figure 6.1 In this figure the Y-axis shows the rotational position or yaw in degrees and the X-axis shows the time in seconds. The green line shows the measurements taken from the potentiometer. In other words this is the actual rotational position of the unit. The black line shows the compass data with its low update rate. The blue line shows the gyroscope data which were integrated over time, with the first compass measurement taken as the starting value. One can see the sensor drift after about 30 seconds. The red line is the estimation using the Kalman-Bucy filter described above. One can now see the improvement from using only gyroscope data to calculate yaw. In this case the gyroscope data at a higher frequency is used to give the finer detail where the lower frequency data of the compass is used to align the result. This is seen in the last few seconds of the graph where the estimate tends back towards the actual position where significant movement in gyroscope data has stopped.

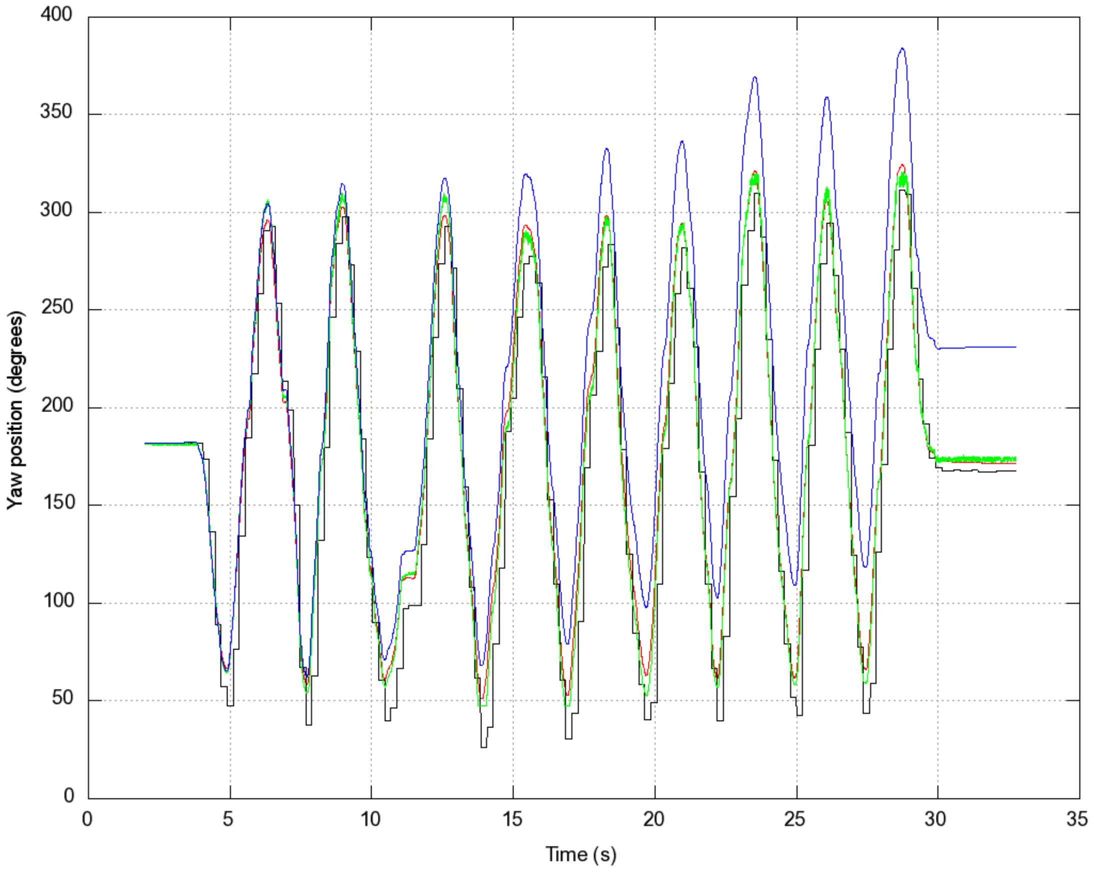

Figure 6.1.: Results from yaw estimation experiment

This section has shown that vehicle yaw estimation through a Kalman-Bucy filter can be a viable solution for data fusion of yaw sensor data. The result is a significant improvement from both sensors and tends toward the actual heading of the sensor pack or in the end, the AUV itself.

6.3. Vehicle Pitch and Roll Estimation

The sensor data used for pitch and roll estimation all comes from the IMU. The X and Y gyroscopes measure roll and pitch velocity where the three accelerometers can be used to calculate the angle between the vertical acceleration vector due to gravity and the X and Y axes which is the pitch and roll angles respectively. The tilt angle for pitch and roll is calculated as shown in equation 6.14. In the equation θ_{pitch} denotes to the pitch angle, X_{acc} to the X acceleration measurement from the IMU, and Z_{acc} to the vertical acceleration measurement taken from the IMU.

$$\theta_{pitch} = \arccos\left(\frac{X_{acc}}{\sqrt{X_{acc}^2 + Z_{acc}^2}}\right) \tag{6.14}$$

The filter model is similar to the case of yaw estimation and is shown in equation 6.15 where velocity is measured in degrees per second and position in degrees.

$$\dot{\boldsymbol{x}} = \begin{bmatrix} velocity \\ position \end{bmatrix} \tag{6.15}$$

The values chosen for A, B, C and D, to complete the model are again similar to the case of yaw estimation and is shown in equations 6.16 to 6.19.

$$\boldsymbol{A} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \tag{6.16}$$

$$\boldsymbol{B} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{6.17}$$

$$\boldsymbol{C} = \begin{bmatrix} 1 & 0 \end{bmatrix} \tag{6.18}$$

$$\boldsymbol{D} = 0 \tag{6.19}$$

The experiment conducted to find optimal estimation parameters was done by tilting the IMU first in the roll directions a few times, then in the pitch direction and then combinations of the two directions. Measurements were recorded for analysis.

The starting values for $\dot{\boldsymbol{x}}$ for these experiments were taken as zero for both pitch and roll velocity and position, as this was seen as a reasonable value for roll and pitch. The starting value for $\boldsymbol{P}$ is shown in equation 6.20.

$$\boldsymbol{P} = \begin{bmatrix} 100 & 0 \\ 0 & 100 \end{bmatrix} \tag{6.20}$$

After running the estimation steps given in equation 6.3 to 6.5 a substantial amount of times it was determined that the following values for R and Q again delivered satisfactory results. In the case of this implementation u is taken as the gyroscope measurement and y as the roll or pitch calculation from the accelerometer data.

$$\boldsymbol{R} = \begin{bmatrix} 2 \end{bmatrix} \tag{6.21}$$

$$\boldsymbol{Q} = \begin{bmatrix} 10 & 0 \\ 0 & 10 \end{bmatrix} \tag{6.22}$$

The results of this experiment are shown in figure 6.2 and 6.3 for pitch and roll respectively. In both figures the black line is the calculation of tilt using the accelerometer data as explained above. The blue line shows the gyroscope data which is again integrated over time. Once again the drift in the gyroscope data in both figures can be seen. The red line shows the estimation using a Kalman-Bucy filter. By playing around with the values of Q and R, one can move the estimate closer to either the gyroscope data or the accelerometer calculation.

The results from this experiment show that there is a significant improvement from using gyroscope data alone for pitch and roll calculation. The estimation also reduces the noise from the accelerometer measurements. The accelerometer data are affected by lateral movement of the AUV, however, and estimation through a Kalman filter would then reduce the error caused by this acceleration.

6.4. Conclusion

This chapter has shown how a Kalman-Bucy filter was used for sensor data fusion through vehicle position estimation. In some cases the estimation improved on the sensor readings and in other cases it was not as successful. The inaccuracy of the sensors has a significant effect on the filter performance. The Kalman-Bucy filter has also been shown to reduce sensor measurement noise without creating lag behind the actual

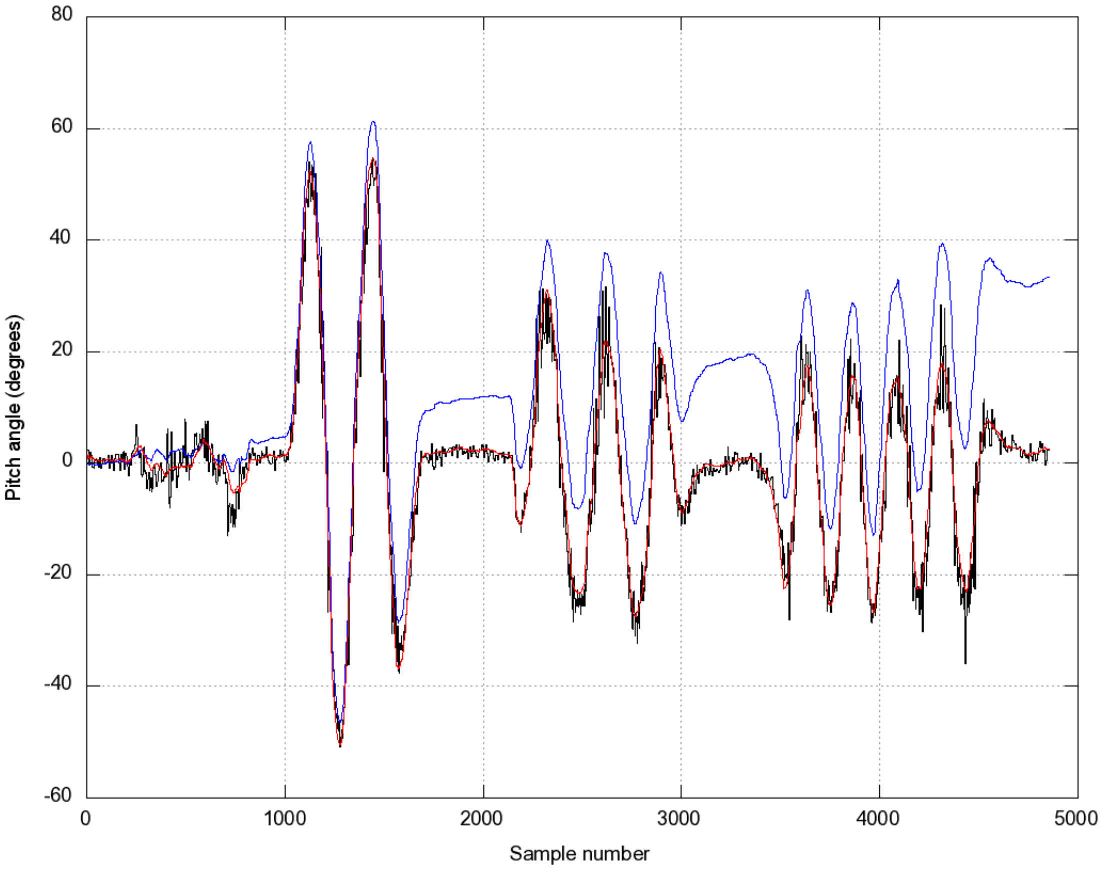

Figure 6.2.: Results from pitch estimation experiment

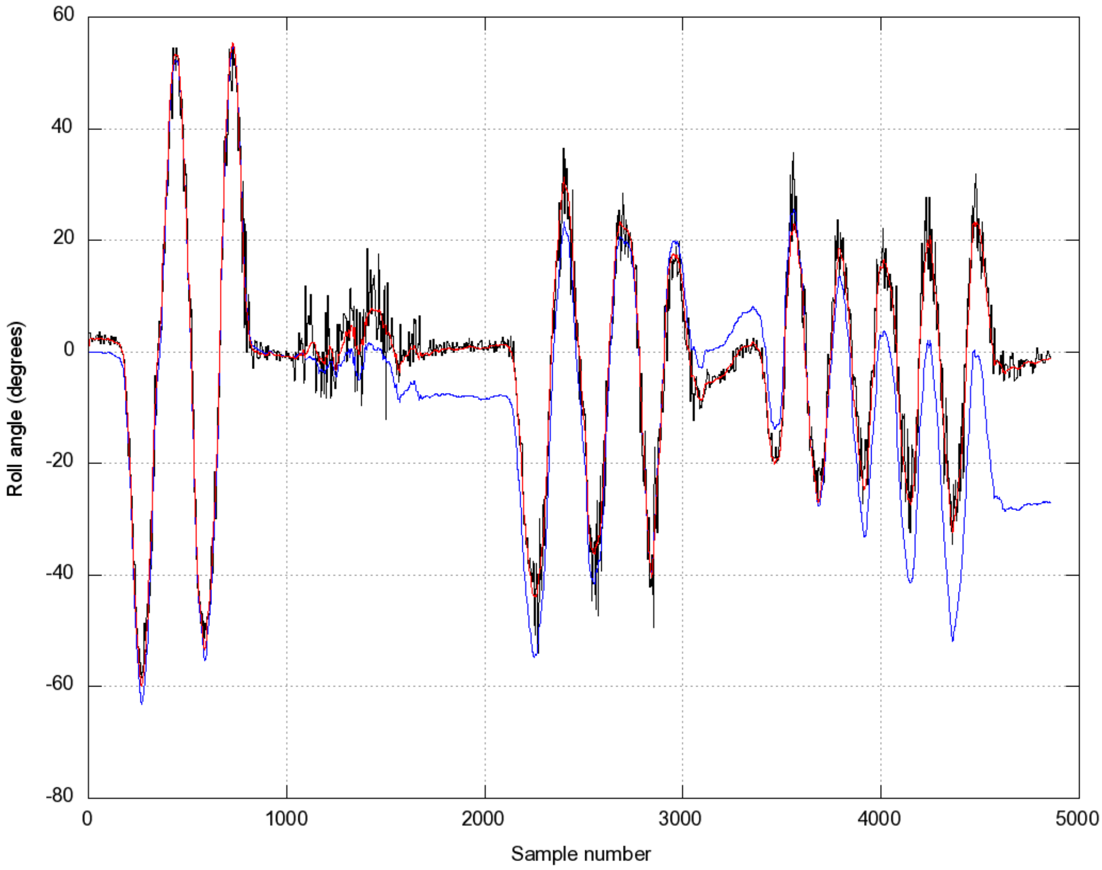

Figure 6.3.: Results from roll estimation experiment

measurements as a simple low pass filter would have done. A Kalman filter can therefore be seen as a viable solution for vehicle state estimation and sensor data fusion.

Chapter 7.

Software Design

This chapter will discuss the software considerations taken into account in the design and development of an AUV. It will show the steps taken in software design and discuss the software implementation for this project. The chapter will start with a section on the firmware developed for the IO board to provide low-level interfaces for sensors and actuators. The next section will discuss the Player robotic platform software, how it works and why it was used. The third section will discuss the software implementation on the on-board computer and the last section will show the base-station software which provides remote control and vehicle monitoring capabilities.

7.1. IO Board Firmware Design

The purpose of the IO board is to provide low-level interfaces to sensors and actuators. The sensors and actuators controlled by the IO board includes the thrusters, ballast system, water-pressure sensor, IMU, magnetometer or compass, water-detection sensor, wheel-encoder sensors, and trilateration receiver and trigger. The interfaces for these sensors have already been discussed and this section will now show how these interfaces were implemented in software.

The IO board software works on an interrupt basis. This means that the software waits for commands on its serial port before it does anything. When a command is received on the serial port, an interrupt request is generated, the unit will process the command and send a reply if necessary. A custom command set and communication protocol was designed for this purpose. The communication structure or packet consists of a command, some data and a terminating character. The terminating character tells the module that a complete packet has now been received. The first character in the packet is the command and tells the unit what type of packet has been received. The commands implemented in the IO board software are as follows.

- Toggle output pin - This command is used to toggle an output pin between 0 and 5 V.

- Read input pins - This command is used to read the value of the input pins. It will read the four digital input pins as well as the analogue pins not used for analogue signals but set up as digital input pins. The input values are sent back in the form of two bytes where each bit represents the state of an input pin. If a pin is set to analogue input the corresponding bit will be set to 0.
- Read IMU - This command will read a single register in the IMU connected to the SPI bus. The command should include the address of the register to be read where the accelerometer or gyroscope readings are stored. The register contents are sent back in the reply. The reply also contains a time stamp to be used for distance calculations. The time stamp is generated from one of the on-board timers in the ATmega 128.
- Read timer - This command is used to send back only a time stamp. It is used by the on-board computer to synchronise or reset its own timer with that of the IO board.
- Read compass - This command is used to read a tilt-compensated heading reading. The reply consists of the heading and roll and pitch angles in tenths of a degree.
- Read magnetometer values - This command is used to read the raw data of the three magnetometers so that the heading can be calculated elsewhere. The reply only contains the three raw measurements.
- Read accelerometer data - This command reads the three accelerometer measurements from the magnetometer unit if it is needed. The reply contains the acceleration measurements.
- Enable ADC - This command is used to enable or disable a specified ADC channel. The channel must be enabled before ADC measurements can be taken and if disabled the pin is assumed to be a digital input pin. The ADC channel needs to be specified in the command.
- Read ADC - This command is used to start an analogue to digital conversion on an ADC channel. The channel needs to be specified in the command. If the ADC channel is not enabled an error message will be sent back. If the channel is enabled an analogue conversion will be started and the result will be sent back in the reply.
- Set thruster - This command sets the thruster speed of a specified thruster given in the command. The thruster speed is set by changing the pulse width of the PWM channels. Only four of the six PWM channels are used for this as there are only four thrusters. If no thruster command has been received within one second of the previous thruster command, all PWM channels will be set to their zero or centre positions. This will ensure that the vehicle stops if something goes wrong with the on-board computer.
- Set ballast - This command is used to set the position of the piston tanks. The command takes the ballast tank, front or rear, together with the position as a

percentage. The wheel encoder sensor data together with micro switches on the piston tanks are used to find its position.

- Pulse triangulation beacon - This command is used to trigger a specified beacon for triangulation. The command specifies the beacon to be triggered. The beacon number is sent over the tether connected to the second RS-232 port on the IO board to the triangulation system controller. When an OK message is received from the controller the IO board sends the trigger signal over the trigger line also included in the tether cable. An acoustic pulse is then generated as described in the chapter on sensors. The receiver on the vehicle will then receive the signal and one of the internal timers on the IO board is used to measure the time it takes until the pulse is received. The reply is then sent back containing the measured time so that the distance can be calculated.

- Reset IO board - In case something goes wrong on the IO board a reset command is available. This command will simply perform a software-reset on the IO board. The IO board will always send a start-up command when the software starts, containing the reason for the reset. This data can then be used for diagnostic purposes in case of an unexpected reset.

The software will perform only two tasks without being requested to do so through a command received. These two tasks are firstly monitoring the four digital input pins with interrupt capabilities. If an interrupt occurs for one of these pins the read input reply will be sent to the on-board computer without it being requested. The second task is to monitor and control the position of the piston tanks. At start-up the IO board will use a set point of zero for the piston tanks until another position set point has been received from the on-board computer. The controller will be discussed in further details in the chapter on Control.

As mentioned before in this chapter the software running on the IO board works on interrupts and then reacts to them. The interrupt signals that the IO board will react to include data received on any of the two serial ports. This means that data has been received from either the on-board computer or the trilateration system controller. A digital input interrupt means that the state of one of the digital input pins with interrupt capabilities has changed. An analogue comparator interrupt means that an acoustic pulse from the trilateration system has been received and the timer value needs to be recorded to measure the travel time of the pulse. Timer overflow interrupts are used for different purposes. The first is to measure the time-out for PWM shut-down to stop the thruster if no thruster command has been received in a certain time. The second is used to measure time for the global timer used to generate time stamps. The third is used to measure the actual travel time of acoustic pulses sent by the trilateration system. The last interrupt is generated by the ADC. This interrupt means that an analogue to digital conversion has been completed and the result is available for use.

The IO board also employs a watchdog timer to ensure that the software does not get stuck in an unending loop. If the watchdog timer is not reset every three seconds, the IO board software will reset itself. The software diagram for the IO board software is shown in figures 7.1 and 7.2. All software code will be shown in the Appendices of this dissertation.

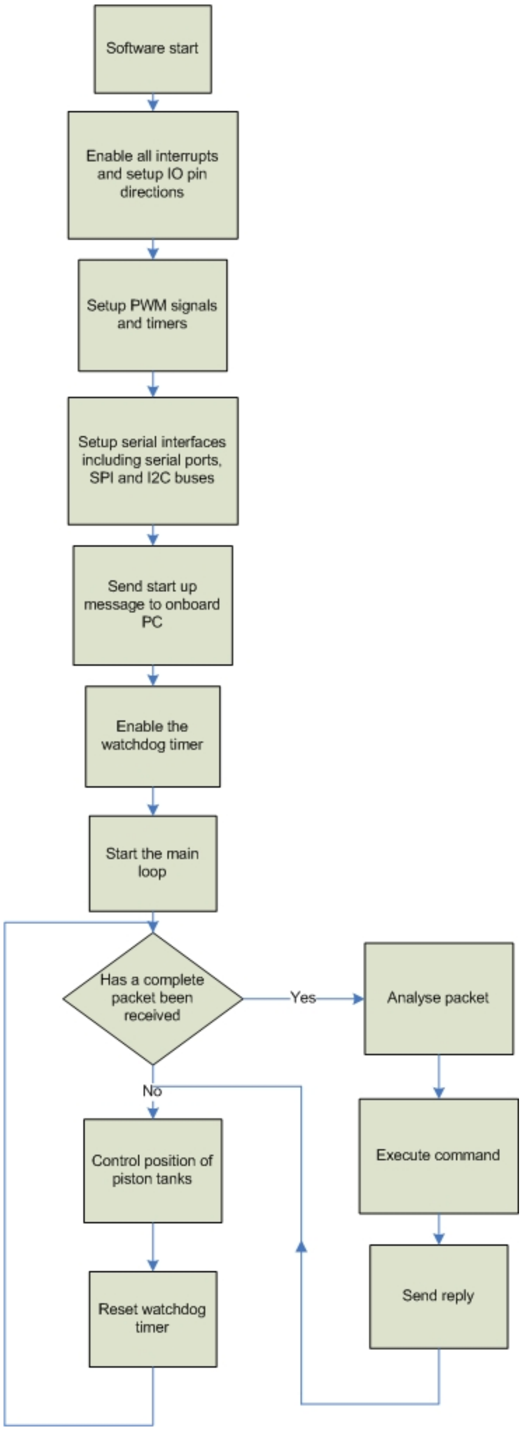

Figure 7.1.: IO Board software diagram

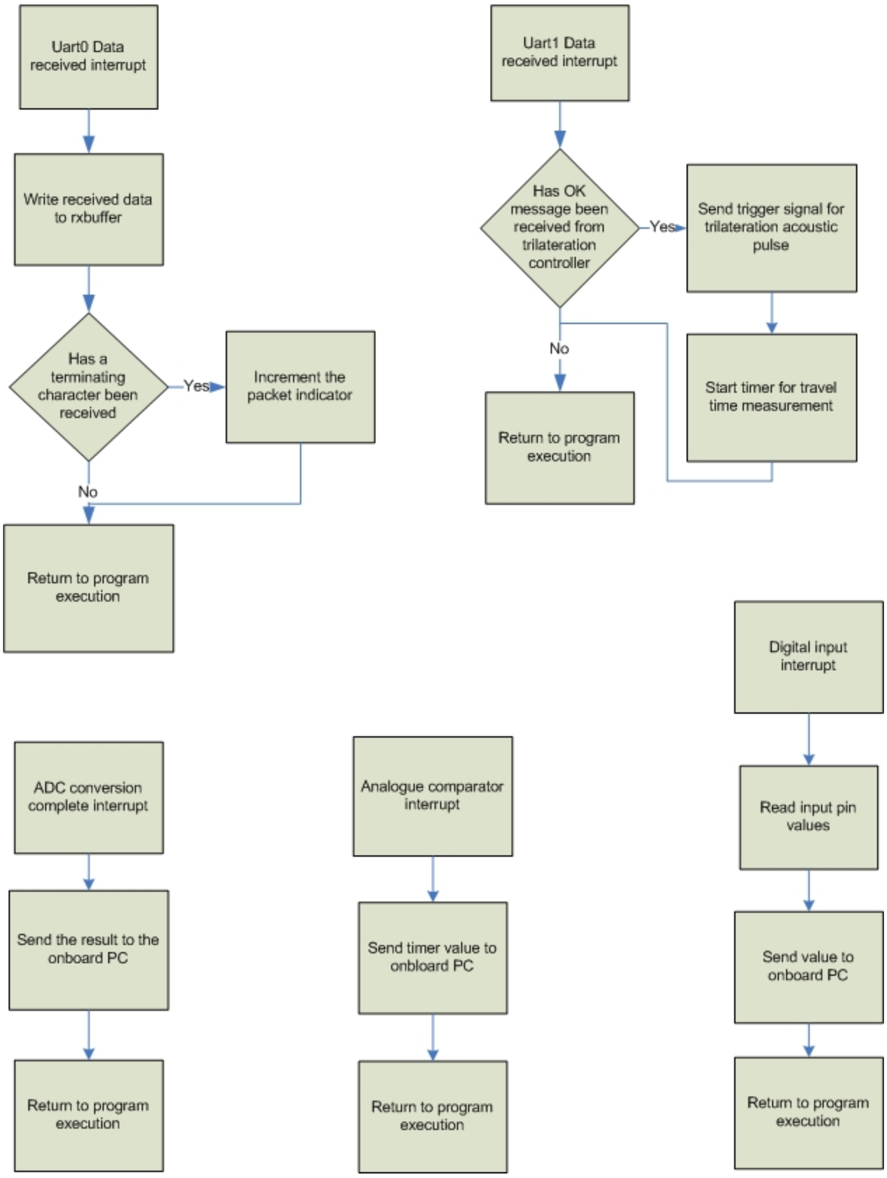

Figure 7.2.: IO board software diagram showing the most significant interrupt procedures

This section showed how the embedded software running on the IO board was successfully implemented. It discussed how the software works and interfaces with the rest of the AUV hardware.

7.2. Player Robotic Control Software

Before moving on to the on-board computer software this section will first discuss the robotic control software used for this project. Player, which is part of the Player-Stage project, is a robotic software platform that provides for modular robotic control software. It also provides hardware-independent interfaces to sensors and actuators to the control software. Player runs on the vehicle itself and provides standard interfaces to all sensors and actuators through network sockets. Control software is then implemented in the form of clients, which connect to the sockets provided by the server to access sensor data or send actuator commands. A Player server can support multiple clients. Plug-in drivers are developed to communicate directly to the hardware and save the sensor data into the standard interfaces or interpret standard commands, executing them by sending the right data to the actuator itself or whatever else the command requires. Several standard interfaces are provided, ranging from position3d to a laser range-finder interface. The developer must choose an interface that best fits the hardware for which it will be used. The client software is not dependent on the hardware itself but only on the interface used. The driver needs to be able to handle all possible requests sent by the client. The requests are also standard to the interface. Sensor data must be stored in the correct fields within an interface and then published for clients to read.

Player has certain standard drivers already implemented for certain robotic hardware as well as drivers for robotic navigation, obstacle avoidance, path planning and many others. These could however not be implemented for this project as they were developed for ground robots which only navigates and moves in two dimensions.

7.3. Onboard Computer Software Implementation

Player was implemented for the project utilising a single plug-in driver. The plug-in driver communicates with the IO board embedded software by either requesting sensor data or sending actuator commands. The interfaces provided by the Player driver includes a dio interface which is used to control or read digital IO pins, position3d which provides vehicle pose and position tracking in three dimensions as well as position control in three dimensions, and position1d which is used to track and control the position of the piston tanks of the ballast system. Three position3d interfaces are provided. One tracks the IMU measurements and position according to the IMU, another is used for the other sensors like the magnetometer, water-pressure sensor, roll and pitch measurements and the X and Y position calculations from the trilateration system. The third position3d interface provides the vehicle state estimation results. Two position1d interfaces are also supplied, one for each ballast system. The structure of the Player implementation for this project is shown in figure 7.3.

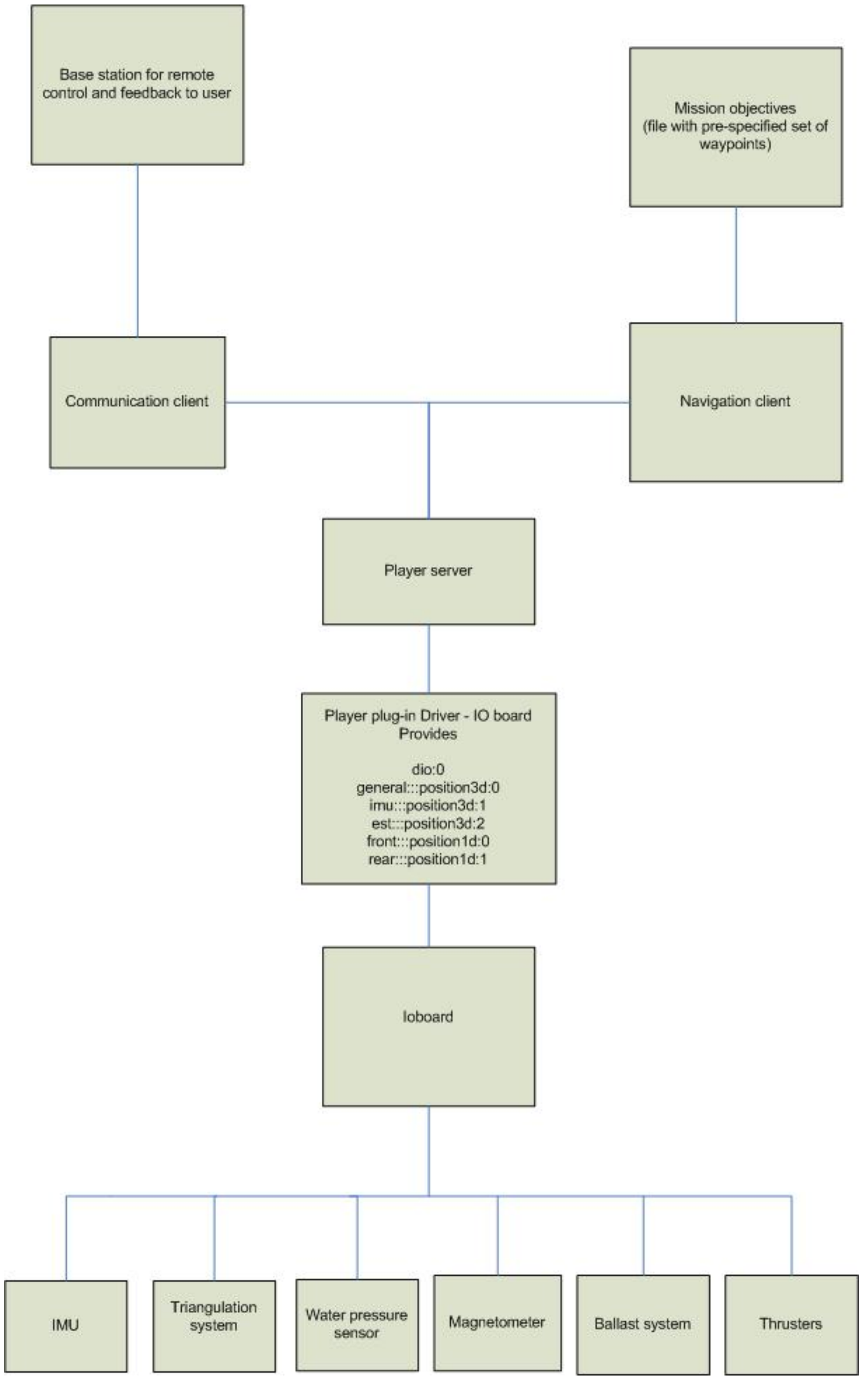

Figure 7.3.: Structure of the Player implementation

The position3d interface used for the IMU data provides the measured velocities and acceleration values taken from the gyroscopes and the accelerometers respectively. The interface does not have a field for acceleration so the acceleration values were stored in the velocity field as well. Even though the positional data are not calculated there are fields available for the data if in the future they are needed. If IMU data is received from the IO board, the data is stored in the correct fields within this interface and then published.

The position3d interface for general position data are used for the other positional sensor data. The first sensor is the magnetometer. It supplies yaw position and the measurement is stored in the yaw position field of the position3d interface. The raw magnetometer values are also stored in the velocity fields of the interface so they can be used for calibration or other purposes. The water-pressure sensor provides vertical or Z position data which is then stored in the Z position field within the interface. The trilateration system supplies the X and Y position data within the interface. The accelerometer data are used to calculate the roll and pitch data for the interface. Velocity commands received on this interface are taken as magnetometer calibration values.

The last position3d interface is used for the estimation results from the Kalman filter. As the data are collected from the sensors, the Kalman filter is used to estimate the vehicle positional state. These results are then stored in the interface and published for the clients. This interface is also used for thruster commands. Commands are sent in the form of forward, yaw and vertical thrust. The value sent through is the required torque from which the motor speed is then calculated. The interface can take velocity or position commands. Velocity mode is when the vehicle is in remote controlled mode. The commands received simply specify the different motor thrusts sent from the operator. In position mode the interface receives positional commands. The vehicle will then use implemented control systems to proceed to the specified position. When the software is in position control mode, thruster velocity commands received will be ignored. The vehicle has three control modes. One is depth control where only vehicle depth is controlled and the software will still accept forward and yaw thrust commands. The second is heading control where the vehicle will control its heading and still accept forward and reverse commands. In fully positional control mode the vehicle will control yaw as well as the position itself. The yaw set point will then be calculated to face directly toward the commanded position, after which the positional control system will be used to minimise the error between the AUVs current position and the commanded position. These control systems will be discussed in the following chapter.

The two position1d interfaces are used to store the position of the two piston tanks' rods which is determined using the wheel encoders and micro switches. The interface also accepts commands to control the position of the piston rods.

The plug-in driver consists of C++ classes. The main class is the IOboard class as the driver is used to communicate with the IO board as discussed earlier. The class firstly implements all the standard functions required by Player. These include the constructor and destructor functions, a set-up function and shut-down function, a subscribe and unsubscribe function to handle clients that subscribe to certain interfaces supplied by this driver and a message processing function where the commands and requests from clients are handled. Other functions also implemented in the class include a function to set digital output pins, a function to set the velocity of the thrusters when a velocity or torque command has been received, a function to set the ballast or piston tank to a given position or fill them to a given percentage, a function to calculate the heading or yaw position of the vehicle from the raw magnetometer measurements, a depth control function used to calculate the thruster speed to control the depth of the vehicle every time a depth measurement is received, a function to calculate the trilateration position of the vehicle from the received distances to the beacons. More functions in the class include a heading control function to calculate the yaw speed to control the heading of the vehicle and position control to calculate the forward velocity for the thrusters to control the positional error of the AUV.

Two more classes were implemented. The first is a general support class containing functions including the Kalman filter implementation, AUV tilt calculation and trilateration calculations. The main IO board class for trilateration is only used to prepare the data and then call the trilateration function in this class. The second implemented class is the PID control class. This class implements the PID control functions including calculating the control output from the error as well as a function to set a new value for the integral term of the PID controller. Three instances of this class are created, one for each controller. The PID controller in the class has been developed in a general way so that it can be used in process. It works with percentages where for example the vehicle position will be used given as a percentage of the positional range. The output will again be a percentage of thruster torque and can be positive or negative to show direction.

To ensure that messages get through to the IO board certain important messages are moved to a second transmit buffer. Messages in this buffer are sent every 100 ms and only removed when a reply on this message is received from the IO board. A timer function is used to create an interrupt every 100 ms and perform the required tasks. The same timer is used to read sensor values from the IO board at a constant frequency. Sensor data are therefore read at a sampling frequency of 10 Hz. An interrupt procedure is also used to handle incoming messages in the same way as the software running on the IO board. Incoming messages trigger the interrupt service routine where the received data are written to the receiving buffer. The received data are monitored to check if a terminating character has been received. If a terminating character is found, the packet indicator is incremented and the packet is analysed.

The driver software structure basically works as follows. It periodically reads sensor data and keeps track of the vehicles position and heading. It then waits for commands from the client software for motion control, whether it is in remote control mode or positional control mode. In remote control mode the thruster velocities are received from the client, whereas in position control mode the X, Y and Z coordinates of a goal point is received and the driver should control the position of the vehicle. The data saved in the standard interfaces are constantly fed to the client as well.

Clients can be implemented in different ways as shown in figure 7.3 where two different clients are presented. The first client is basically for remote control or vehicle monitoring.

The second client is where the AUV is in a fully autonomous mode and way points are pre-programmed in a script file. The vehicle will proceed from way point to way point, using the current way point as set point for the positional controllers.

This section discussed how the on-board computer software was implemented, its role in the AUV and how it interfaces with other components in the AUV. The onboard computer software is the main control module where all major decisions are made.

7.4. Base Station Control Software

The base station software was implemented as a Player client. Since the tether cable is an Ethernet cable, it is easy to connect to the socket provided by the Player server. The client provides a graphical user interface for remote control of the vehicle. It provides a forward, reverse, left, right, up and down button. It also provides a thruster torque box, so that, whenever one of these buttons is pressed the value in the thruster torque box is sent through to the correct thrusters for the required movement. The graphical user interface also provides control for piston tank position and displays the current position of both tanks. The graphical user interface also provides a button to reset the IO board software if required.

The graphical user interface is shown in figure 7.4.

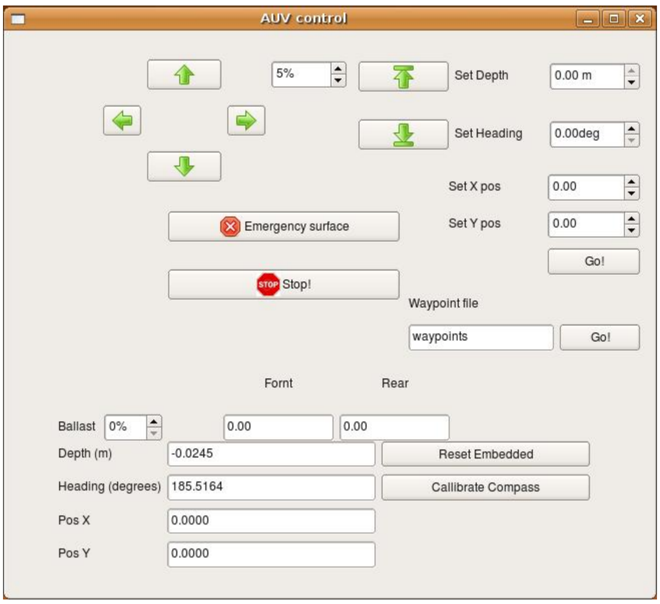

Figure 7.4.: The graphical user interface implementation of the base station software

A display of the current heading measurement from the magnetometer is also provided. A button is provided to start the magnetometer calibration procedure. The procedure involves setting the yaw speed of the vehicle to a certain value. The user should keep the button pressed until at least one full rotation has been completed. The program will then record the three raw magnetometer measurements through the duration of the procedure. Once the button is released the calibration is done as discussed in the chapter on sensors. The calibration values are then sent through to the Player driver.

The user can also change the set points of the control systems for depth, heading and X and Y position. Whenever any these values are changed the new set point is sent through to the AUV for control. Boxes are provided to display the current depth and the current X and Y position of the AUV. A button is provided for emergency surfacing as well. When this button is pressed the vehicle will stop all control and turn the vertical thrusters on to surface. At the same time, the ballast tanks will be emptied as part of the surface procedure.

The IO board will stop all thrusters if the thruster command is not sent through at least once every second. A timer was set up to send the current speed values at a rate of 2 Hz. Data is read from the Player server in the main loop so that the data displayed are as up to date as possible.

The base station software was developed using an integrated development environment called Qt, developed by Nokia. The Qt development environment provides for easy graphical user interface development and implementation into software. The Player client libraries were also easily integrated into the Qt environment. Qt is platform independent and can therefore be used for Windows or Linux development. The platform used in this case was Ubuntu Linux, as the Player libraries are not platform independent and are only available under Linux.

7.5. Conclusion

This chapter discussed the software implementation of the AUV. Three separate programs were implemented. These include the IO board embedded software, the on-board computer main software through a Player server and the base station software through a Player client. The chapter showed that Player can be a very useful tool for robotic software in the case of an AUV.

Chapter 8.

Control System Design and Implementation

This chapter will discuss the control systems implemented on the AUV. The first section will discuss the control strategy followed in the implementation as well as general PID control, how it works and why it was used. The next section will start with the first control system implemented, the controller for the ballast system which controls the position of the piston tank. The third section will discuss the AUV depth controller. The following section will consider the heading controller followed by a section showing the vehicle position controller. The last section will conclude on the findings in this chapter.

8.1. PID Control and Control Strategy

This section will discuss the basic control control strategy implemented in this project. It will also look at the standard PID controller, explain how it works and how it was implemented in this project.

The AUV has four processes to be controlled. These processes include the piston tank position which specifies how much water is inside the ballast tank, the depth or vertical position of the vehicle, the heading of the vehicle and the vehicle's horizontal position. These four processes are controlled independently of each other. The vehicle has four control modes. The first is where all control is switched off and the vehicle accepts motor speed commands from the operator. The second mode is where depth control is activated. In this mode the vehicle will control its depth at a given set point and will still accept thruster commands for the horizontal thrusters. The third mode of control is heading control. In this mode the vehicle will control its heading to a specified set point. The AUV will still accept forward and reverse commands for the horizontal thrusters but not yaw commands. This mode can be used together with depth control. The last control mode is position control. This mode takes a goal position as input. The heading to the goal point is calculated and given to the heading controller as input and so the heading controller will not accept any other heading set points in this mode. The position controller will only start controlling once the vehicle is pointing towards the set goal point. The vehicle will then start forward movement towards the goal position. If the heading error goes outside certain specified bounds the position controller will stop the vehicle and wait until the heading error has been reduced again. This control mode cannot be used together with heading control mode but can be used together with depth control mode. Ballast control is done independently of the other control processes.

All of the above controllers employ a PID controller except for the ballast system. The PID controller is a simple but robust controller to implement. The PID controller can be implemented without the knowledge of the system dynamic model. However, if the system dynamic model is known, the PID controller can be implemented even more effectively. Without the model the PID parameters can be tuned through trial and error until the system performance are found to be acceptable. The structure of the PID controller is shown in figure 8.1.

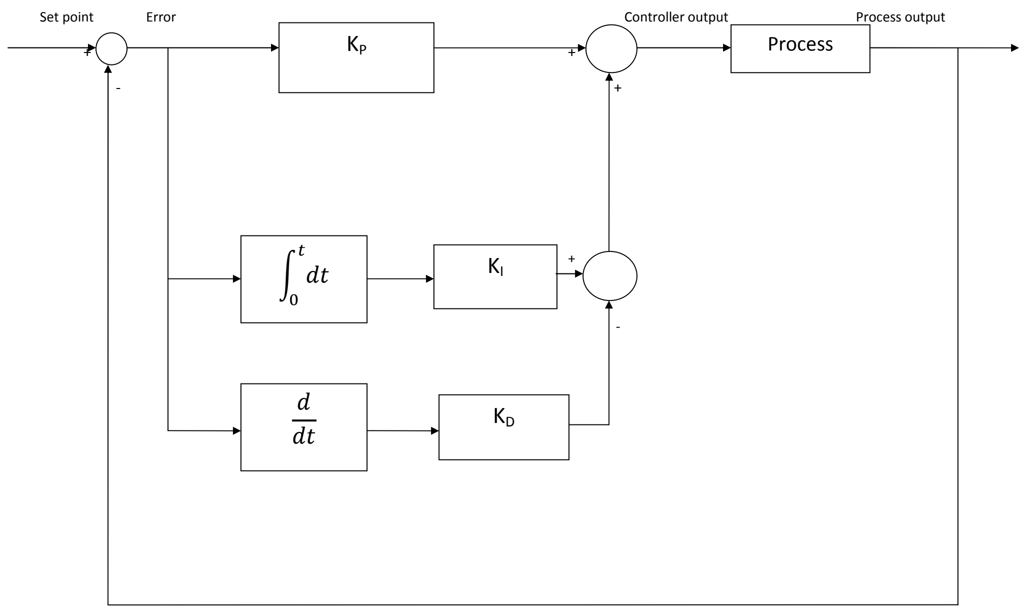

Figure 8.1.: Basic structure of a PID controller

The PID controller consists of three parts. These parts include a proportional, an integral and a derivative part. The proportional part basically takes the error between the current position and the commanded position and multiplies it with the proportional gain to get the proportional output. The integral part adds the consecutive errors and multiplies this by the integral gain to find the integral output. The derivative part first calculates the difference between the previous position and the current position to get an idea of the current speed of the vehicle. This is then multiplied by the derivative gain to find the derivative output. The controller output is then calculated as the proportional gain plus the integral gain minus the derivative gain. The proportional part therefore forms the base of the controller. The further the vehicle is from its goal point the greater the proportional output. The integral section calculates the additive error and will make the controller react quicker. It will also correct smaller errors when the proportional output is too small to have an effect. The integral gain can also cause system oscillation if the gain is too big. The derivative part is used to limit the velocity of the vehicle. Any section of the PID controller can therefore be switched off by using a gain of 0 for that section. The different gain values are then used to tune the controller until acceptable performance is achieved.

For this project a standardised PID controller was implemented. The PID controller is developed in such a way that it can be implemented for almost any process. The process variable or output needs to be converted to a percentage of the complete range of possible outputs or in this case positions. The set point is also converted to a percentage value within this same range. The controller then gives an output of between -100 and 100 % to show direction and power to be used as input for the motors or whatever form of actuation is used. The percentage should then be converted to the correct input for the actuators. In this case the PID controller output was taken as the required thruster torque and the motor speed first had to be calculated to achieve this output torque. This process was described in the chapter on mechanical design. The PID parameters are set beforehand. The parameters utilised in this implementation of the PID controller is the proportional gain, integral gain, derivative gain, dead band and action. The dead band parameter is used to specify a band around the set point were no control is performed. The purpose of this is to cancel the effect of sensor noise on the controller when the output gets really close to the set point. The action parameter specifies the direction of the output as this may differ from process to process.

8.2. Ballast System Position Control

This section will show the control system implemented for piston rod position control of the ballast system.

The ballast system uses a much simpler controller. Since the motor speed of the piston tanks could not be varied, the controllability of the ballast system is limited. The piston motor is either on or off. The chapter on sensors discussed the feedback from the piston position sensors. A section around the set point was specified which is seen as close enough to the goal. When the position measurements enter this band, the motors are switched off. When the piston position is outside this band, the motor is switched on in the correct direction to get to the desired position. The section around the goal point should be big enough so the piston will stop before it exits this section again, as this will cause the system to oscillate. It should also be small enough to ensure an acceptable accuracy of control. In this case, the band around the goal point was selected as 0.25 % of the entire range of the piston rod to either side.

This control system in effect controls the amount of water taken in by the piston tanks as the piston rod position determines the volume to be filled with water. In other words if the piston rod position is set to 50 % it means that the piston will be filled with water to 50 % of its capacity. As mentioned earlier, the capacity of the piston tanks is 800 ml each.

8.3. Depth Control

This section will discuss the control system implemented to control the depth of the AUV. It will give the PID parameters used in the PID controller discussed above and show the controller results.

The control system implemented for depth control is a PID controller. The range set for the controller in this case was taken as the maximum depth, which in the case of the CSIR test tank is 0 to 5 m. This means a set point of 2 m will be sent to the controller as 40 %. A ramp function was also set up to stop the vehicle from moving too fast if the position error is large. If the error is greater than 0.5 m the set point is moved to within 0.5 m of the current position. This means that the controller output will be limited without the need of a derivative term. The PID controller was therefore only used with a proportional term and an integral term. The dead band was specified to be just more than the noise amplitude of the pressure sensor, which was 50 mm to both sides.

The controller output, given as a percentage, was used as the required thruster torque to correct the depth error. A lookup table was created from the results of the experiment on thruster output linearisation. The lookup table was used to find the input for the thrusters to give the required torque.

The tuning method to find the proportional and integral gain was done as follows. The integral gain is first set to zero. The proportional term is started at a very small value. The process is run and output is recorded. The proportional gain is moved up until the process gets close to the set point without any overshoot. The integral gain is then slowly increased to get rid of the small error that the proportional gain could not fix. If the system starts oscillating the integral gain should be decreased. The correct values may produce a little overshoot and oscillations, as long as this is kept within the specified bounds.

The PID parameters were set to the following values to achieve acceptable control. The proportional gain was set to 40 and the integral gain was set to 60. These values are inverted in the controller so the bigger the value the smaller the gain. The controller results are shown in figure 8.2. The figure shows a step response where the set point was changed from 0 to -1 m. The blue line shows the measured depth and the red line shows the set point. The vehicle reaches its set point after eight seconds, then shows a little overshoot before it starts to oscillate around the set point. The overshoot is more or less 10 % of the step change and the oscillations stays within the same bounds. The oscillations are acceptable as it stays within the specified limit of 0.2 m. The oscillation frequency is about 0.1 Hz which is slow enough not to effect the AUV performance too much.

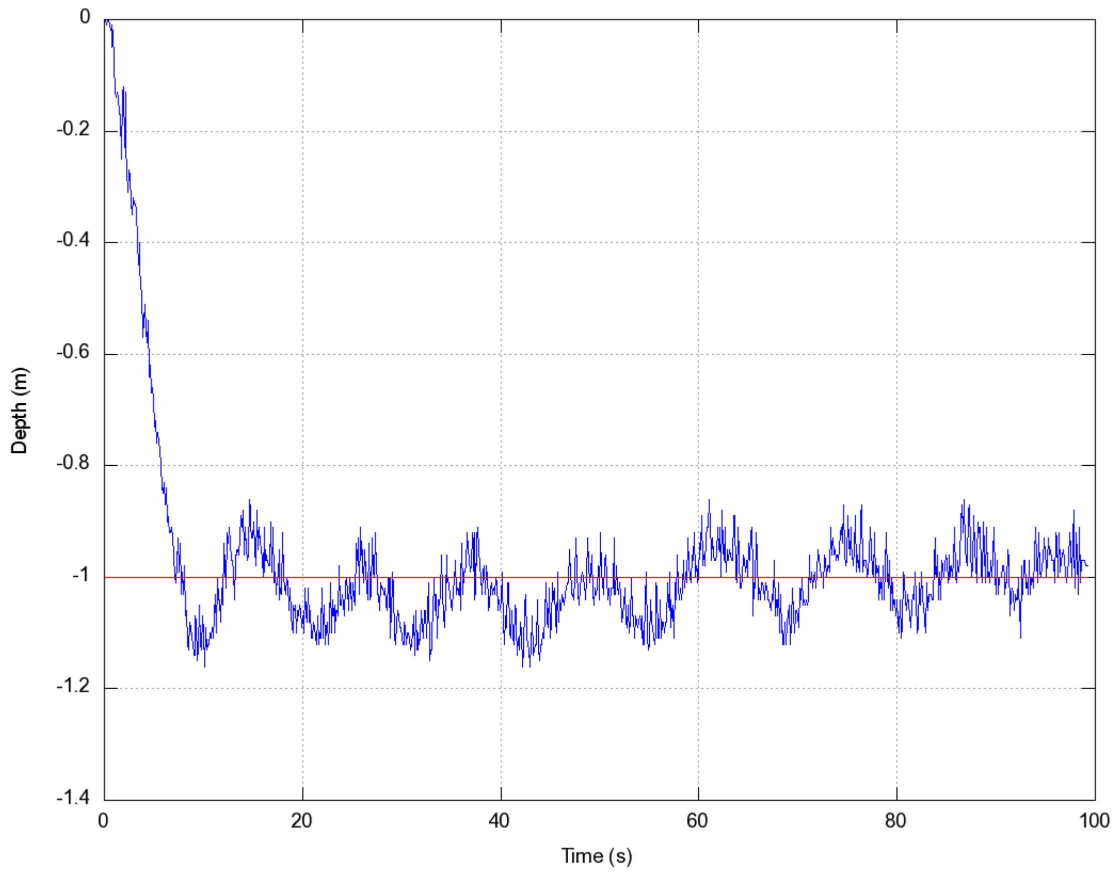

Figure 8.2.: Depth controller step response

8.4. Heading Control

This section describes the controller implemented for heading control of the AUV. It will show the PID parameters used for the above mentioned PID controller and give the controller results.

The control system implemented for control of vehicle heading was the above-mentioned PID controller. To be able to use this PID controller, a range had to be set up so that a set point could be taken as a percentage of the range. The range was decided to be two full rotations or 720 degrees. The reason for using two full rotations instead of a single one is to ensure that the control system will always check which rotation direction is the shortest. This is useful in cases where for example the set point is at 10 degrees and the current position at 340 degrees. If the difference between the set point and the current position is greater than 180 degrees it means the other direction should be taken. The controller will then add 360 degrees to the lowest value of the two to ensure that the controller will go in the right direction. It was found that very little force was required to turn the vehicle and its turning momentum could easily make the controller overshoot. A ramp function was again used to limit the turning velocity of the vehicle and therefore limit the momentum. The ramp function would move the set point closer to the current position if the error is more than 45 degrees. The set point will be placed at 45 degrees from the current position until it gets closer to the set point. This controller was also used only with proportional and integral terms. Heading feedback from this controller comes from the heading calculations discussed in the chapters on sensors and data fusion.

The same PID tuning method, as discussed in the previous section, was followed in tuning the heading controller. The proportional gain used for the heading controller was 150 and the integral gain was 200. Both these values are inverted in the controller so bigger values in this case actually means smaller gain. Since the yaw actuation of the AUV is very sensitive the gains used for the controller had to be quite small. The controller results is shown in figure 8.3. The figure shows a step response of about 180 degrees. The controller reaches the set point within nine seconds. The controller then shows a small overshoot and then a few oscillations. The figure also shows the steady state of the controller as it holds its position for 80 seconds. There are three spikes in the magnetometer measurements which are interpreted as errors. These however did not affect the controller too much and only caused some minor oscillations for a few seconds. The steady state error when the controller has settled after the oscillations was measured at less than 10 degrees or 0.17 radians.

8.5. Vehicle Position Control

This section will discuss the control system implemented for control of the vehicle's horizontal position. It will show the PID parameters used and the PID controller performance.

This controller is used to follow a set of way points. Therefore it is not required of the controller to hold the position but only reach it and move on to the next way point. The more important controller implemented to reach a goal point is the heading controller discussed in the previous section. The position controller will wait for the heading controller to first point the AUV in the right direction before it starts controlling the position. Once the error in the heading grows to more than a specified value, the position controller will be stopped until the heading controller has corrected its error and only

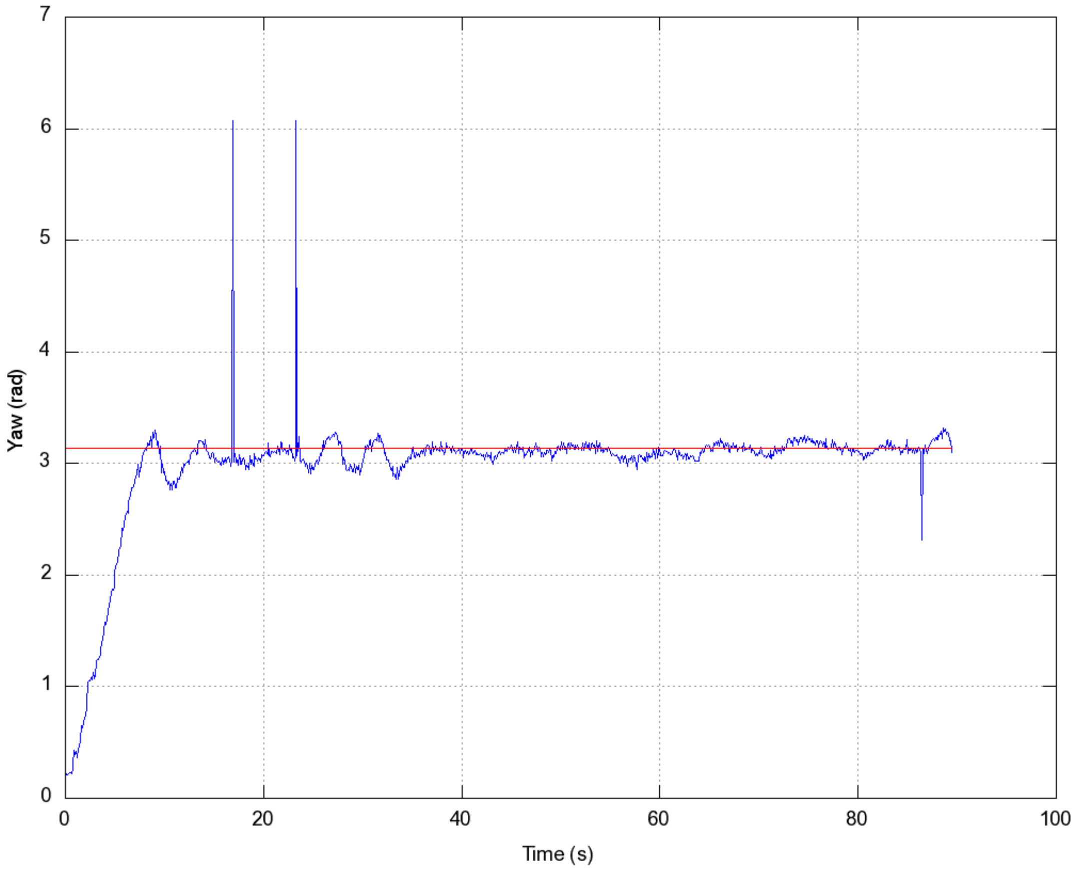

Figure 8.3.: Heading controller step response

then will it continue. Positional feedback for this controller comes from the trilateration calculation.

The PID controller was implemented to minimise the direct horizontal distance between the vehicle's current position and the goal position. This is done through simple forward thrust. The PID controller output was used differently from the PID controllers in the previous two cases. The output of the positional PID controller was added to the current motor thrust so that the vehicle will more gradually pick up speed instead of just shooting away towards it goal. The reason for this gradual increase of speed is that high acceleration negatively affects the heading controller. If the vehicle's speed is gradually increased the heading controller is still able to control the heading efficiently. The proportional gain for this controller was set at 800. Such a large value was chosen to limit the motor speed. The integral gain was also set at 800. The reason for this was to so that the integral term will grow very slowly and not make the vehicle accelerate too fast. A derivative term was added with a gain of 30 to limit the vehicle speed a little bit. The position error was also limited to reduce the controller output to ensure that the vehicle will not accelerate too quickly. The vehicle's velocity was also limited to minimise the positional error made by the trilateration system.

The position controller will select the next way point in the list as soon as the vehicle comes to within 0.5 m of the current way point. The way point navigation results are shown in figure 8.4 where the blue line shows the vehicle path measured by the trilateration system, and the way points are shown in green with a 0.5 m radius around each of them. The vehicle's starting point is shown with a red plus sign. The AUV started of at (-1.5, 2.5, -1) and proceeded to the first way point which was positioned at (-2, 2, -1). After it reached this way point it had to turn around towards the next way point at (-2, 5, -1). When this way point was reached the AUV had to dive down and turn for the next way point situated at (-5, 5, -2). The third way point was then positioned at (-5, 2, -1) where the AUV first missed the way point then turned around to reach it in a second attempt. The vehicle then proceeded to the last way point at (-2, 2, -1) where it finished the experiment. All way points have therefore been reached to an accuracy of less than 0.5 m. Even though the figure only shows two dimensional navigation, the way points were implemented in three dimensions using varying depths for the way points to obtain full three dimensional navigation.

8.6. Conclusion

This chapter discussed the implementation of vehicle position control on the AUV. It showed that an AUV's position can be successfully controlled in three dimensions. Some of the degrees of freedom are passively controlled through weight distribution inside the AUV and others by using the actuators installed on the AUV, namely the thrusters and ballast system. The chapter discussed how a PID controller works and how it was implemented to control the AUV.

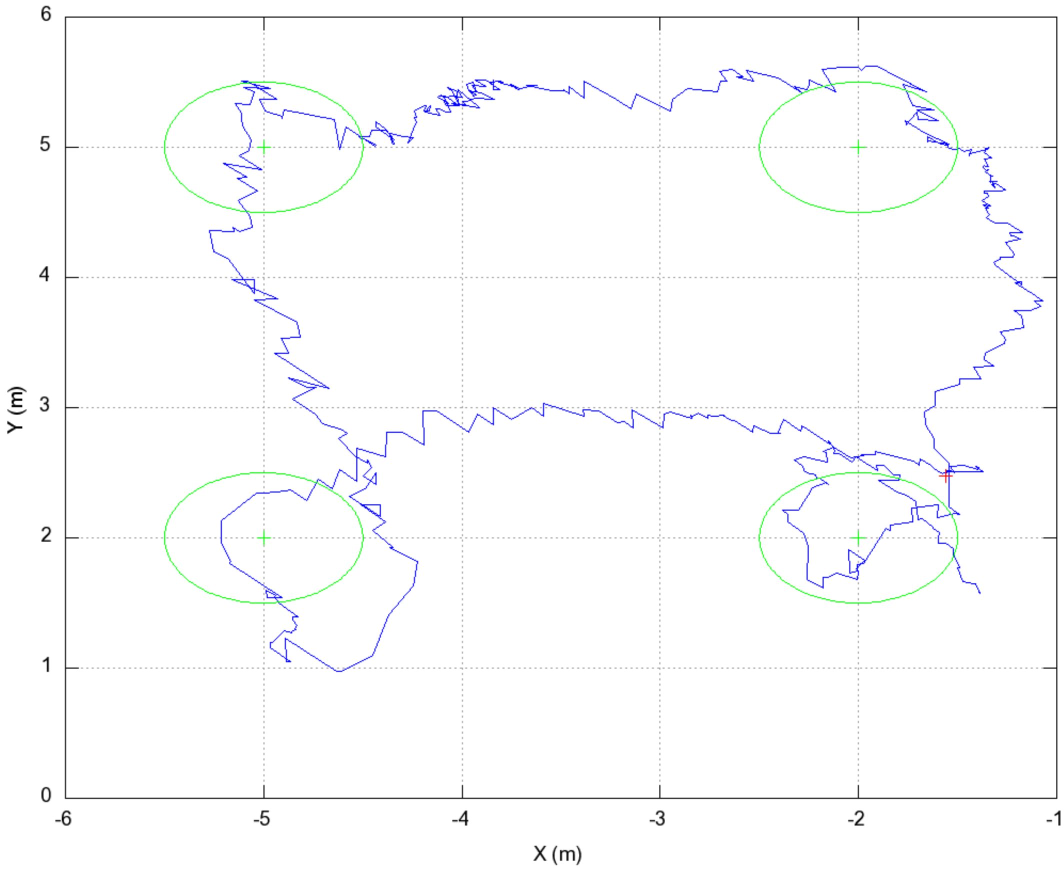

Figure 8.4.: AUV way point navigation results

Chapter 9.

Validation and Conclusion

The purpose of this chapter is firstly to validate the research through the research questions and system specifications given in the introduction and to measure if the research study was successful. The chapter will also draw conclusions from the study. A summary of contributions will then be given followed by suggestions for further research.

9.1. Validation

This section will look at the research questions posed in the introduction of this dissertation and attempt to provide answers with the help of the results achieved in this research study. The system specifications will also be tested in this section.

The first question posed was whether a small AUV can be developed using relatively low-cost sensors and actuators. The study has shown that this can in fact be done. The AUV developed in this case is small compared to most AUVs on the market. The sensors and actuators are all low-cost devices. Many of the sensors and actuators are devices normally used by robotics hobbyists and are all below R6 000 per unit, which is not very expensive compared to some of the navigation systems used in AUVs.

The second research question was whether such an AUV can accurately track its position in an underwater environment. The chapters on sensors and data fusion has shown how relatively inaccurate sensors can be used together with data fusion and vehicle state estimation to improve on the errors of the sensors and to accurately track the position and movement of the AUV. This has been done in an underwater three dimensional environment with acceptable results as has been shown in the chapters on sensors and data fusion.

The third question was whether the AUV can reliably navigate and control its position in an underwater three-dimensional environment. This was shown in the chapter on control systems. The chapter illustrated how a set of way points could be used for navigation and different control systems was implemented for the AUV positional control. Control systems were implemented for depth, heading and horizontal positioning. The other degrees of freedom were passively controlled through weight distribution within the vehicle. The results given in the same chapter shows that the vehicle's position can be accurately controlled and that such a navigation system can be successfully implemented.

The system specifications given in the introduction can now be tested to measure if the project was a success. The specification test results are as follows.

- The watertight container of the AUV was tested to a depth of 5 m and still remained watertight in spite of the pressure at this depth. This test was discussed in the chapter on the mechanical design of the AUV.
- The AUV is actuated in three degrees of freedom. The placement of thrusters can be seen in the chapter on the mechanical design of the AUV. The thruster placement allows for surge, heave and yaw actuation.
- The battery life of the AUV is much longer than the specified one hour. Pool tests were conducted where the vehicle was not removed from the water for charging for over two hours.
- The AUV has the ability to change its buoyancy. The ballast system is described in the chapters on mechanical and electrical design. The ballast system uses two piston tanks with a volume of 800 ml each. This allows for a buoyancy variation of up to 1.6 kg.
- The vehicle's maximum speed measured during the pool tests was 1.18 m/s. This was measured by logging the AUV position together with time while supplying maximum output to the thrusters. The values were then used afterwards to calculate the maximum speed during the experiment.
- The vehicle yaw could be tracked with an accuracy of less than 3.5 degrees as shown in the chapter on data fusion. However, the faster the vehicle was rotating the bigger the error, due to the low update rate of the compass. Vehicle rotation velocity is however limited to achieve the required accuracy for yaw tracking. This was shown in the chapter on data fusion.
- The vehicle's roll and pitch could be tracked with an accuracy of less than 2 degrees according to the experiments conducted in the chapter on data fusion.
- The vehicle's depth or vertical position could be tracked with an accuracy of 0.092 m, which is less than the specified 0.1 m, as shown in the chapter on sensors.
- The AUV's horizontal or X and Y position could be tracked with an accuracy of 0.21 m, which again is less than the specified 0.25 m, as shown in the chapter on sensors.
- Through PID control, the AUV was able to control its depth with a steady state error of less than 0.2 m as discussed in the chapter on control systems.

- The AUV was also able to control its heading, using a PID control system, with a steady state error of less than 10 degrees which is within the specified limits.
- The AUV could also control its horizontal position, through following a set of way points, with an accuracy of less than 0.5 m as shown in the chapter on control systems.

9.2. Conclusions

This research study has shown that a small AUV can be designed and developed using relatively low-cost components. Such an AUV can successfully track its position in a three-dimensional underwater environment and also control its position. The study showed that one can get relatively accurate AUV navigation using low-cost sensors. Sensor technology has improved significantly and the accuracy of the low-cost sensors will still improve. Vehicle buoyancy was shown as an effective tool to save energy. A vehicle with a close to neutral buoyancy requires less power for diving than a positively buoyant vehicle. This project has also shown how the buoyancy of the vehicle can be varied. Different navigation systems have been implemented. The implemented trilateration system is similar to the long baseline navigation systems discussed in the literature and has proven to be an effective navigation tool for AUV navigation as it is not affected by the travel distance of the vehicle in the same way as odometry-based sensors. Other sensors that have proven to be very effective include a water pressure sensor for depth measurements and a magnetometer for heading measurements. In the literature IMUs have been shown to be very effective and accurate for short range missions. The IMU used in this project was a low-cost sensor and was not that effective for navigation. Even though it did make a small contribution to the accuracy of the navigation system it was not as effective as the ones discussed in the literature. If an IMU is to be used for AUV navigation it should be a high-quality IMU as the error of a low-cost IMU is still too big.

9.3. Summary of Contributions

This research study has shown contributions from three disciplines of engineering. These include mechanical, electronic and software design. The mechanical contributions made during this research study were firstly the design and construction of the vehicle body as well as the component layout to ensure vehicle stability. Another mechanical contribution was the thruster output modelling that enabled more efficient control of the vehicle through linearisation of the thruster torque.

The contributions made to this research study from an electronic point of view, were the design and implementation of the electronic components. The IO board was one of the biggest electronic contributions. The board was designed as a generic CPU board for use in robotics projects. The low-level interfaces to sensors can also be shown as a contribution to the electronic design of the AUV. Another electronic contribution was the whole power distribution system, which includes the power supplies and a single distribution board which all units can simply plug into. The design and implementation of the trilateration system was also a contribution made to the electronic systems implemented in the AUV.

The software contribution made in this research study includes the implementation of the IO board software, the implementation of the Player plug-in driver and the implementation of the base station software and navigation software as Player clients. This contribution to the software was seen as quite significant, as three separate software programs were constantly communicating with each other and working together towards a common goal. Different navigation systems, control systems and vehicle safety measures that have been implemented in the software can also be shown as contributions to the success of the software systems of this AUV.

9.4. Suggestions for Further Research

There are many more fields in which further research on AUVs can be done. One field is more accurate vehicle state estimation. An improvement in the vehicle state estimation can advance the accuracy of vehicle navigation using low-cost sensors even further.

More research is also required in the modelling of hydrodynamic forces acting on an AUV. An accurate model of the hydro dynamic forces may improve the controllability of the AUV.

Other navigation strategies such as environmental feature navigation systems like SLAM also requires much more research and need to be perfected to increase the navigation capabilities of the AUV in long range missions.

Different propulsion systems should be investigated to obtain more effective propulsion for AUVs and to achieve greater output torque using less power. This could improve mission endurance as the propulsion system normally consumes the greatest amount of power. Other types of AUVs such as gliders or vehicles with buoyancy varying capabilities, needs to be improved for even longer missions.

The operating depths of AUVs also need to be increased as their are still large sections of the ocean to be explored beyond the depths already achieved by underwater vehicles.

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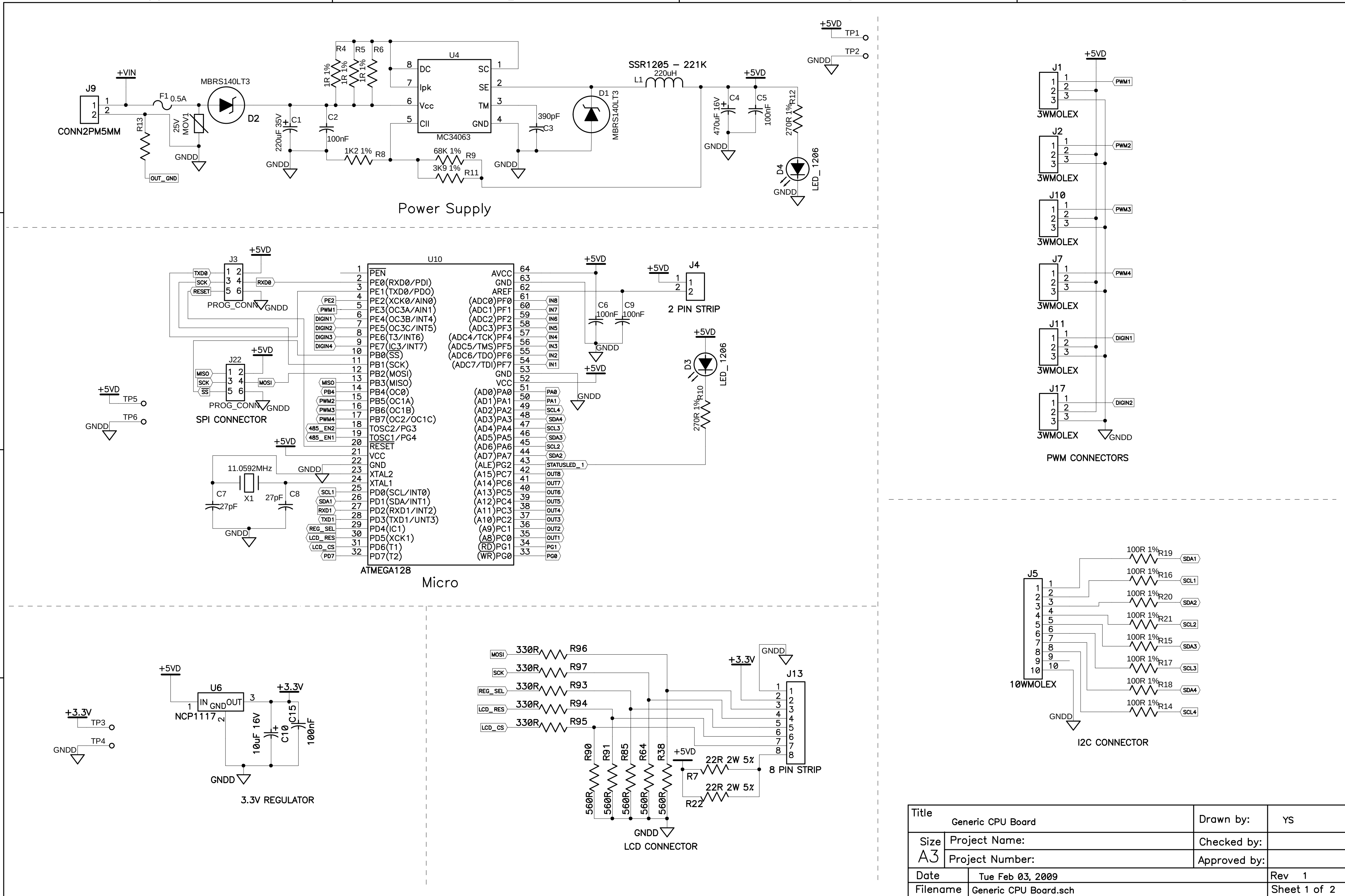
Appendix A.

Electronic Schematics and PCB Layout of the IO board

This appendix shows the electronic schematics of the IO board used on the AUV as well as the PCB layout of the IO board.



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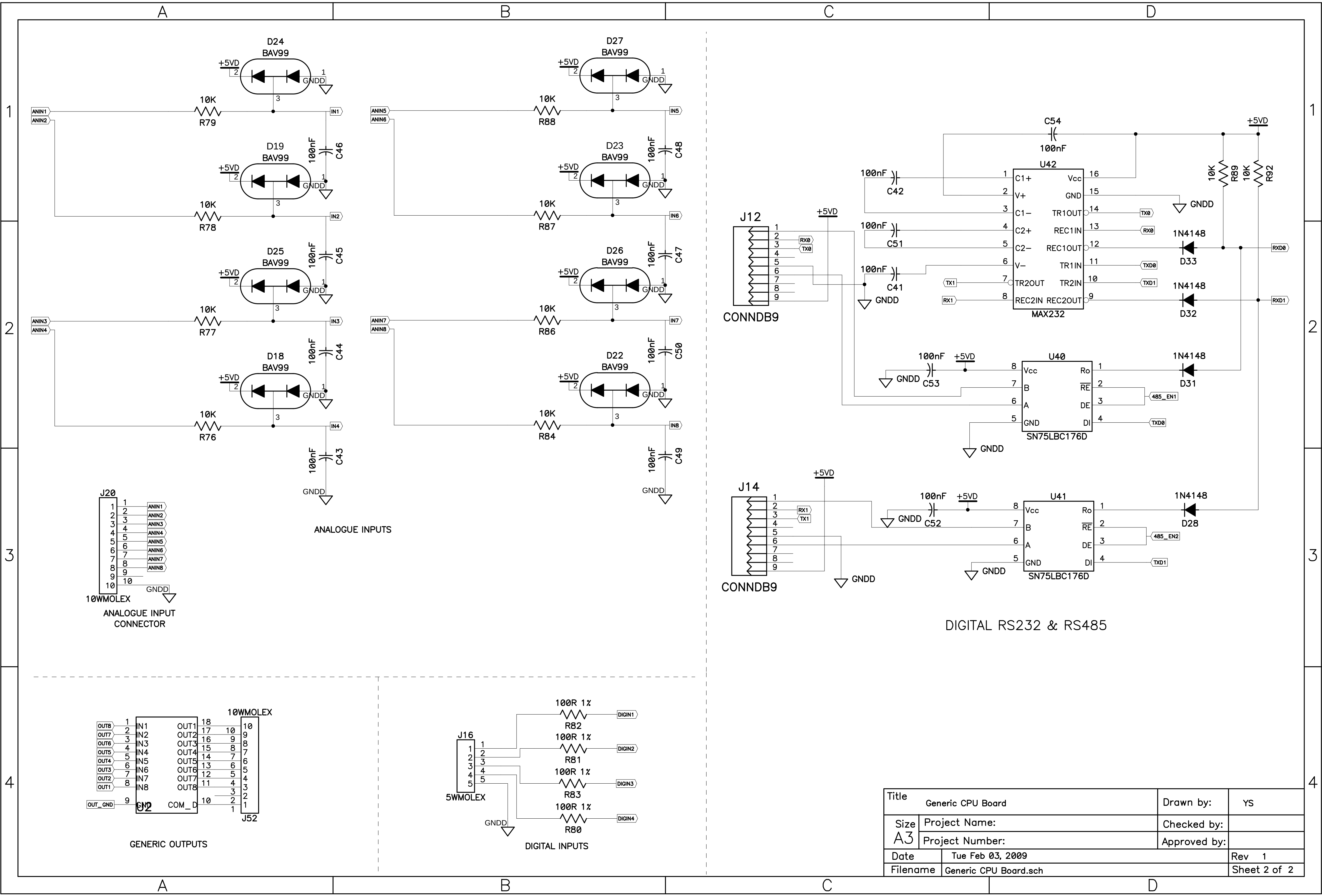
	Project Number:	Approved by:	
Date	Tue Feb 03, 2009	Rev 1	
Filename	Generic CPU Board.sch	Sheet 1 of 2	



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Date	Tue Feb 03, 2009	Rev 1	
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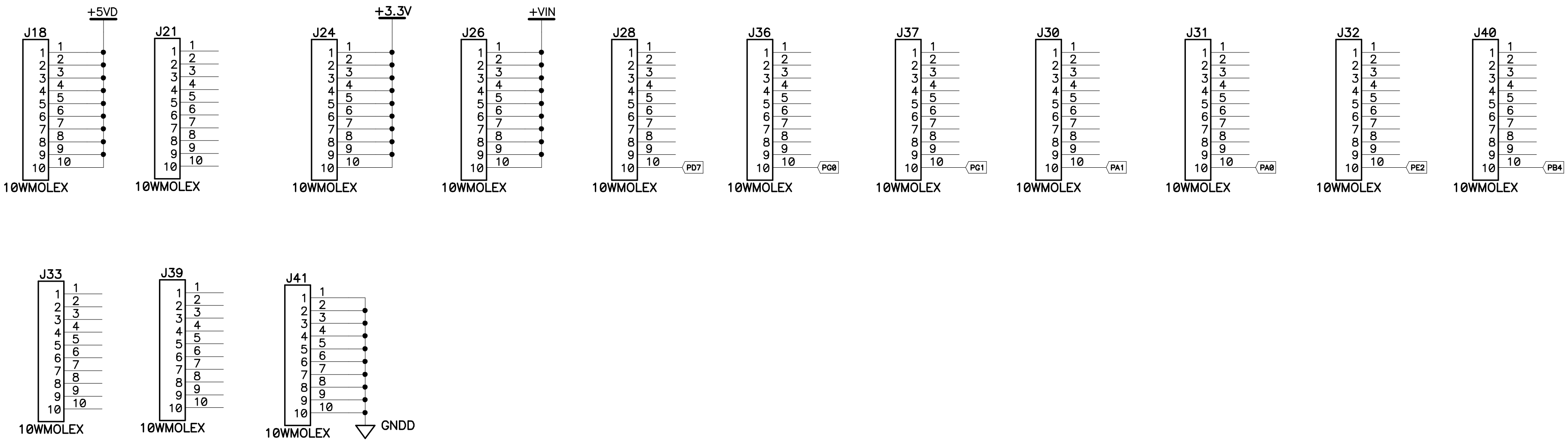

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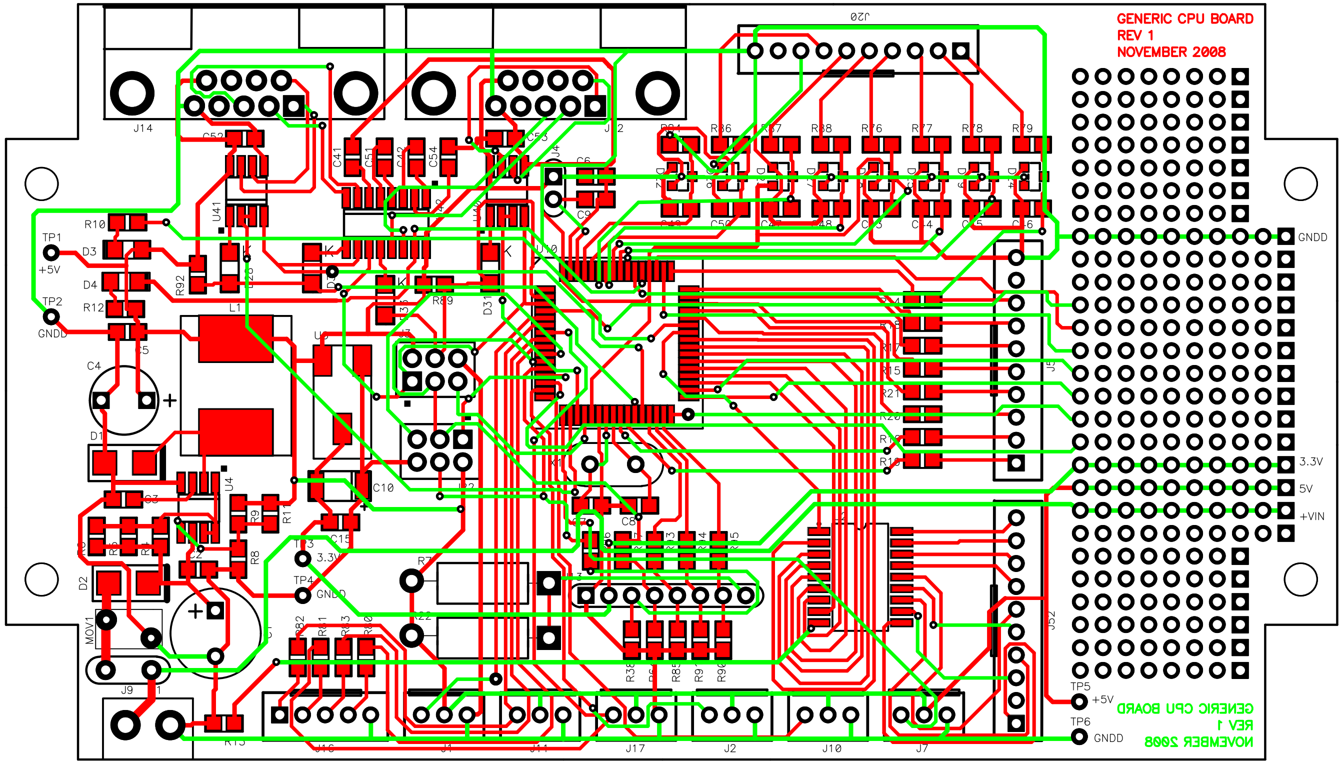
Date	Tue Feb 03, 2009	Rev 1	
Filename	Generic CPU Board.sch	Sheet 3 of 3	


GENERIC CPU BOARD
REV 1
NOVEMBER 2008

Appendix B.

Embedded Software for the IO Board

This appendix is used to show the software running on the IO board. The software consists of 14 files. These files include the following:

- Main.c
- Main.h
- Adc.c
- Adc.h
- Ballast.c
- Ballast.h
- I2c.c
- I2c.h
- Spi.c
- Spi.h
- Triangulation.c
- Triangulation.h
- Uart.c
- Uart.h

The software can be found on the CD submitted with this dissertation.

Appendix C.

Player Driver for Onboard Computer

The purpose of this appendix is to show the software code of the player driver implemented on the onboard computer. The driver consists of six files which includes the following.

- ioboard.cc
- ioboard.h
- kalman.cc
- kalman.h
- pid.cc
- pid.h

The driver also uses a text file to get the positions of the trilateration beacon positions. This file is called beacons.txt. The configuration file, AUV.cfg, is then used to tell Player which driver to use aswell as some configuration details.

All these files can be found on the CD submitted with this dissertation.

Appendix D.

Base Station Software

The purpose of this appendix is to show the software running on the base station computer. In this case QT developer was used to create a graphical user interface and the underlying code was then added. The software consists of 7 files which includes the following.

- Main.cpp
- Widget.cpp
- Widget.h
- Widget.ui
- Dialog.cpp
- Dialog.h
- Dialog.ui

The files can be found on the CD submitted with this dissertation. An example of a way point file is also included on the CD.