The Development of an AUV

A thesis

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by

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For Mum and Dad

ABSTRACT

The Deepwater Access Reconnaissance Television (DART) Remote Operated Vehicle (ROV) was received from Oceaneering in Singapore in an outdated and inoperable state. It was desired to convert the manually controlled DART ROV into a semi-autonomous, functioning submersible craft. Such a conversion required rebuilding the DART's motors, redesigning the motor drivers, installation of a new camera system, a complete redesign of the system electronics, as well as the inclusion of a Pentium III equivalent motherboard and data acquisition card.

This thesis details the process of the DART's conversion, and presents the completed, fully functional result, the DELPHINUS, an ideal platform for future underwater research by the Mechatronics Group of the University of Waikato.

ACKNOWLEDGEMENTS

To my supervisor, Dale, whom I have finally come to understand, thank you for challenging me, and illustrating that there are no limits.

Thank you to Michael Taylor for your unique way of teaching physics, even when it was not easy to teach me, and your encouragement to pursue electronics.

This project would never have been possible without the generosity of Nevil Fenwick of Oceaneering, who donated the DART ROV, and instilled an affection for the submersible vehicle that I am eternally grateful for.

I am appreciatively indebted to Paul Gaynor for your practical support and advice, and to Shaun Hurd for selflessly giving your time and knowledge. To my flatmate, Trinh, thank you for looking after me through those last few months, and motivating me to try again when everything went wrong.

Thank you to Jonathon Skipwith who suffered alongside me, to Bruce Rhodes, Scott Forbes and all the Physics technical staff of the University of Waikato, for your experience, humour, and making the work enjoyable. Thanks are also due to Stuart Pilling for his help in the development of the LabVIEW main program.

Immeasurable gratitude to Richard Templer and staff of Industrial Research Ltd. (IRL), for the funding which has enabled such a sophisticated mechatron.

Appreciation to the following commercial sponsors: Stewart Kidd and Tim Hales of Magellan Technologies Ltd., Rob Carrillo of Carrillo Underwater Systems, Paul Ware and staff of Adilam Electronics, Philips Semiconductors NZ, and Jim McFarlane and staff of International Submarine Engineers (ISE).

Finally, I owe the greatest gratitude to my mother Theresa, my father Martin, and my brother Paul, whom without which I would not be what I am today.

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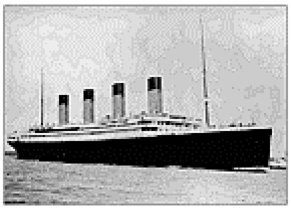
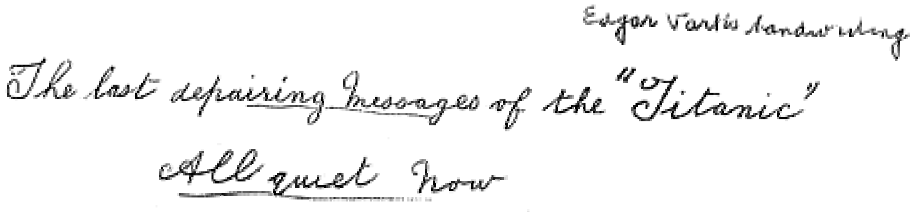


Prologue*

Flat calm seas glittered with the reflections of multitudes of stars on the quiet moonless evening of Sunday, April 14th, 1912. It was 11.40pm when the cold night was witness to the three pulls of the bell in the crow's nest and the chilling call of lookout Frederick Fleet's words, "Iceberg, right ahead". Frantic messages were exchanged with Captain Moore of the 'Mount Temple' in the early hours of the 15th. Communication was also extended to other boats in the area that tragically were too far away to respond in time. "Come quick", was the urgent request of a terror stricken boat, but the messages rapidly declined in strength as the ship's auxiliary batteries ran down, the icy Atlantic water swiftly immersing the dying dynamo of the vessel.



AN EXTRACT FROM EDGAR PARKS JOURNAL – AN APPRENTICE ABOARD THE MOUNT TEMPLE DURING THE SINKING OF THE TITANIC.

The shock and fear of those left behind was thick and heavy, unmoved by the jolly music played by the bands. Those who were spared death from the falling petals of the Titanic flower either drowned or froze to death. At 2.17am the bow plunged under, three minutes later the stern gave up to the sea.

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* *Adapted from http://www.skarr.com/titanic/ accessed July 2001*

"Her deck was turned slightly toward us. We could see groups of the almost 1,500 people still aboard, clinging in clusters or bunches, like swarming bees; only to fall in masses, pairs or singly as the great afterpart of the ship, 250 feet of it, rose into the sky."
Jack Thayer 17, 1st class passenger.

Approaching 2am, September 1st, 1985, astounding images were received by a camera attached to a search vessel. At a depth of 13,000 feet, ghostly pictures of the largest man-made movable object ever built showed the colossal R.M.S Titanic boilers in their silent cold grave. Returning one year later, Dr. Robert Ballard and his team of researchers equipped with a manned underwater vehicle, the DSV Alvin, and a custom built underwater Remote Operated Vehicle (ROV), the Jason Jr. (refer Figure P1), explored the ship photographing the conclusion to one of the greatest mysteries of the world.

Figure P1. THE JASON JR. IN ACTION WITH THE R.M.S TITANIC IN THE BACKGROUND.

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So marked one of the most famous ROV missions in the short history of the Unmanned Underwater Vehicle (UUV). Over a period of forty years this instrument has developed from an unpredictable prototype used for research and military purposes into an essential component of the deep-sea industry today [1].

1. INTRODUCTION

The deep ocean has always been a source of unparalleled mystery, and has always captured the imagination of mankind. Navigating into the depths of the underwater world has seen the development of undersea technology from the original unreliable Remote Operated Vehicle (ROV) developed by military contractors, to machinery so advanced as to enable man to realise hopes of eventually conquering the oceans.

As early as 1775, man-made submersibles were used to discover what lay hidden beneath the waves. Today, ROVs are continuously pushing the limits to dive to deeper depths, the Titanic at 3810 metres undersea being one of the greatest achievements.

ROVs have a wide range of applications including mining for precious diamonds, minerals and oil, searching for lost treasures, shipwrecks, and victims of tragedy, performing rescues, and working in hostile environments such as biologically or chemically contaminated waters. The deep-sea industry could not function without the workforce ROVs that are used for many tasks such as cable laying, pipeline inspection and oceanographic mapping. Marine biotechnology research has made great advances, thanks to deep diving ROVs with the capability to retrieve deep-sea fish alive inside special pressure enclosures, allowing study of the fish in their natural form.

ROVs provide a cost-effective solution because they eliminate the need for a human to be at depth or in dangerous conditions; the ROV getting trapped or lost pales in comparison to loss of life. Expenditure is a forefront concern in many operations, and the ROV eliminates the need for large numbers of support crew and divers, reduces many safety concerns and protocols, and can also work continuously underwater. Some examples of ROVs used in the underwater industry are shown in Figures 1.1, 1.2, and 1.3.

The Max Rover ROV (Figure 1.1) is used for installations and inspections. It has ‘plug and play’ capability, with 5-function manipulators, and operates to a maximum depth of 3000m. The Centaur ROV (Figure 1.2) is a 300 horsepower tracked cable burial system, operating to a depth of 2000m. The VideoRay is a small inspection ROV (Figure 1.3) shown exploring the USS Arizona, which was deemed unsafe for divers.

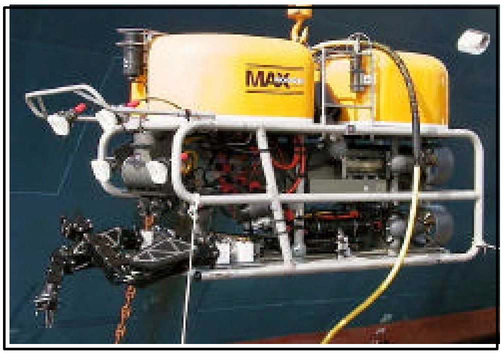

Figure 1.1 THE MAX ROVER ROV.

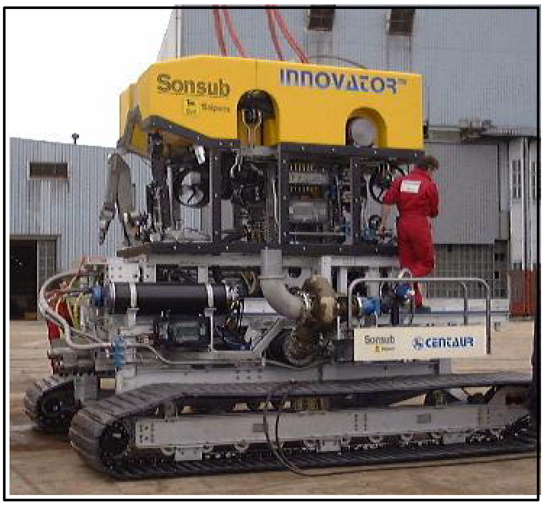

Figure 1.2 THE CENTAUR ROV.

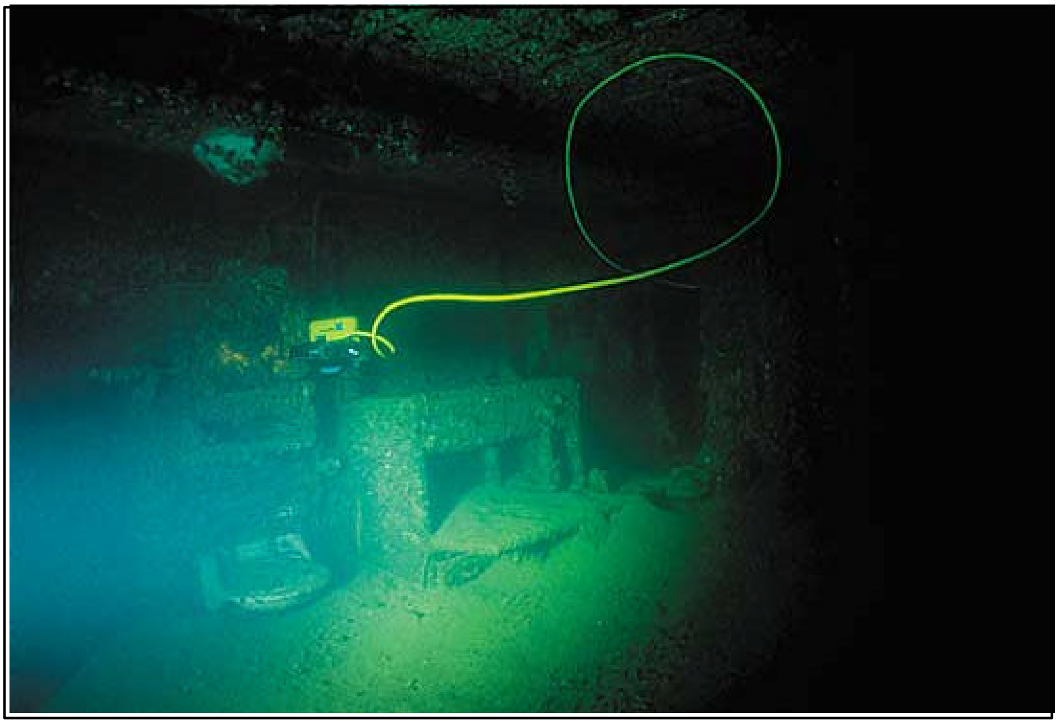

Figure 1.3 THE VIDEORAY ROV.

To date, the research activities of the Mechatronics Group at the University of Waikato have focused on air and land based projects such as autonomous helicopter flight, legged robots, maze-exploring micromice and large-scale security robots. Extending the expertise of the Mechatronics Group to encompass marine-based electronics means exploring the world of submersible technology.

Typically the first consideration in a robotic project is the chassis that will house the electronic system. To create a submersible mechatron, a specialised chassis must be used to cope with the harsh underwater environment.

1.1 THE CHASSIS

A worldwide search was undertaken via the Internet to obtain a suitable chassis. Initially a kitset model submarine was thought to be an adequate solution as they are inexpensive and easily acquired. The design of submarines means they have to be flown through the water much like a plane through the air due to the single rear propeller. This renders the submarine incapable of performing the simple task of maintaining a set position in varying current conditions.

In comparison, a ROV has multiple propellers operating in different directions, allowing the vehicle to operate like an underwater helicopter. This extensive manoeuvrability means the ROV can effectively hover at a set position irrespective of surrounding water currents.

Given this flexibility, it was decided that a ROV chassis and design would be more appropriate. Additionally, a ROV hull would provide a larger enclosed area than a model submarine, enabling an increased payload of electronics. The hull would also provide a greater depth capability due to the ROV chassis being made out of stronger material than available kitset submarines.

1.2 THE ROV

Many hulls were available from underwater industry suppliers, but they proved too expensive considering the allowed budget of the project. Nevil Fenwick of Oceaneering in Singapore generously offered an unused Deepwater Access Reconnaissance Television (DART) ROV to the Mechatronics Group for this project. This offer also included the donation of the sensing equipment located within the vehicle, and was gratefully accepted.

1.3 A ROV SYSTEM OVERVIEW

There are two major components to a ROV system: the surface components, and the sub-surface components, illustrated in Figure 1.4 below.

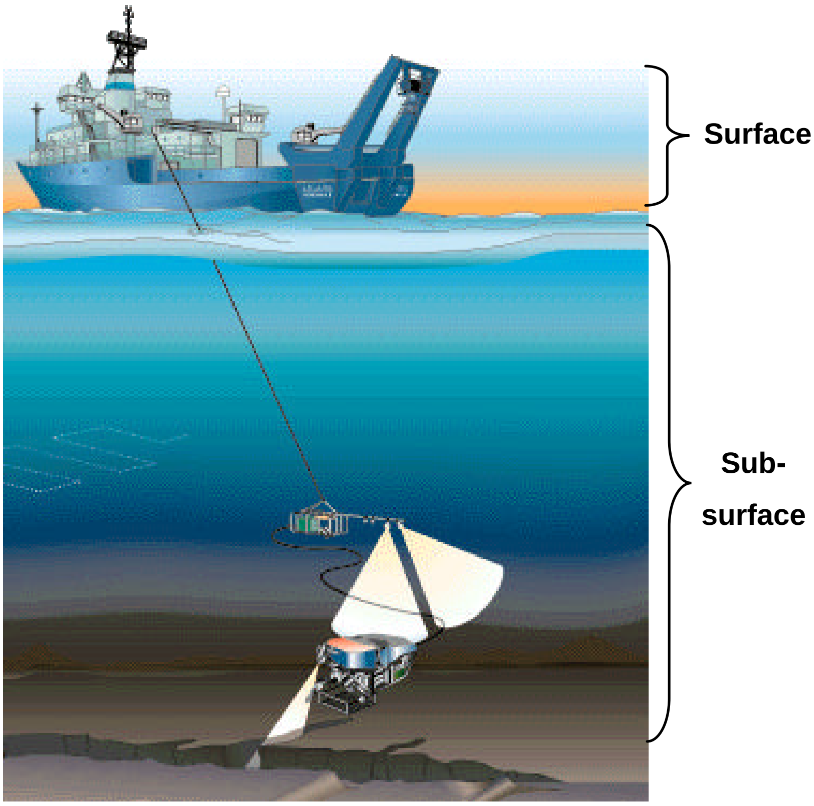

Figure 1.4 THE SURFACE AND SUBSURFACE COMPONENTS OF AN ROV SYSTEM.
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The link between the surface and the ROV is via an umbilical cable. This cable provides the ROV with communication for surface monitoring and/or instruction, and also supplies vehicle power. It is common for the power supply of a ROV to be at the surface as it becomes difficult to accommodate the extensive weight of an onboard supply within the average ROV payload. The existence of this tether negates the term “autonomous” as the vehicle is not completely free, so the ROV developed in this thesis is technically a hybrid between an Autonomous Underwater Vehicle (AUV) and an ROV.

1.4 THE ORIGINAL SYSTEM

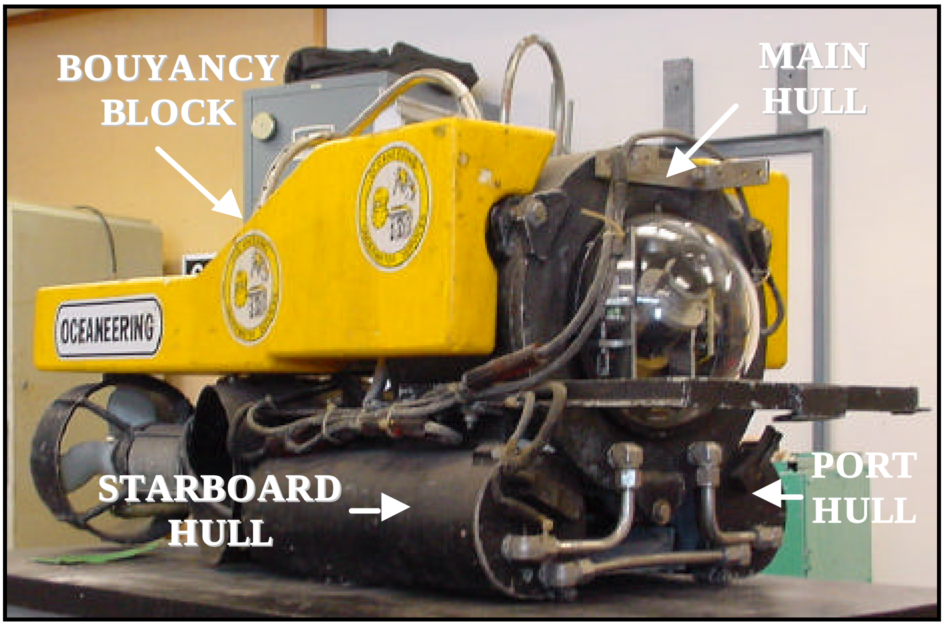
The original DART ROV manuals were located after an extensive internet search, a copy of the manual was kindly donated by Jim McFarlane of International Submarine Engineers (ISE) in Canada. Manuals for the DART were also located in Singapore and sent at a later date by Nevil Fenwick.

Designed primarily to be an observational tool for underwater activity, the DART ROV incorporated a closed circuit television system with simple navigational capabilities. The ROV as it arrived is pictured in Figure 1.5.

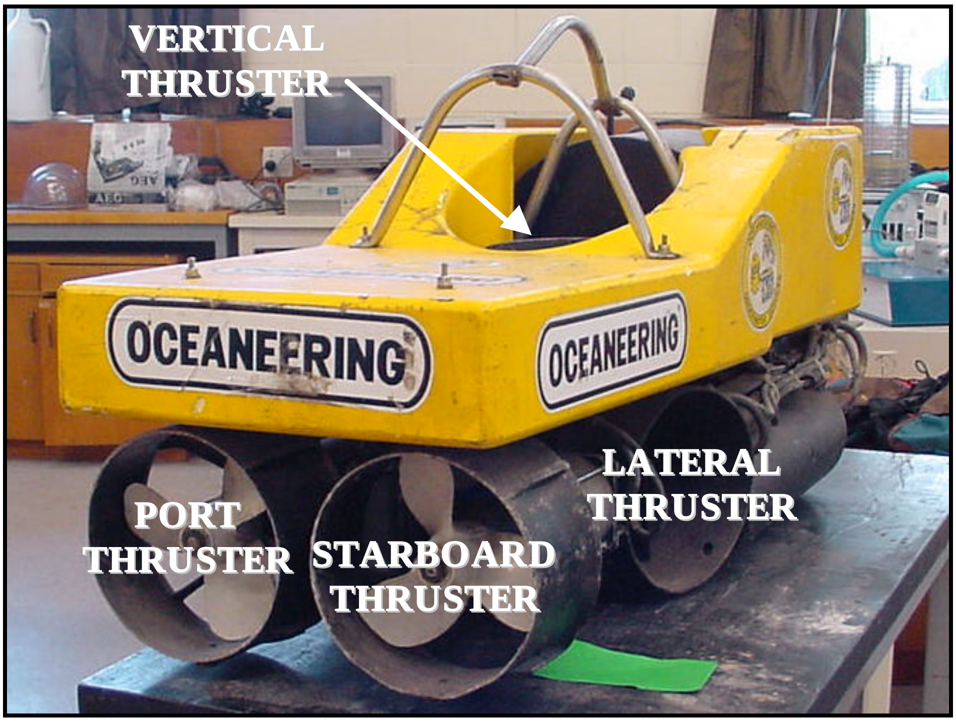
The DART has many features unique to submersible vehicles. The yellow buoyancy foam block bolted to the top of the chassis causes the ROV to remain slightly positively buoyant throughout a dive. This prevents the operator from losing the ROV should failure of the ROV thrusters occur, as it will simply float back up to the surface.

Four thrusters located at the starboard, port, lateral and vertical positions manipulate the movement of the ROV in three dimensions. The chassis consists of three hulls: main, port and starboard. The main hull has two clear acrylic domes; the inner dome strengthened for the pressure experienced at depth, and the outer protecting the inner dome from scratches and breaks. The domes allow a camera system to be mounted inside the ROV, and the two smaller hulls provide housing for sensors and electronics.

Wiring between all three hulls ran through stainless steel Swage-Loc tubing fitted to the front caps of each of the hulls. All three hull-caps are removed as one unit should access be required. The umbilical of the DART is connected via a waterproof plug situated underneath the buoyancy block between the two rear thrusters.



(a)



(b)

Figure 1.5 (a) FRONT AND (b) REAR VIEWS OF THE DART ROV ON ARRIVAL.

Although the DART is not designed for any manipulative tasks, additional equipment such as oceanographic survey devices, navigational beams, and still cameras can be mounted easily on the frame. A high power-to-weight ratio makes it very manoeuvrable in high current conditions.

Specifications of the DART system are as follows:

- Overall length : 105 cm
- Overall width : 46 cm
- Overall height : 34 cm
- Weight : 55 kg fully loaded
- Diving depth : 360 m
- Hull structure fabricated from 6061 T-6 marine grade aluminium

1.4.1 Component Location

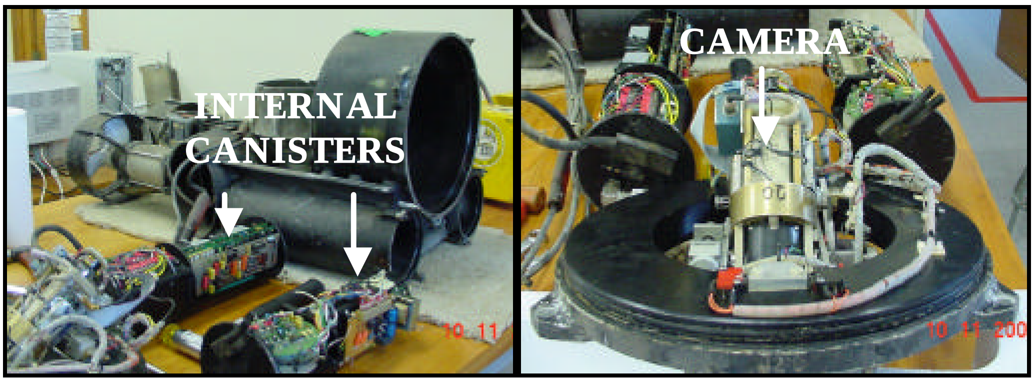


Figure 1.6 THE INTERNAL COMPONENTS OF THE DART ROV.

Figure 1.6 above shows the ROV in its original state with the buoyancy block removed and the internal canisters pulled from the hulls. The main hull contained a Panasonic 1350 black and white vacuum tube TV camera, the port hull contained a flux-gate compass and the camera control unit, and the starboard hull contained all telemetry boards and the pressure transducer.

1.4.2 Sub-Surface Components

An overview of the sub-surface components of the original system is shown in Figure 1.7. The electronic boards located in the starboard hull were the T176A, the TV305, and the R170.

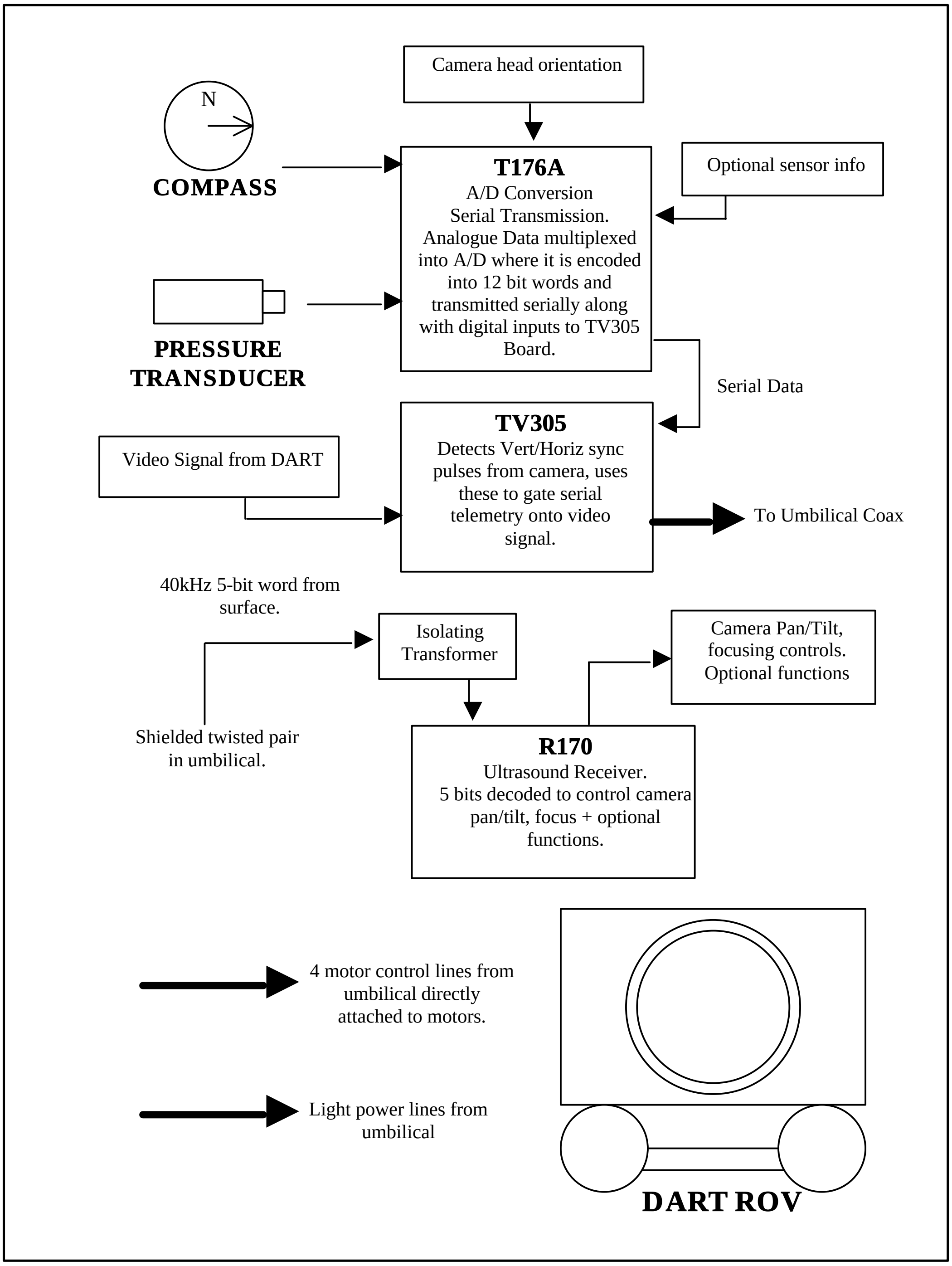


Figure 1.7 AN OVERVIEW OF THE ORIGINAL SUB-SURFACE COMPONENTS.

The T176A board received analogue signals from the compass, pressure transducer, two potentiometers attached to the pan/tilt mechanism of the camera and any other added sensors.

These analogue signals were translated into 12-bit digital words which were transmitted (along with any digital inputs) to the TV305 board. The TV305 board detected the vertical and horizontal synchronisation pulses of the video signal from the camera, and used them to gate the serial data onto the video signal for transmission to the surface via the coaxial cable.

Communication from the surface was sent down through a shielded twisted pair which also supplied power to the electronics. On this pair, the R170 Ultrasound Receiver board read in a 40kHz 5-bit word through an isolating transformer, which was then decoded into camera pan, tilt, focus and any optional functions.

The four motors were all surface controlled. Power was sent down to each thruster via individual conductors in the umbilical to control the speed and direction.

1.4.3 Surface Components

An overview of the surface components of the original system is shown in Figure 1.8. A surface TV305 board de-multiplexed the 12-bit word from the video signal to find camera and compass orientations, depth and any optional functions. The ROV data and the video signal were then both sent to the MB901 microcontroller.

The MB901 microcontroller conveyed the data to the video boards for display on monitors, but could also use the depth sensor information to control the DART if in auto-depth mode. In this mode the microcontroller would send motor control signals to the Z516 board, controlling the vertical thruster based on an instruction called ‘set-point’ which allowed the operator to set a depth the ROV would automatically dive or rise to and maintain. The microcontroller formed the electronic brain of the system displaying system diagnostics, and performing basic troubleshooting of the system.

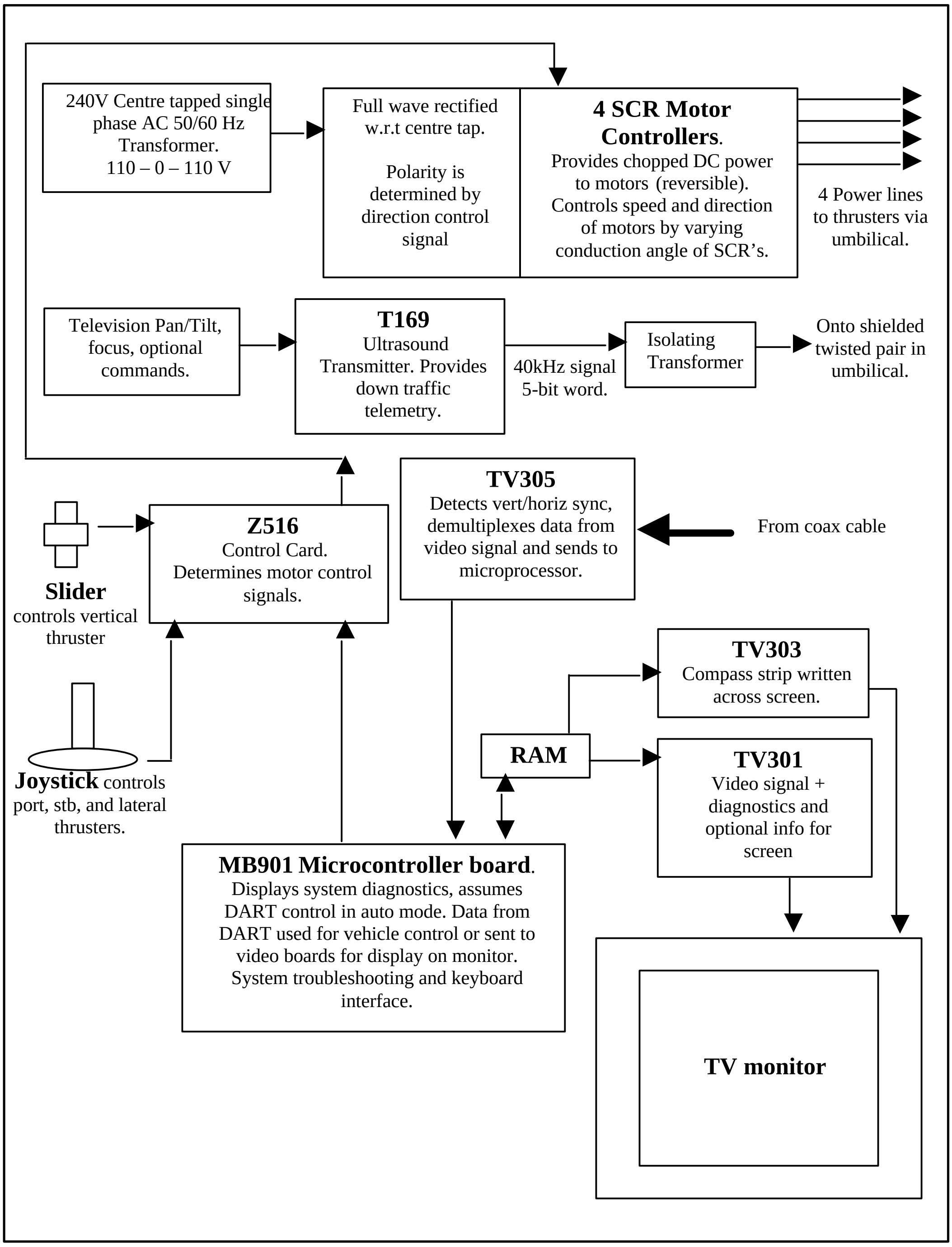


Figure 1.8 AN OVERVIEW OF THE ORIGINAL SURFACE COMPONENTS.

The Z516 board received signals from the MB901 microcontroller or from the pilot in manual mode. The pilot controlled the DART through the manipulation of a slider to control the vertical thruster and a joystick to control the other three. The Z516 board interpreted these signals and formed them into four 0/5V direction signals and four 0 to 5V speed signals.

The direction and speed signals were sent to four Silicon Controlled Rectifier (SCR) Motor Controllers (also called Dilor Controllers). These provided chopped full-wave rectified DC power to each motor via the umbilical.

Other commands for the ROV such as camera pan, tilt, focus and any optional functions were transmitted through the T169 ultrasound transmitter card onto the shielded twisted pair in the form of a 40kHz 5-bit word.

1.4.4 The DART on Arrival

The DART arrived in a non-operational form; none of the surface components were received with the DART except for two SCR Motor Controllers. This meant that the telemetry electronics onboard the ROV could not be utilised. The state of the electronics received with the ROV rendered most of it useless, except for the compass and pressure transducer.

No umbilical was received, nor a female umbilical plug to fit the male plug attached to the ROV chassis. Corrosion of the chassis, seals and stainless steel tubing had also caused many parts around the exterior of the ROV to need extensive repair or replacement, and three of the four thrusters motors had seized.

The camera received with the ROV was antiquated and large enough to completely fill the central dome, limiting the space available within the central hull. It required a separate 50? coaxial cable, and displayed images in black and white only.

1.5 THESIS OBJECTIVES

The aim of this project is to complete a redesign of the DART ROV and rebuild it to a fully operational vehicle. To do this the following objectives must be met:

- Rebuild seized motors
- Develop a motor control system
- Develop a motor power supply

- ✍✍Research which sensors are needed for the ROV to function effectively
- ✍✍Obtain the relevant sensors
- ✍✍Retrieve information from each sensor
- ✍✍Calibrate the signals from each sensor
- ✍✍Fit the sensors into the ROV

- ✍✍Develop the camera system to a working state
- ✍✍Develop hardware to provide an intelligent system to encapsulate the motor control, sensor data and camera signal.
- ✍✍Develop software to display the motor controls, sensor data and camera signal.

- ✍✍Provide a communication link between the ROV and the surface
- ✍✍Develop a power supply for the ROV

The dictum of the Mechatronics Group is always to extend the capabilities of each project, towards eventual autonomous control. This means that the entire ROV system has to be engineered to allow all the computational power and sensing systems to be completely contained within the vehicle, while remaining flexible enough to provide a suitable platform for future projects.

Delphinus is the new name of the ROV, so named for the dolphin of Greek myth who performed a great service to man. Amphitrite was the love of Poseidon, but had fled into hiding, and a very distraught Poseidon sent many searchers to find her. Delphinus found her at Mount Atlas, and convinced her to return. A euphoric Poseidon decreed the dolphin the highest honours of the seas, and placed nine stars into the heavens in the shape of a dolphin to forever remind man of Delphinus (refer Figure 1.9).

Figure 1.9 THE CONSTELLATION DELPHINUS.

1.5.1 System Overview

The form of the new system is outlined in Figure 1.10. A central microcontroller will read in the signals from the sensors. It will control the motors through a motor control interface, which will manage the high-power electronics needed to rotate the thrusters. The surface will communicate with the DELPHINUS via the microcontroller. Software will be developed to control the motors, read the sensor data and communicate with the surface.

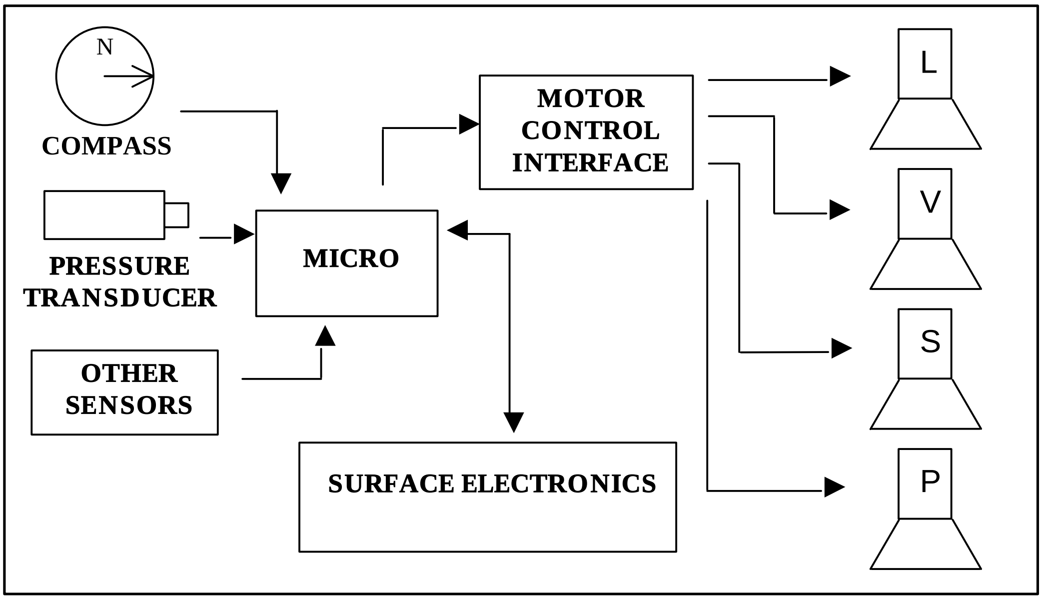


Figure 1.10 PLANS FOR THE NEW ROV SYSTEM.

1.6 THESIS STRUCTURE

This thesis is presented as follows:

Chapter 2 focuses on the propulsion system used by the DELPHINUS. Motor theory will be introduced, and an overview of the original motor control method will be given. The development of a new motor control system is explored.

Chapter 3 introduces the hardware utilised inside the ROV. The complete system is outlined showing the interactions between all the components. The operation of the DELPHINUS system is explained and compared with the original DART.

Chapter 4 discusses the software requirements of the DELPHINUS and the capabilities of the system.

Chapter 5 outlines the numerous considerations of an underwater project, and details the preparation of the DELPHINUS before it was submerged.

Chapter 6 presents the results of underwater tests.

Chapter 7 concludes the thesis by evaluating the developed DELPHINUS ROV system. Possible extensions to the work are discussed, before the entire thesis is summarised.

2. PROPULSION

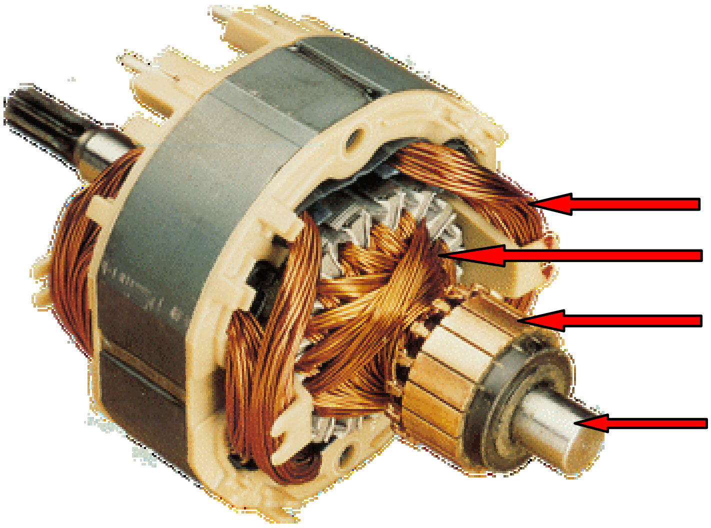


Figure 2.1 THE INTERNALS OF AN AC SERIES WOUND UNIVERSAL MOTOR [2].

2.1 PROPULSION OVERVIEW

The motion of the ROV must be controlled in three dimensions. Each of the four thrusters allow the ROV to be delicately manoeuvred in the sub-surface environment. This chapter explores the manoeuvrability of the ROV thrusters and the development of a system to control the speed and direction of each motor.

To control a motor, an understanding of its operation and theory is required. The process of developing a new system began by looking at the original control system in detail, overhauling the seized motors and looking at common motor control techniques.

The first technique tested was a triac method modelled on the original system. After experimentation, this approach was deemed unsatisfactory. A different scheme was then implemented using MOSFETs as they are an industry standard in power electronics, and proved to be a much more reliable method of control. An overview of the complete DELPHINUS motor control system concludes the chapter.

2.2 MANOEUVRING THE ROV

Manoeuvring the ROV is performed by manipulation of the four thrusters (refer Figure 2.2). The vertical thruster (**1**) forces the ROV underwater during a dive, consequently this motor is usually active during operation with the speed controlling the depth. The lateral thruster (**2**) corrects against current drift left and right. The starboard and port motors (**3** & **4** respectively) move the ROV forwards or backwards, and they can also be used to rotate the ROV if they are powered in opposite directions.

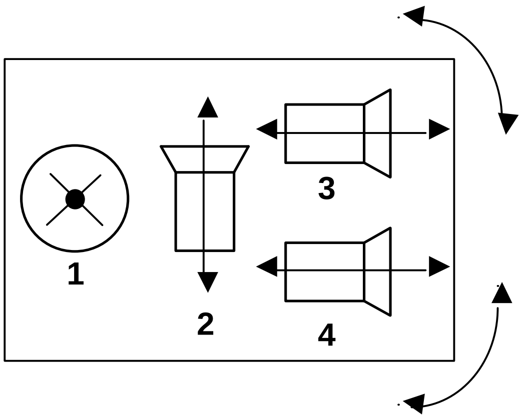


Figure 2.2 TOP VIEW OF THE THRUSTER LAYOUT AND DIRECTION OF MOTION.

The four motors utilised in the ROV are ½ horsepower 110V Universal AEG drill motors that formed part of the original DART system. Each drill motor is custom fitted inside a Kort nozzle housing to provide an inexpensive, easily replaceable thruster. The field and brush position for each motor is altered from standard to ensure optimum performance in both directions.

2.3 THE UNIVERSAL MOTOR

The term "universal" means the motor has the capability to operate from either a direct current (DC) or a single-phase alternating current (AC) supply [3]. The armature (rotor) and field (stator) both conduct the same current, hence the reason why these motors are also called series motors [4]. A low-power motor (usually in the range of 3 to 550W), they are commonly used in household appliances such as drills, or vacuum cleaners.

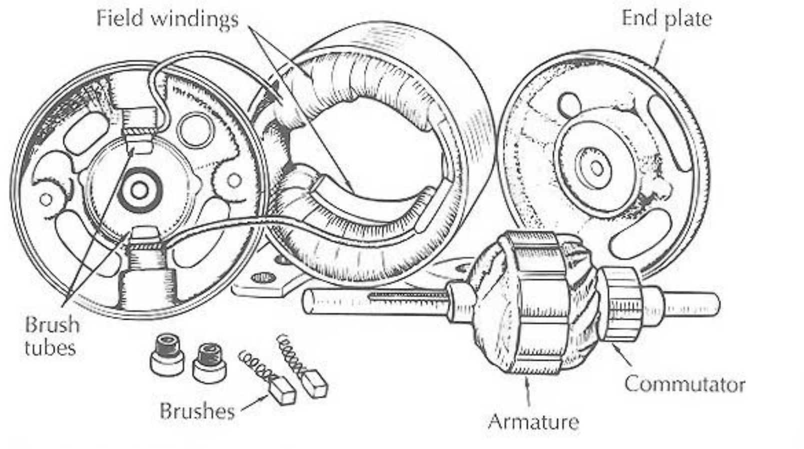


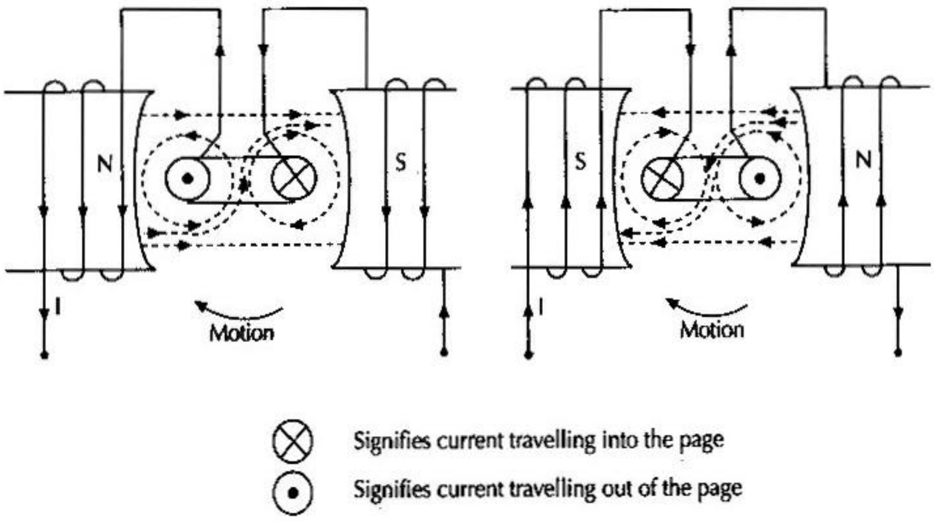
Figure 2.3 THE COMPONENTS OF A UNIVERSAL MOTOR [3].

The armature is one of three main components in the universal motor (refer Figure 2.3). Mounted on a steel shaft, the laminated core is connected to the commutator through a series of leads. The field poles are the second main component and consist of iron laminates with the field coil wound around to form the field windings. The brushes are the third, and connect to the commutator when the armature is placed inside the field windings (refer Figure 2.1).

2.3.1 Principle of Operation

The direction of rotation of a universal motor in relation to current path is shown in Figure 2.4. In (a), the current is flowing from the south pole to the north. This creates a magnetic field which interacts with the magnetic flux of the armature causing a force on the conductors, which in turn rotates the armature. The direction of turning motion is established by Fleming's left-hand rule (refer Figure 2.5).

If the forefinger and second finger are at right angles to each other and pointed in the direction of **F**lux (in case (a) from north to south) and **C**urrent respectively, the thumb (if also held at a right angle) will point in the direction of **M**otion for a current-carrying conductor in a magnetic field.



(a) **(b)**

Figure 2.4 DIRECTION OF MOTION OF THE UNIVERSAL MOTOR [3].

In case (b) of Figure 2.4, the current direction is reversed. Notice that although the supply current has changed direction, the magnetic field flux and the direction of current through the armature has also changed. This resulting switch of polarities causes the same forces to act on the armature, which turns the armature in the same direction as in case (a).

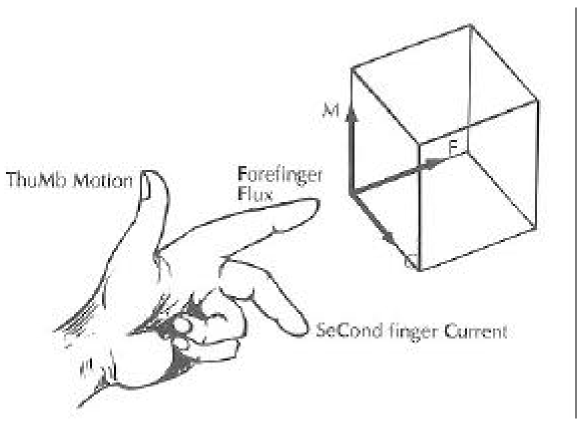
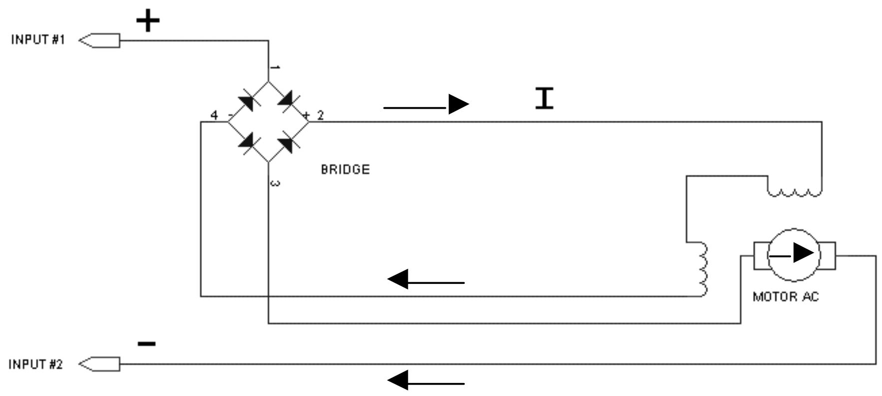


Figure 2.5 FLEMING'S LEFT HAND RULE [3].

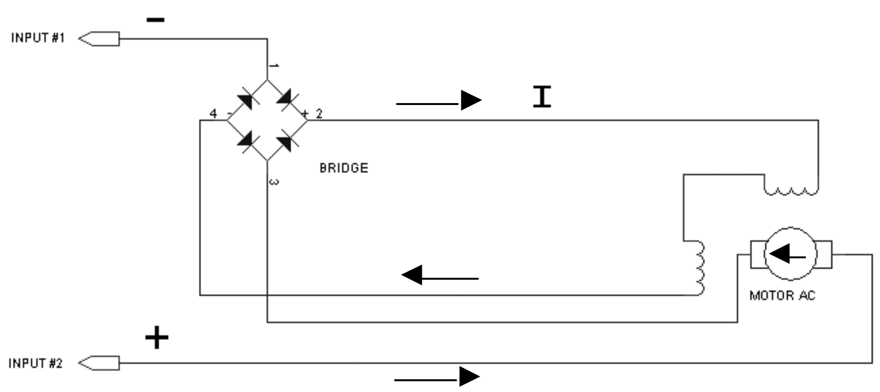
In order to change the direction of rotation of the universal motor, the polarity of the main field must be changed in relation to the direction of armature current. Simply interchanging supply leads will have no effect as explained earlier. To change the polarity of the main field or the armature, the field leads or the armature leads must be switched, but not both.

2.3.2 Overcoming Fleming's Left Hand Rule

To overcome the problem of interchanging either the field leads or the armature leads, a bridge rectifier is used. This provides a very simple yet effective way of being able to change the polarity of the supply leads for direction control of the motor.



(a)



(b)

Figure 2.6 THE OPERATION OF THE BRIDGE RECTIFIER INSIDE EACH THRUSTER.

In Figure 2.6 (a), the polarity of the supply leads are such that INPUT#1 is positive with respect to INPUT#2. Using current convention, the direction of current flow will be through the path of the forward biased diode 1-2 following the path of the arrows through the field windings and diode 4-3, through the motor and returning to the negative side.

In Figure 2.6 (b), the polarity of the supply leads has changed. The current will now flow from INPUT#2 to INPUT#1. The current through the motor has changed direction, but the path of the current through the field windings remains the same. This allows the motor to change direction by simply reversing the supply leads.

2.4 MOTOR CONTROL – DART ROV

In the DART system, power was switched and sent down to each motor through individual conductors in the umbilical.

2.4.1 The Original Motor Control System

Analogue control for the lateral (L), port (P) and starboard (S) motors came from a joystick, with a separate analogue slider for the vertical (V) thruster. The outputs from the joystick and the slider were sent to the Z516 control card which determined the motor control signals to send to each of the four respective Dilor Controllers (refer Figure 2.7). The signals from the Z516 card consisted of four 0/5V direction signals, and four 0 to 5V speed signals.

120/240 VAC centre-tapped power was input to each Dilor Controller (refer Section 1.4.3) and full-wave rectified with the polarity determined by the direction signal from the Z516 card.

Figure 2.8 shows an overview of the Dilor Controller full-wave rectifier, which has been simplified for clarity. The four SCRs were controlled in pairs; Q1 and Q2 forming one pair and Q3 and Q4 forming the second pair. L1 and L2 are 180? out of phase, with the neutral line from the centre tap of the transformer.

An SCR will not conduct until a signal is applied to the gate, allowing the current path through the motor to be precisely controlled. In operation, the firing signal was applied to a SCR pair, for example Q3 and Q4. The SCR with the correct anode to cathode polarity would turn on and allow the current to flow through the motor. One SCR conducted through the positive half of the cycle, and the other conducted through the negative half of the cycle. To change the direction of the motor, the firing signal was applied to the opposite pair Q1 and Q2.

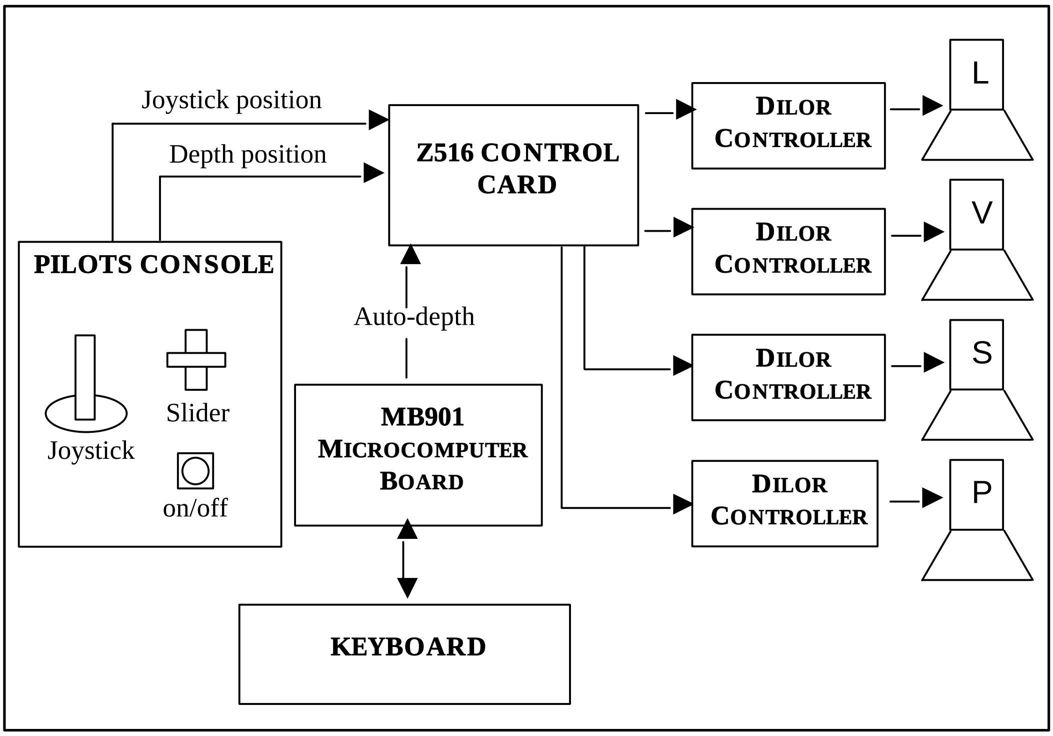


Figure 2.7 AN OVERVIEW OF THE ORIGINAL MOTOR CONTROL SYSTEM.

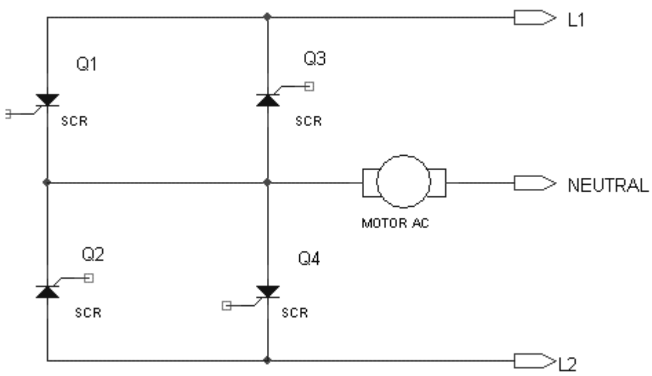


Figure 2.8 THE DILOR CONTROLLER FULL-WAVE RECTIFIER.

The 0 to 5V speed signal altered the firing angle of the SCRs used in the Dilor Controllers. This method of speed control is called phase angle control and is used in common light dimmer circuits.

2.4.2 Phase Angle Control

Phase angle control means applying only a portion of the supply waveform to the load. A simple resistive load is presented in Figure 2.9. The length of time the SCR blocks the supply is the 'delay angle'. The time from when the SCR is fired until the current drops to zero is the 'conduction angle'. By altering the firing time, the average power to the load can be controlled.

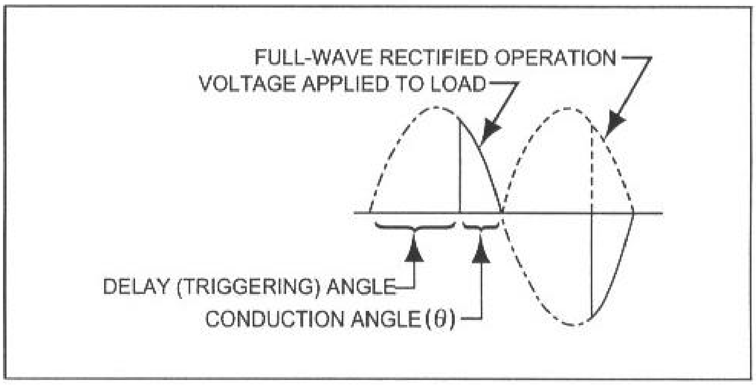


Figure 2.9 PHASE ANGLE CONTROL [5].

One of the original Dilor controllers measured 20 cm by 10 cm and weighed 1.5kg. Because of this excessive size and weight, a new motor control system has to be designed. It must be small and light enough to fit inside the starboard hull of the ROV, and provide accurate and reliable control of the speed and direction of each of the four thruster motors.

Before the motor control system can be developed, three motors have to be overhauled to allow them to work again.

2.5 OVERHAULING THE MOTORS

On arrival of the DART, three of the four thruster motors were found to be seized. This required the complete dismantling of each thruster and motor, and the cleaning out of old grease, sea salt residue and corrosion. The primary seized component in each motor was found to be the motor driver bearing or the head bearing.

The seized bearing was removed and new bearings were sized and purchased. Each new bearing was carefully repacked with grease, in a clean and sterile environment. The grease was pushed through on one side only until it appeared on the other. This ensured the grease fully enclosed each ball bearing. To place the bearing back onto the shaft, the bearing was heated evenly. This caused the bearing to expand, allowing it to be inserted back onto the shaft. After cooling had contracted the bearing size, it locked tightly onto the shaft of the rotor.

After the seized bearings were replaced, every working bearing and gear was cleaned with petrol and greased. Each motor was then reconstructed, and the bladders were replaced and filled with new oil as required. When the ROV is operating underwater, the bladders equalise the pressure on the motor seals by being compressed by the external water pressure (refer Section 5.4.2).

A spare motor received with the ROV was also cleaned and greased, so that it could be used as a replacement part if needed.

2.6 MOTOR CONTROL TECHNIQUES

There are many different methods that can be used to control the speed and direction of a universal motor. Some of the most common use tapped-field winding, continuously rated variable resistors and electronic methods [3].

An electronic method is the only suitable technique for this application as the motors are to be controlled by digital signals from an onboard central controller. Some common techniques of electronic control use semiconductor devices such as SCRs, triacs, diacs and Metal Oxide Semiconductor Field Effect Transistors (MOSFETs).

The original system used Phase Angle control, so it was decided to trial a similar method using triacs. Triacs are preferred over SCRs because they are capable of uni-directional current flow, and are able to full-wave rectify an AC power supply in a standard bridge configuration as pictured in Figure 2.10.

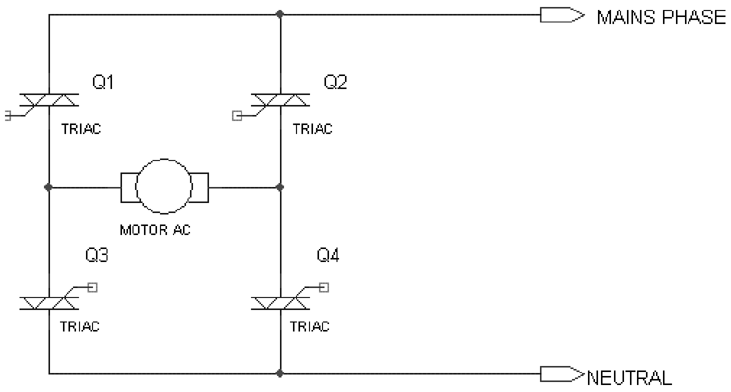


Figure 2.10 **A TRIAC FULL BRIDGE CONFIGURATION.**

A timing signal triggered the firing angle of the triacs, controlling the speed of the motor in a similar fashion to the original system. The motor turns forwards if Q1 and Q4 are fired during the positive half of the cycle, and Q3 and Q3 are fired during the negative half. To reverse the motor, the opposite pairs are fired respectively.

To achieve correct control, the timing of the firing signal must be in phase with the mains power. To implement this, a mains synchronised firing signal is generated.

2.6.1 Generation of a Timing Signal

To achieve a correct timing signal for the trigger pulses, a zero-crossing detector and ramp generator circuit is used. The circuits are adapted from [6].

Figure 2.11 illustrates the mains synchronising signal circuit. Two BiMOS operational amplifiers are used to provide two 0/15V square wave signals 180? out of phase from each other at the 50 Hz mains frequency. The op-amp outputs are logic high when the positive input passes the threshold voltage set by resistors R1 and R2, which also set the ramp-starting angle. Point A is logic high through the positive half of the cycle, and point B is logic high during the negative half of the cycle. The NOR gate output is logic high during the brief period of time when both A and B are logic low, acting as a zero crossing detector.

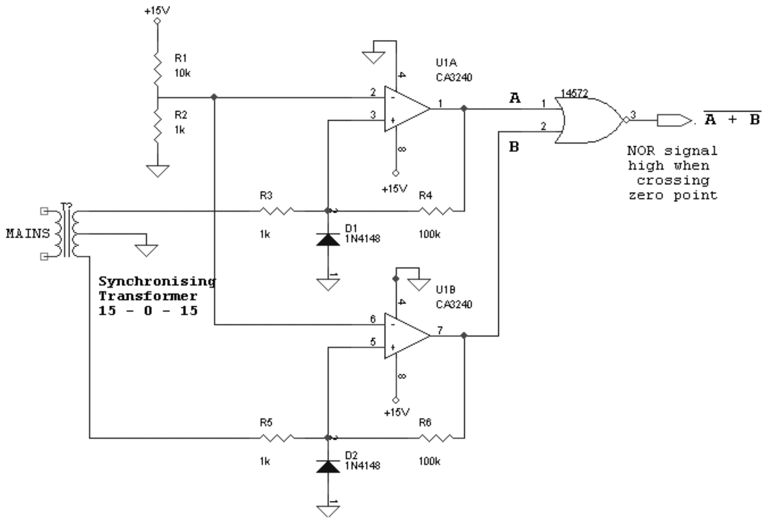


Figure 2.11 MAINS SYNCHRONISING SIGNAL CIRCUIT.

The circuit in Figure 2.12 generates the ramp signal. When the NOR signal is logic high the transistor Q1 turns on, discharging the capacitor C4. When the NOR signal returns to a low level the capacitor begins to charge via the constant charging current provided by the resistors to create the ramp signal.

This circuit is called a boot-strap integrator. The ramp signal *y(t)* is given by:

$$y(t) ? \frac{2V_{cc}}{RC} t \qquad \textbf{EQUATION 2-1}$$

where *R* is the value of the resistors R7, R8, R10 and R11 in Figure 2.12, *C* is the value of capacitor C4, and time *t* starts from zero when the transistor switches off.

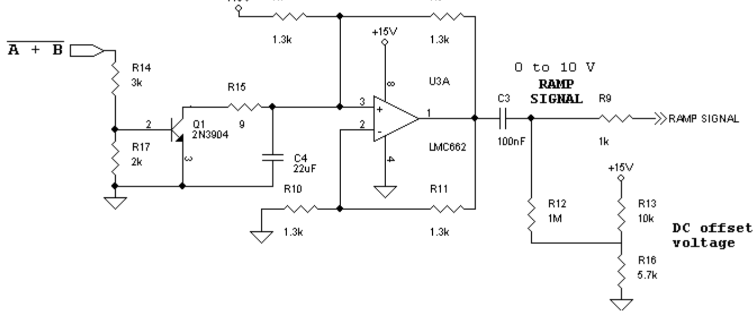


Figure 2.12 BOOT-STRAP INTEGRATOR.

R and *C* are chosen to vary the ramp signal from 0 to 10V when the synchronising voltage varies from 10 ? sin (5?) to 10 ? sin (175?) (allowing a 10? period for the zero crossing). This ramp signal is input to a comparator along with a 0 to 10V speed control voltage. The value of the speed control voltage varies the duty cycle of the output from the comparator and provides a firing signal. The earlier the firing signal is applied, the greater is the power delivered to the load.

With a suitable mains synchronised firing signal, the many operational characteristics of triacs must be taken into account. The firing signal must be applied at the correct angle, there must be sufficient turn-on current delivered to the gate of each triac, and the polarity of the firing signal on the gate must be correct.

2.6.2 Triac Operation

A universal motor is a highly inductive load, and therefore the current through it will lag the voltage across it by an angle ? [7]. This requires careful attention to the firing angle ?. If ? is greater than ?, the triac will conduct symmetrically as in Figure 2.13. After firing, the triac charges the inductive load. As the voltage passes through zero, the inductive load starts to discharge until the triac turns off when the holding current drops below the gate current.

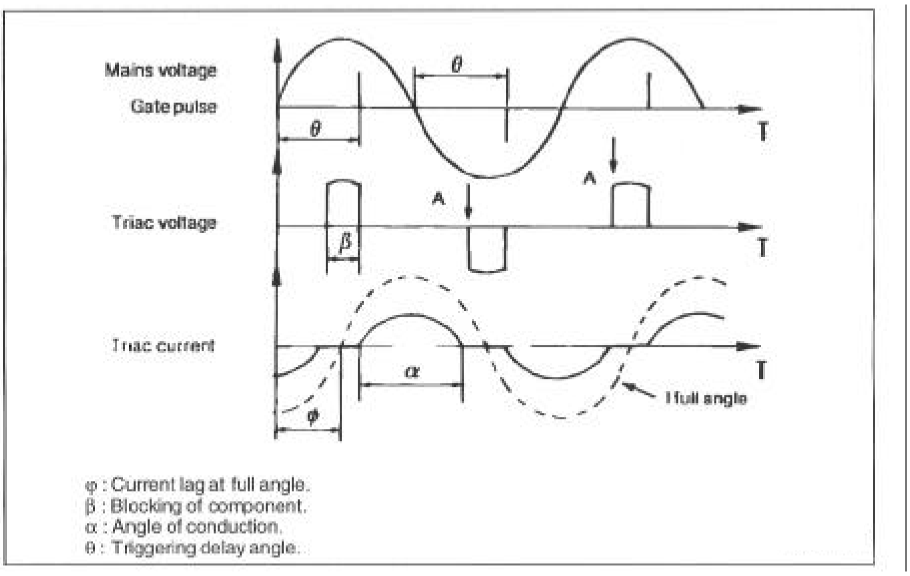


Figure 2.13 SYMMETRICAL OPERATION OF A MAINS SYNCHRONISED TRIAC [7].

In Figure 2.14 below, the angle ? is less than ?. The current will begin to charge the inductive load much earlier, and therefore have a longer discharge time when the voltage crosses zero. This causes the triac to conduct at an angle ? greater than 180? making operation asymmetrical. When the second firing pulse is received at point C, the triac is still conducting and will not be affected until the third firing pulse is received half a wave later.

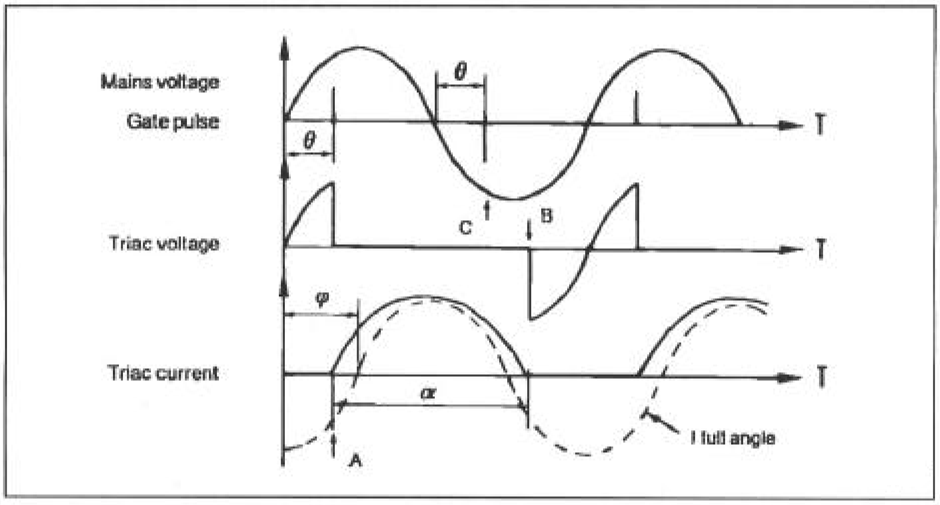


Figure 2.14 ASYMMETRICAL OPERATION OF A MAINS SYNCHRONISED TRIAC [7].

A highly inductive motor can be subject to variances in impedance which can cause imbalances that also lead to asymmetrical operation, making a correctly timed firing pulse difficult [7].

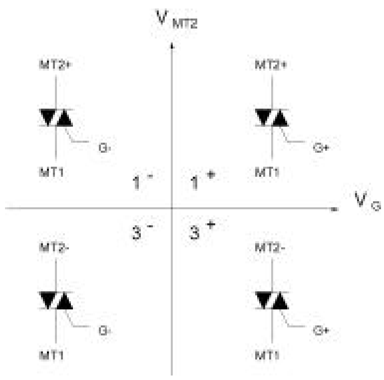


Figure 2.15 THE FOUR QUADRANTS OF TRIAC TRIGGERING.

The firing signals for the triacs used also require certain polarities for the trigger voltage with respect to the MT2 side of the triac as shown in Figure 2.15.

Triggering must be avoided where possible in the 3^+ quadrant (MT2-, G+). A negative gate current is preferred due to the internal construction of the triac [8].

2.6.3 Triac Firing Circuits

The first trial circuit to fire a triac using an opto-isolated triac-driver is shown in Figure 2.16. However, this circuit was not effective because the triac requires a certain amount of current to the gate to trigger the 'on' state, which would vary due to the series resistor (depending on what angle the trigger signal is applied). The value of the resistor could not be lowered as it limits the current to the gate when the triac is fired at the maximum load current period.

If the trigger is applied at the correct angle, the circuit would start conducting, but it would also trigger in the negative half of the cycle, making the motor alternate rapidly between forwards and backwards motion.

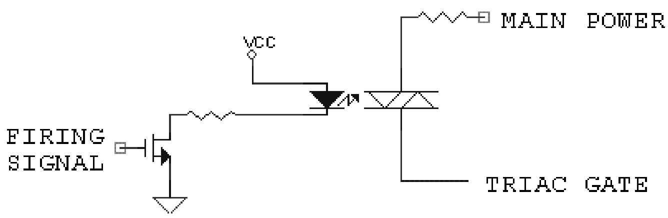


Figure 2.16 TRIAC FIRING CIRCUIT ONE.

Figure 2.17 illustrates the second firing circuit used to trigger the triac into the 'on' state. The diode is used to prevent triggering in the negative half of the cycle. Charge is stored in the capacitor and maintained at a certain voltage by the resistor-divider network 1 and 2. The capacitor value is chosen for fast charge and discharge, while still being able to store enough charge to turn on the triac.

When the firing signal is applied, the capacitor is discharged through the gate, turning on the triac. The zener diode prevents the voltage between the gate and the triac cathode exceeding the absolute maximum rating. This firing circuit works only during quadrant 1^+ (refer Figure 2.15) because of the series diode. However, in a bridge configuration, negative pulses would be used to trigger the gates. This means that a different circuit would have to be constructed, so this method was abandoned due to time constraints.

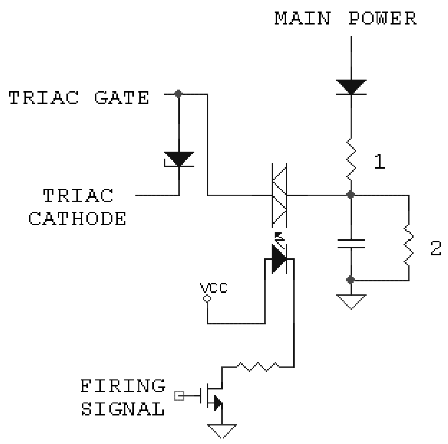


Figure 2.17 TRIAC FIRING CIRCUIT TWO.

Although an alternative to a triac full-bridge configuration is to full-wave rectify the supply, control the phase angle with a triac and switch the direction of the motor with a relay, the circuitry required for this method became increasingly large and complex to a point where it would not prove viable.

Complications leading to the rejection of this method are:

- Firing signals must be of a certain polarity for reliable operation (avoiding operating the triac in 3^+ quadrant [8]).
- Total inductance and resistance parameters must remain constant for stable operation, and it is difficult to adjust for variation in the motor impedance [7].
- Firing angle ? must be greater than the delay angle ? for symmetrical operation [7].
- High peak-to-peak current from AC operation leads to high brush temperature, limiting the motor lifetime and efficiency [9].
- The extra circuitry required increases the size and weight of the system and decreases the reliability.

A DC solution is opted for as it provides the following benefits:

- ✍✍Simpler speed and direction control of the motors.
- ✍✍RMS and peak-to-peak currents are reduced, decreasing losses and brush temperature [9].
- ✍✍MOSFETs can be used, which are a robust industry-standard solution.
- ✍✍Motor lifetime increased [9].
- ✍✍DC performance is better than AC with higher efficiency and output [4].
- ✍✍Reduced noise [9].

A common method of motor control is to use MOSFETs with Pulse Width Modulation (PWM). MOSFETs are advantageous because they offer high input impedance and low internal noise. They are capable of very fast switching and are easy to turn on with a digital signal. The turn-off is also controllable, unlike a triac where the current must pass through zero.

2.6.4 A DC MOSFET Solution

Pulse Width Modulation (PWM) involves the varying of the duty cycle of a square wave. It controls the conduction time of the MOSFET, and the average power delivered to the load.

Four MOSFETs are arranged in a bridge configuration. The MOSFETs are required to have the following characteristics:

- ✍✍N-channel FET. This allows the gate to be switched on by a positive voltage with respect to the source.
- ✍✍Drain current (I_D) rating of at least 10A. The maximum current each motor will draw is 10A.
- ✍✍Drain-source voltage (V_{DS}) of at least 200V. This protects the MOSFET from breaking down when connected across the supply rails of approximately 70VDC.

- Compatible with a gate-source voltage (V_{GS}) of 15V. The planned driving signal is a 0/15V digital signal.
- Less than 0.5? on-resistance (R_{DS}). This prevents the MOSFET dissipating large amounts of energy when high current is drawn.

The IRF740 N-Channel PowerMESH? MOSFET is chosen for the following reasons:

- It is an N-Channel device
- I_D = 10A
- V_{DS} = 400V
- V_{GS} = ? 20V
- R_{DS} = 0.48?

The circuits constructed in Figures 2.11 and 2.12 provide a variable duty cycle at a frequency of 50Hz. A slow switching frequency is preferred with an inductive load as it reduces the need for bulky snubber networks to limit the turn-on and turn-off voltages.

The circuit shown in Figure 2.18 below is the first attempt at a motor control circuit using MOSFETs. For simplicity, only one direction is described, with FETs Q2 and Q3 using the same arrangement to reverse the current through the motor.

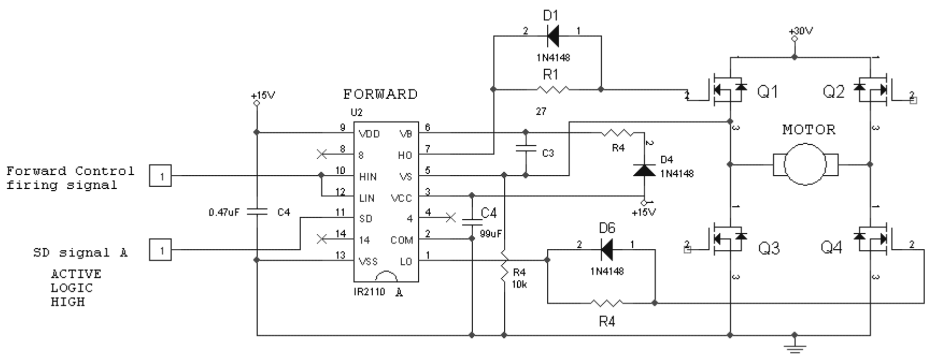


Figure 2.18 A FULL-BRIDGE FET MOTOR CONTROL CIRCUIT.

The IR2110 is a high voltage, fast power MOSFET/IGBT driver, with two independent output channels capable of driving one high side and one low side device. A digital 0/15V PWM signal is tied to both the HIN and LIN inputs of the IR2110. This signal is then present on the HO and LO outputs, and is used to turn on the high and low side FET's respectively for forwards motion of the motor.

During the high period of the PWM duty cycle, the driver internally connects pins 6 and 7. This allows charge accumulated on capacitor C3 during the low period to be discharged into the gate of the high side FET Q1. Concurrently, the LO output is internally connected to the 15V supply of the chip. These connections turn on FET's Q1 and Q4 through the high period.

During the low period, pins 5 and 7 are shorted for the high side, and LO pin 1 is internally connected to circuit ground turning off both transistors. During this low period, pin 5 should be pulled low recharging the bootstrap capacitor C3 for the next cycle.

The main problem with this circuit is the failure of pin 5 to be pulled to ground during the low period, causing the high side FET to fail to turn on during the high period due to a lack of charge on the bootstrap capacitor. A solution is to turn on Q3 during the time that Q1 and Q4 are off (for forwards motion) to guarantee the bootstrap capacitor will be pulled low, but this would also increase the complexity of the driving signals to the IR2110 drivers.

2.7 THE MOTOR DRIVER CIRCUITRY

The IR2110 driver from the previous circuit is utilised, but as a half-bridge is used only one driver and two FET's are required per motor. The circuit in Figure 2.19 is adapted from [10]. An isolated supply is now used to power the high side FET, provided by the Electronics Transformer located in the starboard canister (refer Section 2.9.3).

The motor driver circuitry consists of four half-bridge circuits with on/off, speed and direction control. Each half-bridge has a digital 0/15V PWM signal input to the HIN or LIN pins of the IR2110 driver. This signal turns on either the high or low side FET respectively. When HIN receives logic high the IR2110 driver internally connects pins 6 and 7 as discussed earlier, providing the gate of the high side FET with an isolated 15VDC. When HIN is logic low, pins 5 and 7 are internally connected. LIN works similarly, except the gate of the low side FET switches between ground and the 15V supply of the circuit.

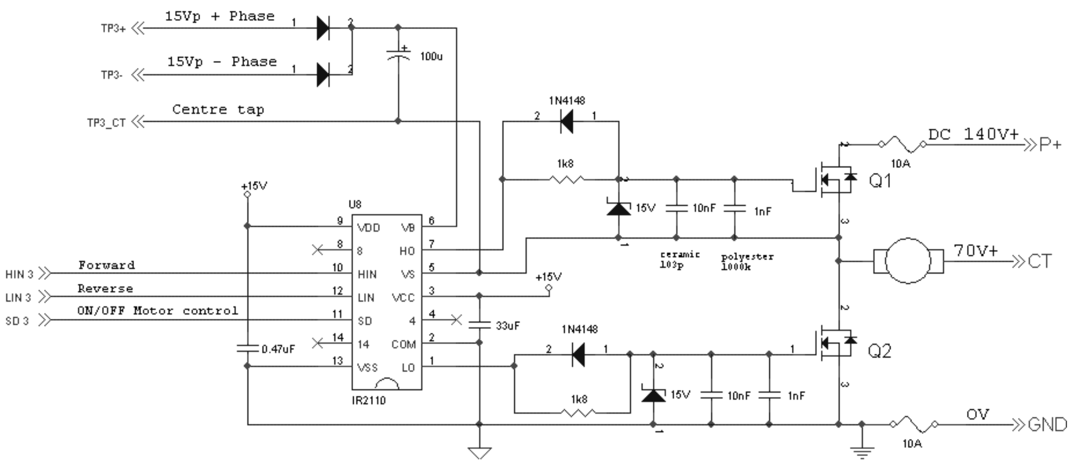


Figure 2.19 A HALF-BRIDGE DRIVER CIRCUIT FOR ONE MOTOR.

Noise induced during switching can cause large spikes between the gate and source of the power transistor. To prevent accidental turn on, a 15V zener diode is used to clamp the inputs against any voltage over 15V. The 10nF and 1nF capacitors also reduce noise on the gates during switching.

Although the IR2110 chip has internal time delays to guard against both the high and low sides being on simultaneously, the direction circuit shown in Figure 2.20 is designed to safeguard the MOSFETs. It utilises gates with very similar propagation delays. If the Direction signal toggles, the initial AND and NAND gates will almost simultaneously switch the subsequent AND gates, toggling the PWM signal between the HIN and LIN pins. This circuit also provides a way to change the direction of each motor with one digital signal. The On/Off control signal activates the internal shutdown of the IR2110 when high.

The main advantages of using a half-bridge arrangement include:

- Reduced cost due to fewer IR2110 drivers and power MOSFETs
- Increased robustness of system due to less components

- Easily controlled from digital signals
- Reduced component count decreases the size of the circuitry
- Easier to troubleshoot
- Industry standard

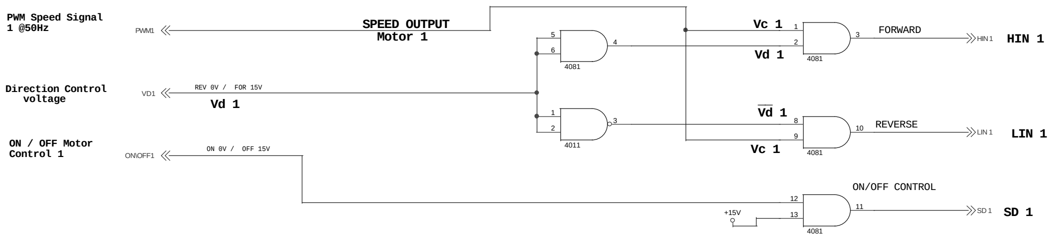


Figure 2.20 THE DIRECTION AND ON/OFF CONTROL LOGIC FOR ONE MOTOR.

2.8 MOTOR CONTROL - DELPHINUS

An overview of the interactions between the hardware used for the new motor control system is shown in Figure 2.21.

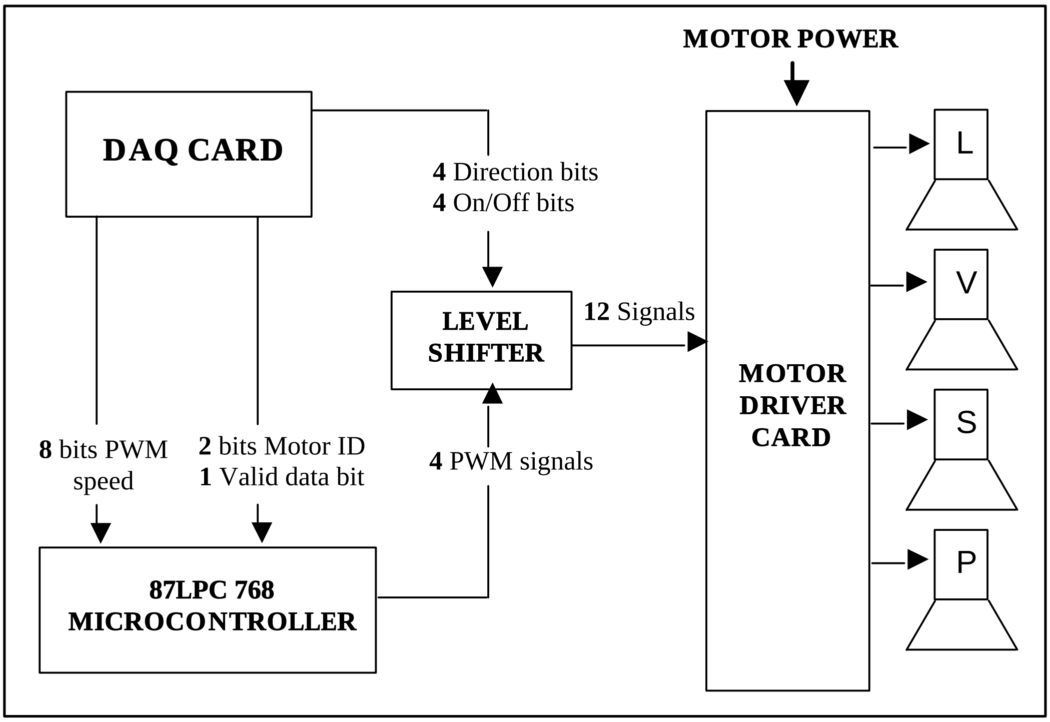


Figure 2.21 AN OVERVIEW OF THE NEW MOTOR CONTROL SYSTEM.

The four thruster motors are controlled by the Motor Driver card, which incorporates the four half-bridge drivers. The Motor Driver card is controlled by 12 signals; 8 On/Off and Direction signals from the DAQ card and 4 PWM signals from the 87LPC768 microcontroller. The Level Shifter board is used to convert the TTL outputs of the DAQ card and micrcontroller to 15V CMOS levels for input to the Motor Driver card.

2.8.1 The Motor Driver Card

The development of the Motor Driver card involved many stages. Three of the four prototype boards built are shown in Figure 2.22.

The final version of the Motor Driver card can be seen in Figure 2.23. The power transistors are mounted on the aluminium heatsink along with large freewheeling diodes to protect the MOSFETs from the back EMF of the thrusters. The IR2110 MOSFET drivers are located near the green capacitors, and the control logic and power supply utilise the remaining space on the board.

The Motor Driver card controls the main power to each of the four thrusters. The dimensions of the board are restricted to allow it to fit inside the starboard hull. The PCB card design is chosen as the existing DART system used PCB connectors for all the electronic cards in the starboard hull, and would be difficult and unnecessary to alter. The PCB layout also allows for easy removal of the Motor Driver card should a fault occur.

The Motor Driver card expects twelve digital signals; consisting of four PWM speed signals, four On/Off control signals and four Direction control signals. The card switches the main power according to these signals directly out to each motor.

The main power input to the card is provided by a centre-tapped supply. An isolated ground, +70VDC and +140VDC is supplied to each motor (refer Figure 2.19). This is provided on the back of the card via four 3-pin plugs which connect into a 40A connector box (refer Section 5.3.2). Four 2-pin plugs connect each motor to the respective half-bridge driver. The input voltage levels to the card are limited by the maximum allowable potential across each thruster motor.

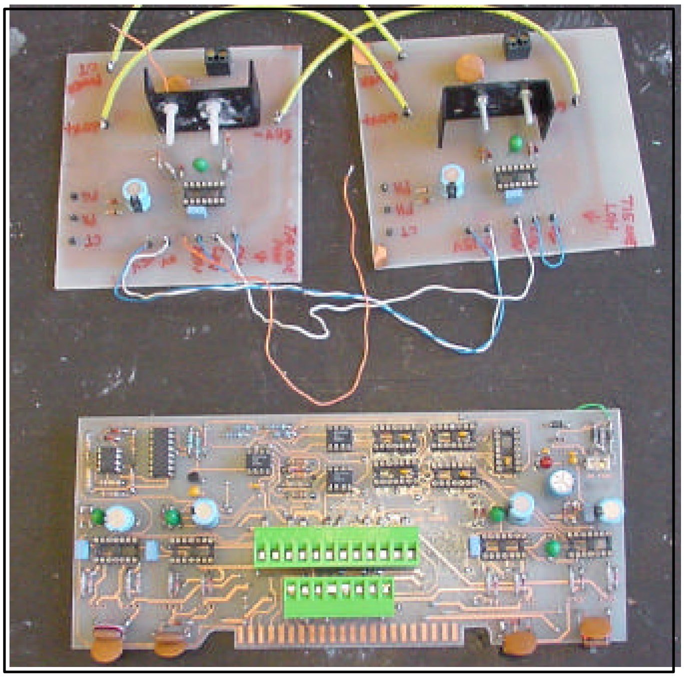


Figure 2.22 THREE PROTOTYPE BOARDS BUILT DURING THE DESIGN PROCESS.

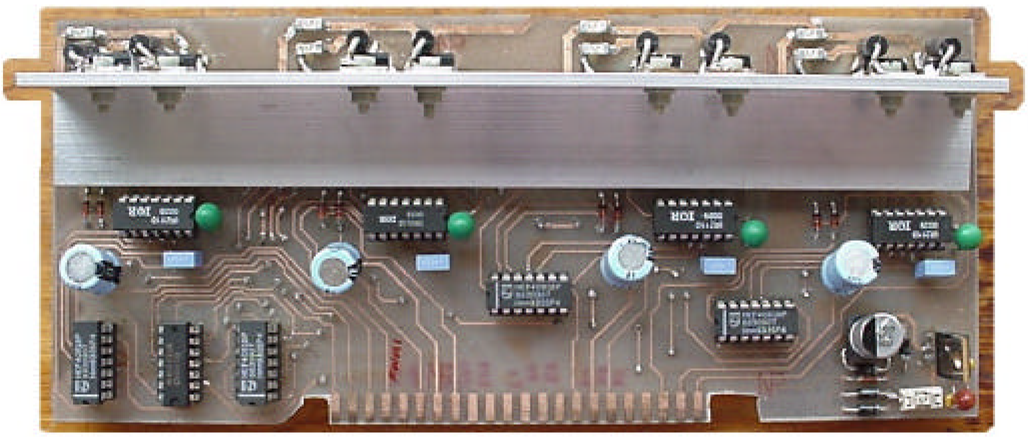


Figure 2.23 THE MOTOR DRIVER CARD.

2.8.2 PWM Signal Generation

The 87LPC768 microcontroller provides a simple method of producing four PWM signals. The 87LPC768 has four PWM channels, each with ten-bit resolution. Eight-bit resolution is considered sufficient for motor control applications, so only eight bits on the DAQ card are used to communicate the duty cycle.

The DAQ card can provide up to 24 digital I/O bits. Eight of these bits provide the four Direction and four On/Off controls to the Motor Driver card via the Level Shifter board. Eleven bits are used to communicate to the 87LPC768 microcontroller the PWM speed, the Motor ID, and a Valid Data bit for each motor.

Using eleven digital I/O pins to read the multiplexed eleven-bit words from the DAQ card, the microcontroller provides four PWM signals to each of the four PWM inputs on the Motor Driver card. An example of an eleven-bit word is shown in Figure 2.24.

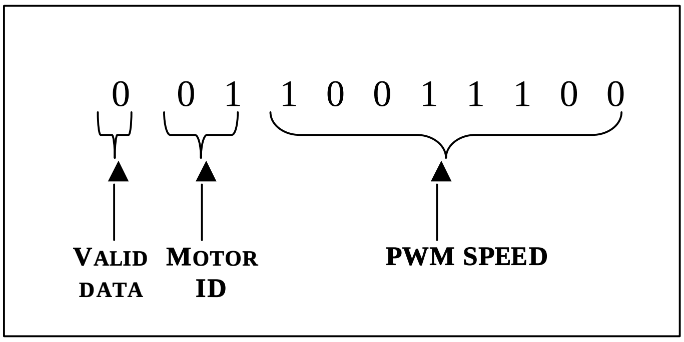


Figure 2.24 ALLOCATION OF THE ELEVEN-BIT CONTROL WORD.

When a new word is written to indicate a change to a specific motors speed, the DAQ card resets the eleven bits to zero before the new value can be written. To prevent erroneous data being read by the micro, a Valid Data bit is used which serves as a flag. The two Motor ID bits tell the micro which of its four PWM outputs to write to (refer Table 2.1). The remaining eight bits provide the 87LPC768 with a duty cycle to create the PWM signal.

The Motor ID bits are as follows:

MOTOR	ID #
Lateral 1	00
Vertical 2	01
Starboard 3	10
Port 4	11

Table 2-1 MOTOR ID NUMBERS.

2.9 MOTOR POWER

A specially designed Motor Transformer is rectified by the Motor Power Rectification board, and supplies the power to the Motor Driver card. Power to the electronics and Motor Driver card is supplied by an Electronics Transfomer and Power Supply card.

Each motor has a maximum voltage rating of approximately 70VDC. To allow the ROV to be at a floating potential, an isolating source must be used. This power source is located on the surface and connected to the ROV via the umbilical cable.

2.9.1 Motor Transformer

Copper conductors in the umbilical cable have a DC resistance which is proportional to the length of the cable when a DC supply is used. This resistance is given by:

$$R ? \frac{L}{A} ? \qquad \textbf{EQUATION 2-2}$$

where:

L = length of the cable

A = cross-sectional area of the conductor

? = resistivity of wire (copper = 1.68 ? 10^{-8} ? m)

Once the resistance over the intended length of conductor is known, the voltage drop can be calculated using Ohm's law.

For example, the resistance of a 12 AWG 7/20 stranding cable that is 30m long is 0.14? , which equates to a 5.6V drop across the full length when 40A of current is drawn.

To anticipate situations where different lengths of umbilical will be needed, resulting in different voltage drops, a specially made variable Motor Transformer is designed to power each of the four thruster motors.

Specifications of the Motor Transformer include:

- 5kW power
- Five primary taps, centre-tapped secondary
- Output voltage across each phase with respect to the centre tap is variable from $60V_{rms}$ to $85V_{rms}$
- 60kg weight
- Dimensions: 250 ? 320 ? 170 mm

The Motor Transformer is pictured in Figure 2.25. Connecting different combinations of the primary taps to the mains allows the secondary voltage across each phase with respect to the centre tap to vary from approximately $60V_{rms}$ to $85V_{rms}$. This allows the same power to be present at the ROV should the umbilical length be changed without replacing the supply.

For example, if 60VDC average is required at the ROV, in the case when the maximum current of 40A is drawn and a 12 AWG 7/20 stranding cable is used, the transformer can be adjusted to allow cable lengths of approximately 10m to 130m. If the chosen cable has less DC resistance, or the current drawn is less than the 40A maximum, then even longer lengths of cable can be used. Due to the size and weight of the Motor Transformer, the ROV chassis will never be able to accommodate it onboard.

The transformer is able to provide the full load current of 40A on both sides of its secondary simultaneously, allowing for the case when all of the motors are running off the same output.

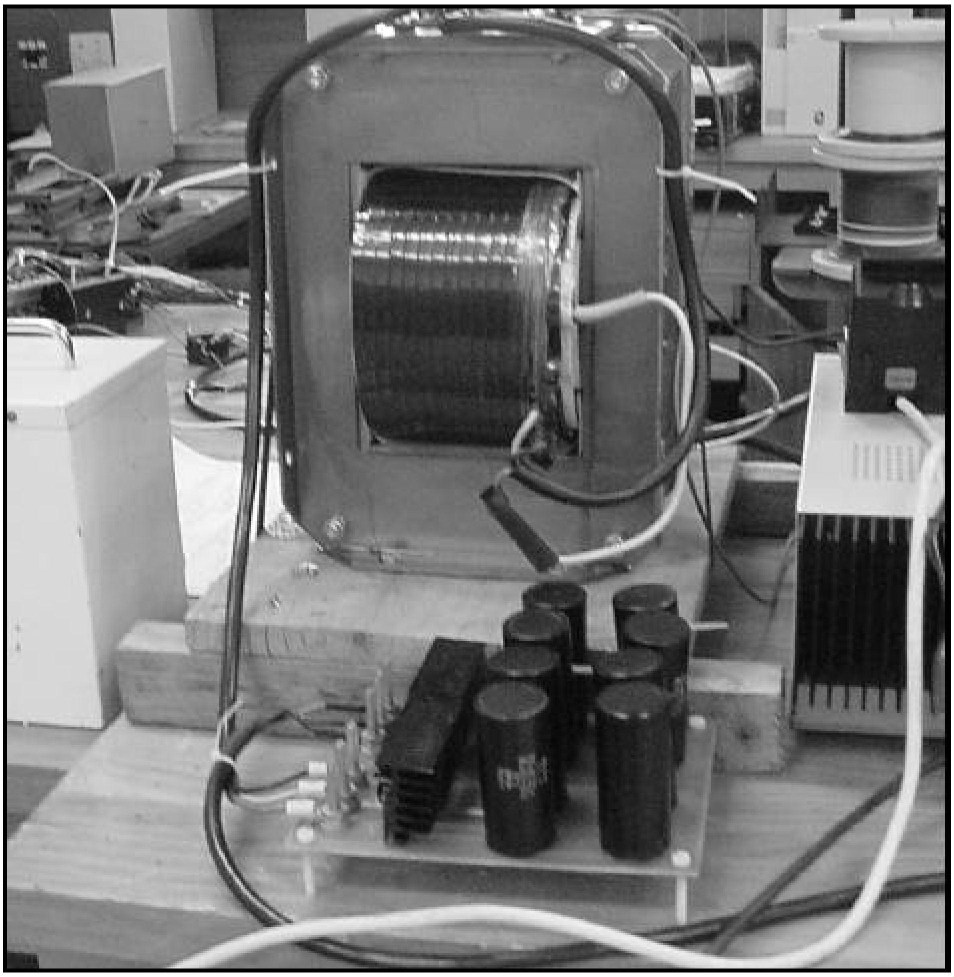


Figure 2.25 THE MOTOR TRANSFORMER AND POWER RECTIFICATION BOARD.

2.9.2 The Motor Power Rectification Board

To full-wave rectify the centre-tapped single phase AC from the secondary of the Motor Transformer, a Motor Power Rectification board is designed.

To rectify the centre-tapped secondary, four power diodes are required. Each diode must be able to withstand an AC reverse voltage (V_{RRM}) of 85V_{rms} or 120V_p for the case when the transformer is configured for maximum output. The current rating (I_{FSM}) must be at least 40A. To prevent high power dissipation a small forward voltage drop V_F (less than 2V) is necessary.

The *SAFE*IR 40EPS power diode is chosen for the following specifications:

- V_{RRM} = 1200V
- I_{FSM} = 475A
- V_F < 1V at 20A

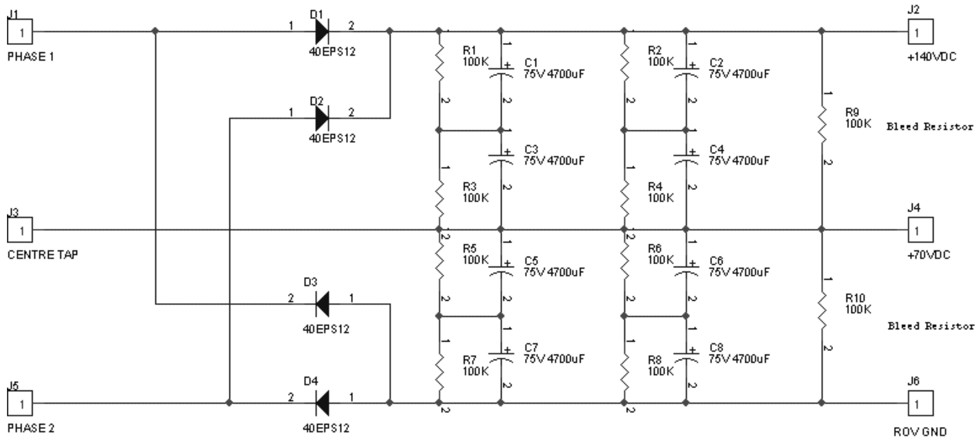


Figure 2.26 THE MOTOR POWER RECTIFICATION CIRCUIT.

Eight 75V 4700?F capacitors smooth the rectified waveform (refer Figure 2.26). The capacitors are connected in pairs in a series configuration. To prevent damage to the capacitors resulting from an inbalance of voltage, a resistor-divider network is connected across each pair to maintain the voltage across each capacitor at exactly half the rail voltage. At the maximum output of 120V_p across each phase with respect to the centre-tap, 60V_p will be across each capacitor.

Two capacitors are used in place of a single capacitor to reduce the overall size of the rectifier (a higher voltage rating increases the size of a capacitor). A PCB board incorporates the four power diodes and the eight smoothing capacitors. The diodes are mounted onto finned heatsinks to protect against overheating. Six 5mm brass bolts are used to attach the transformer secondary to the board, and allow the umbilical to connect to the rectified outputs. The Motor Power Rectification board is shown in front of the Motor Transformer in Figure 2.25.

2.9.3 Electronics Transformer

To provide power to the onboard electronics of the ROV, a 60VA transformer is specially designed to fit within the starboard hull. It is totally enclosed by the aluminium shell of the canister, which is grounded to protect the PCB cards from noise. The transformer has 230V mains input and five isolated centre-tapped outputs. The five outputs comprise one $40V_{rms}$ and four $20V_{rms}$ supplies.

The $40V_{rms}$ output is capable of supplying 3A, and is input to both the Motor Driver card and the Power Supply card located in the starboard hull. Both cards full-wave rectify and smooth the output from the transformer into a 15VDC power supply with the circuit shown in Figure 2.27. The four $20V_{rms}$ outputs are input to the Motor Driver card to provide the isolated supplies for the high side FET's in the four half-bridge circuits.

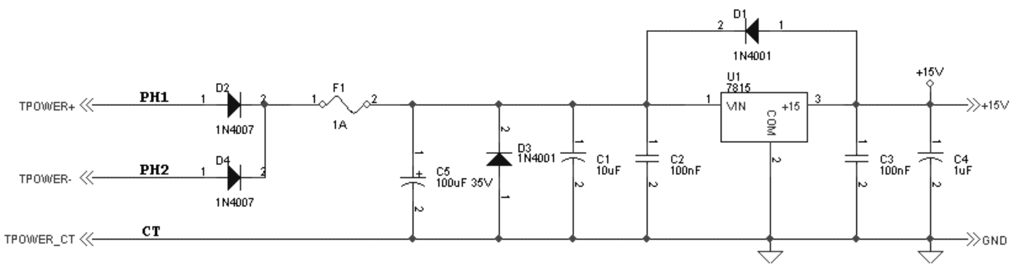


Figure 2.27 THE POWER SUPPLY CARD SCHEMATIC.

The Power Supply card provides 15VDC to the Camera Pan/Tilt board, Pressure transducer, Tilt sensor, Compass power supply board and the Level Shifter board.

3. HARDWARE

3.1 HARDWARE OVERVIEW

An outline of the new DELPHINUS ROV system, showing the interaction between hardware components, is shown below in Figure 3.1.

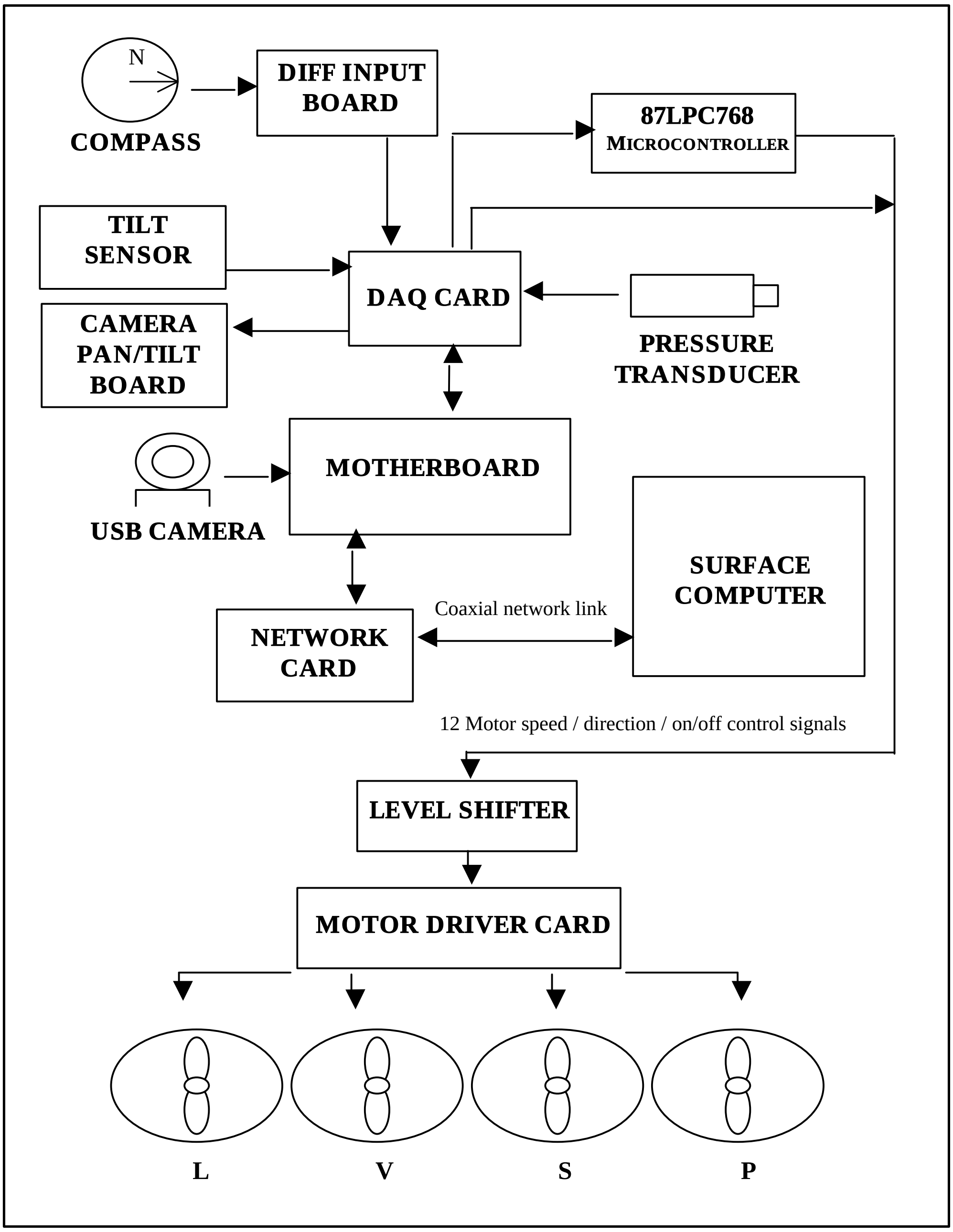


Figure 3.1 AN OVERVIEW OF THE NEW HARDWARE COMPONENTS.

The redesigned system incorporates additional components selected to provide the vehicle with sufficient onboard intelligence to allow it to operate autonomously. A GA-5VMM Motherboard with AMD K62500 processor is the main element around which all the other hardware is based. It provides advanced processing capabilities and controls the complete ROV within a LabVIEW? software environment. The Motherboard accesses the analogue and digital information supplied by the DAQ card and transforms it into a readable form using LabVIEW Virtual Instruments.

A Philips ¼” CCD camera provides digital video and photographic capabilities, and connects directly to the Universal Serial Bus (USB) port of the Motherboard. The camera allows the operator visual confirmation of the subsurface environment in colour or black and white.

The Data Acquisition card (DAQ) provides a link between the motors, sensors and control cards, interfacing directly with the Motherboard through the ISA slot. The card outputs 23 digital signals to the onboard hardware. Eight are motor On/Off and Direction signals, eleven are multiplexed to the 87LPC768 microcontroller, and four control the direction of the camera. The Compass, Tilt and Pressure sensors are input to the card via five analogue input channels.

The Tilt and Pressure sensors output analogue data relating to the roll, pitch and depth of the ROV. The Compass (via the Differential Input board) supplies heading information. The pointing direction of the USB camera is controlled by four digital outputs on the DAQ card, which are sent to the Camera Pan/Tilt board.

The 87LPC768 microcontroller receives the four multiplexed 11-bit words from the DAQ card and decodes them to control each of its four PWM output channels.

The Level Shifter board translates the four PWM signals and the eight motor On/Off and Direction signals into CMOS 0/15V digital levels for input to the Motor Driver card.

The Motor Driver card reads in the PWM, On/Off and Direction signals, which are used to switch the high power from the Motor Transformer out to each of the four thrusters.

A D-Link DE-528 Series network card establishes a link with the surface. A Local Area Network (LAN) is created and Virtual Networking software allows the surface computer to monitor and control the ROV though a standard coaxial network connection, via the umbilical cable.

3.2 MOTHERBOARD

The GA-5VMM Motherboard was chosen as its dimensions allow it to fit within the confined central hull. With the AMDK62 500MHz processor, it provides an ideal platform for underwater tasks that require computationally intensive software. The main advantage of using a Windows based platform rather than a single chip microcontroller is the ability to run many types of commercially available software, and to use them all simultaneously in real time. This is useful when a specific sensor or task requires specialised drivers. Additionally it decreases software development time.

The Motherboard provides a basis for the software environment LabVIEW, which is a reliable and powerful tool specially designed for data acquisition and control systems. The USB ports provide a simple interface for video and sensing equipment, reducing the complexity of the system and allowing the DELPHINUS to have plug and play capability.

In the development of an autonomous control program, the ROV may need to map its environment, demanding processing and storage capabilities which are provided by the Motherboard and hard drive. Sonar sensors can be easily integrated into the system to create images which can be utilised in the control system (refer Figure 3.2). The behaviour of the ROV in relation to these maps can then be studied *in situ* or at a later date without losing time to extensive data downloading.

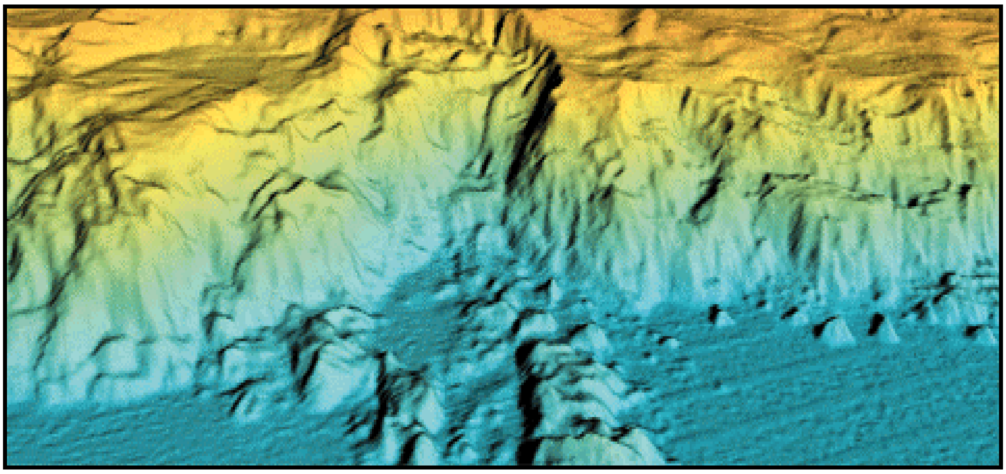


Figure 3.2 A SONAR IMAGE OF AN UNDERWATER ENVIRONMENT.

The ROV may be required to track and determine contaminants in rivers or pools. Chemical sensors can be incorporated directly into the system to retrieve data for analysis or evidence. An application like this would necessitate extended periods of data logging; the results viewed in real-time and/or stored for future use.

3.2.1 GA-5VMM Specifications

- Dimensions: 24.6 cm ? 18.6 cm
- 128MB RAM
- Three PCI slots, plus one ISA slot
- Four USB ports
- 500 MHz AMDK62 Processor

Added software includes:

- Microsoft? Windows SE? operating system
- National Instruments LabVIEW? version 5.1
- WinVNC? Virtual Networking software version 3.3.3R7
- Philips Vesta Camera driver version 1.3
- D-Link Corporation DE-528 PCI Ethernet Adapter Driver Program 98/99
- Microsoft Windows® NetMeeting®

Added components include:

- 14.3GB Hard Drive
- Power Supply

3.2.2 Incorporating the Motherboard in the ROV

The Motherboard is mounted in a computer frame which is cut to fit inside the main hull of the ROV (refer Figure 3.3). This provides the peripheral cards with support and protection. The computer frame is mounted on a piece of Perspex giving the underside of the Motherboard a smooth flat surface for attaching to the polished rear wall of the aluminium hull. The Perspex is attached inside the hull via three strips of industrial strength Velcro, allowing the Motherboard to be attached securely yet easily removable.

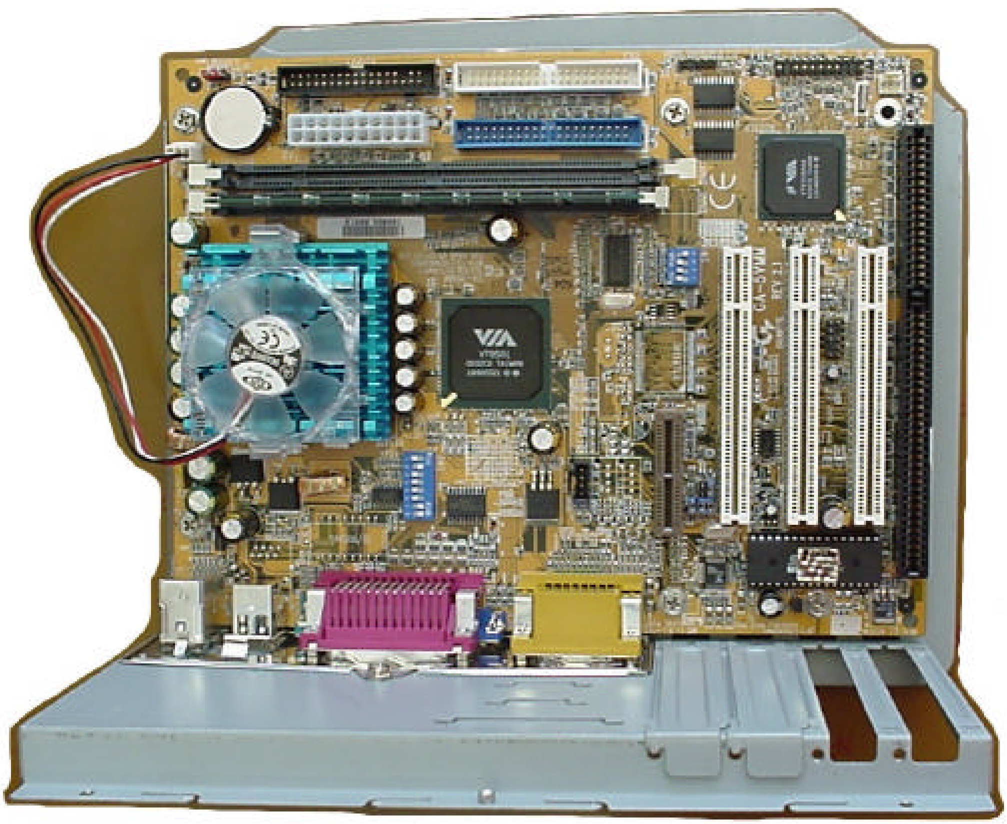


Figure 3.3 THE GA-5VMM MOTHERBOARD.

3.3 DATA ACQUISITION CARD

The National Instruments Lab-PC+ Data Acquisition (DAQ) card forms the link between the central computer and all other control systems and sensors. It is a low-cost multifunction digital, analogue, and timing I/O board providing fast and reliable transfer of data between the computer, control cards, microcontroller and sensors. The card provides 24 digital I/O lines in three eight-bit ports, an 8-channel analogue input port, and two channels of analogue output (refer Figure 3.4).

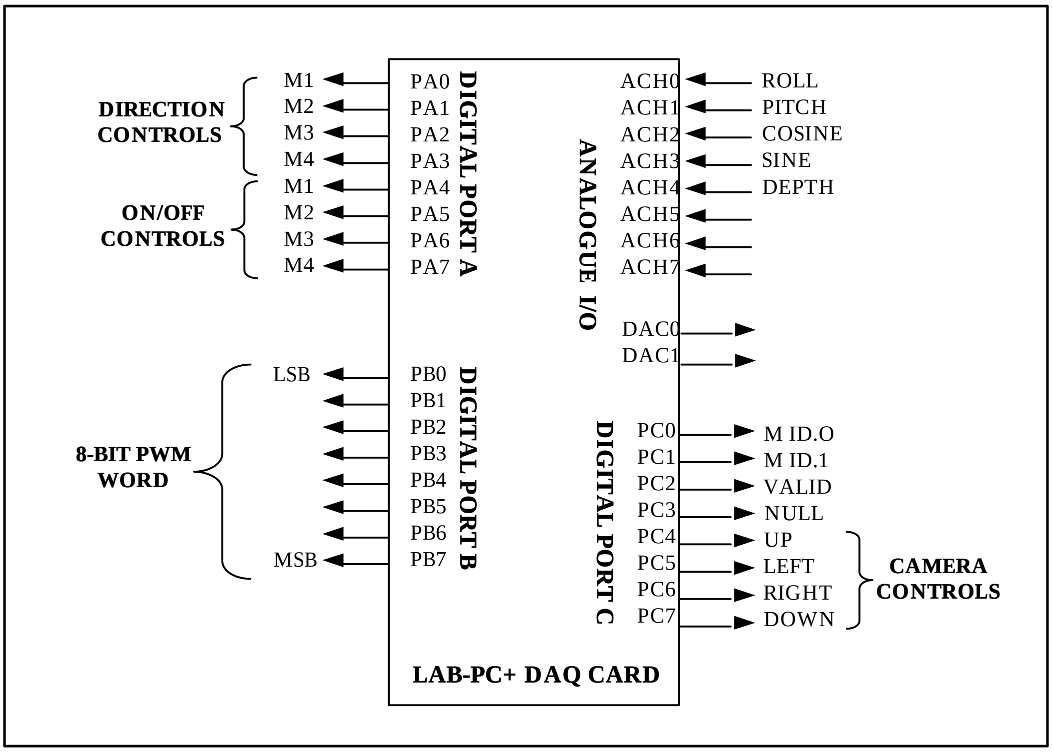


Figure 3.4 BLOCK DIAGRAM OF THE LAB-PC+ DAQ CARD.

ACH*n* is the analogue input port; each channel can be configured to different programmable ranges from ?156 mV to ?10V full-scale. Ports A, B and C are the three 8-bit digital TTL I/O ports configured in software for reading or writing.

Six jumpers and one DIP switch configure the analogue I/O settings and PC bus interface. Different combinations of the jumpers and DIP switch select the analogue input channels to be one of three input modes: referenced single-ended, non-referenced single-ended or differential. The inputs and outputs are either bipolar or unipolar with jumper configurable ranges.

The board jumpers are set to an input range of ?5V to allow for the ?1V Compass outputs, and to allow the 0-5V outputs of the Tilt sensor and Pressure transducer to be read. They are single-ended referenced, which provides sufficient channels to read in the utilised sensors (refer Section 4.2.2), and leaves three spare inputs for other sensors as the application requires.

Software drivers included with the card include LabVIEW? , LabWindows/CVI and NI-DAQ. Additionally, programming can be done at register level. The Lab-PC+ DAQ card is ‘plug and play’, providing an interface for analogue inputs and digital I/O through the ISA slot of the Motherboard. One 50-pin connector accesses all the I/O on the board. The connector attaches to a DAQ I/O card by a 3-foot ribbon cable, allowing the hardware be controlled or scanned at a distance remote to the DAQ card.

3.3.1 Lab-PC+ Specifications

- 12-bit 83 k samples/s successive approximation ADC
- Eight single-ended or four differential analogue inputs
- Two 12-bit DACs with voltage outputs
- 24 TTL digital I/O lines
- Six 16-bit counter/timer channels for timing I/O
- ISA slot format

3.4 NETWORK CARD

The D-Link DE-528 Series Network card (pictured in Figure 3.5) provides the link between the ROV and the surface. A 50? coaxial cable in the umbilical connects the Network card to the computer at the surface. A Local Area Network (LAN) is created between the surface Laptop and the ROV computer. This allows the onboard software to be altered at the surface while the ROV is underwater, and concurrently monitor all sensors, control the motors and capture video data from the USB camera. The card is placed into the Motherboard PCI slot directly underneath the DAQ card, in order to use as little room as possible within the central hull. A T-junction connector attaches a 50? terminator and the coaxial cable to the output connector on the Network card. The coaxial cable is connected to the umbilical coaxial via another T-connector in the junction box (refer Figure 5.10). The umbilical coaxial connects to the surface computer and another 50? terminator via an additional T-connector (refer Figure 3.34).

Specifications of the DE-528 include:

- Ethernet 10BASE-T and 10BASE-2 network compatible
- 10Mbps data transfer rate
- BNC and RJ-45 connector compatible
- 32-Bit PCI-Bus
- 16KB SRAM
- Standard PCI card ‘plug and play’ capability

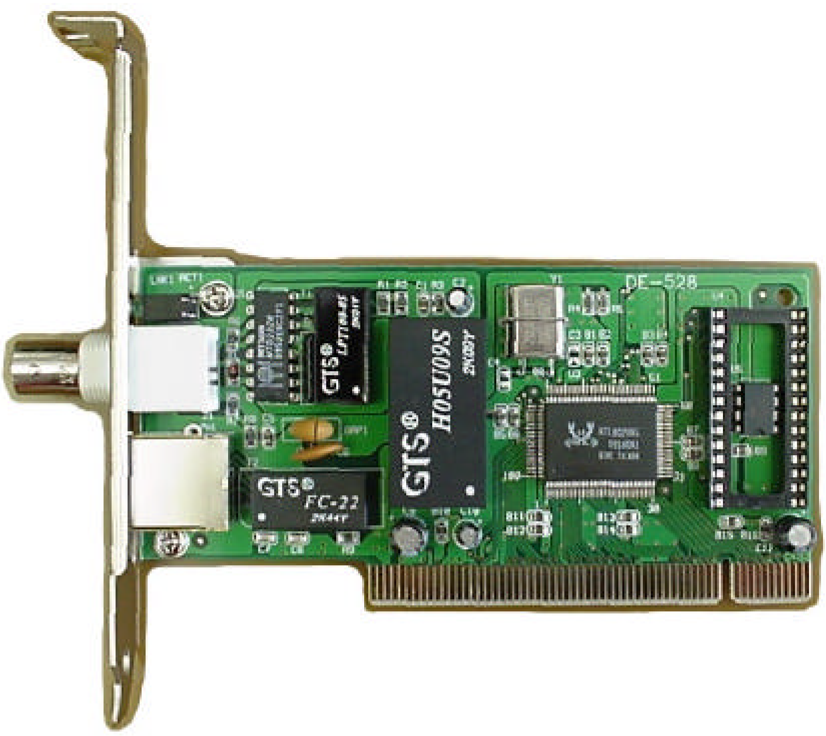


Figure 3.5 THE D-LINK DE-528 SERIES NETWORK CARD.

3.5 87LPC768 MICROCONTROLLER

The DAQ card provides direct control over the eight On/Off and Direction signals of the Motor Driver card. To control the speed of each thruster, four individual 8-bit PWM signals are required. The four PWM signals provide the Motor Driver card with a duty cycle to control the average power to each of the four thruster motors. In a ROV system, the ability to delicately adjust the speed of the motors greatly enhances the manoeuvrability in the water. Eight-bit resolution is sufficient as it provides 256 steps of motor speed control.

A microcontroller provides a straightforward solution to performing digital to PWM conversion. The microcontroller must have at least eleven digital inputs to read in the 11-bits from the DAQ card (refer Figure 2.24), and four PWM output channels. Sufficient onboard RAM is preferable, as the microcontroller board can be made considerably smaller if external program memory is not required. At least 2 kbytes of internal RAM is required to provide enough memory for the code necessary to convert the 11-bit digital words to PWM values.

The 87LPC768 microcontroller is chosen for its low pin count and four 10-bit PWM output channels. It is a 20-pin DIP single-chip package providing eleven digital inputs, 4 kbytes of EPROM memory and 128 bytes of RAM.

3.5.1 87LPC768 Specifications

- Four-channels of 10-bit PWM
- 2.7 V to 6 V digital output operating range
- Configurable on-chip oscillator, requiring no external components
- 4 kbytes EPROM memory
- 128 byte RAM memory
- 14 I/O pins available when using all four PWM outputs
- Only power/ground connections are required when on-chip oscillator and software reset options are chosen

The 87LPC768 provides many advantages over other microcontrollers. The 10-bit resolution of the four PWM channels exceeds the 8-bit requirement given for effective motor control. It is software configurable to operate from an onboard oscillator (the frequency of which is adjustable within software), eliminating the need to incorporate an external crystal. The default setting for all the digital I/O pins is quasi-bidirectional allowing input or output without software configuration. The 87LPC768 also provides all the functions of a standard microcontroller, such as timers, I^2C Bus, a watchdog timer, brownout detection and oscillator failure detection.

3.5.2 The 87LPC768 Microcontroller Board

The loan of a Philips family LPC emulator and programmer from Adilam Electronics facilitated the development of the microcontroller software as described in Section 4.3. The first prototype microcontroller board is pictured in Figure 3.6. A 20-pin header links each pin of the micro to a 20-way ribbon cable, allowing the board to be completely removed from the motor control system. A surface-mount de-coupling capacitor is connected between the power and ground pins of the micro directly underneath the chip.

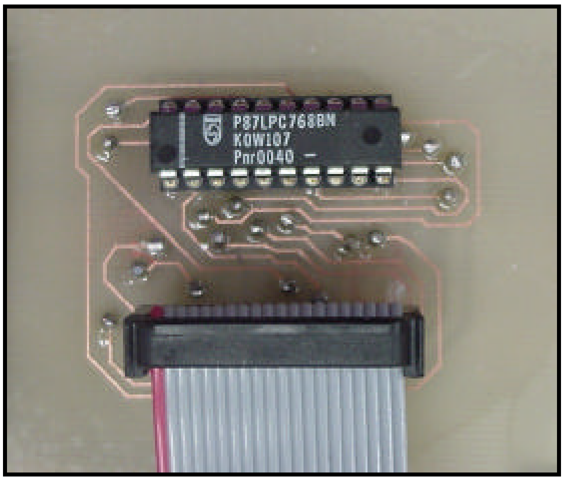


Figure 3.6 THE FIRST MICROCONTROLLER BOARD.

The 20-way ribbon cable is connected to another 20-pin header plug, permitting the microcontroller board to plug into a development board. The development board is designed so the input pins of the micro can be toggled, specifically the 11 pins used to read in the 11-bit word from the DAQ card.

The P8xLPCx emulator (used to develop the software) plugs into the micro board via a 20 pin DIP, in place of an actual 87LPC768 chip. The emulator effectively imitates the 87LPC768 micro, allowing the program code to be modified many times until it operates correctly. This is essential as the only downfall of the 87LPC768 is that it is One-Time-Programmable (OTP).

Once the code (refer Section 4.3.2) worked successfully with the development board, the Philips P8xLPC76x programmer was used to program the 87LPC768 microcontroller. This involved a blank check of the device, and the setting of the UCFG1 register inside the 87LPC768 (refer Section 4.3.1). The UCFG1 register controls settings for the watchdog, reset, port reset state, brownout voltage, clock rate and oscillator. After programming, the micro was tested with the development board to verify correct operation by writing specific words on the input pins, to change the value of the respective PWM output channel.

The 20-pin plug at the tail end of the micro board connects the eleven input pins to the respective DAQ outputs PB0-7 and PC0-2 (refer Figure 3.4), and the four PWM outputs to the Level Shifter board. The power supply pins are connected to the +5VDC rail and digital ground of the DAQ card.

The operation of the entire motor control system was tested by incorporating the components as specified in Figure 2.21. Testing revealed unreliable speed control when the motors were powered, the PWM signal at the micro randomly lost or gained pulses, remained high or low, and worked intermittently. When the power to the motors was removed, the signal returned to the correct PWM duty cycle.

Investigation as to the cause revealed that voltage spikes were appearing randomly on the input pins of the micro when the motors were powered and running. These spikes caused the micro to read in digital words that were incorrect, changing the duty cycle of the PWM outputs. Due to the erratic nature of the noise, the motors were generally unresponsive to speed control signals. This was unacceptable and needed to be remedied.

The output signals from the PWM were isolated from the driving signal using opto-isolators, and a different power supply utilised to investigate if the source of the noise was due to the Motor Transformer. This did not improve the condition of the signals, as the noise was still coupled through the conductors. To rectify the voltage spikes on the input and output pins of the micro, de-coupling capacitors were added to every pin of the chip.

These improvements rectified the problem and a new board was constructed to incorporate the changes (refer Figure 3.7). A ground plane was added to further reduce motor noise. Extensive testing revealed no further problems and the micro board was placed into the ROV system. To further prevent interference due to radiated noise, the largest electrolytic and polyester capacitors that were able to fit onto the Motor Driver card were placed across GND, +70V and +140V at each of the 3-pin plugs, and across the Power Connector box (refer Section 5.3.2). These capacitors prevent large current draw through the conductors during switching, as they are able to supply some of the current needed, thereby reducing the radiated electric and magnetic fields.

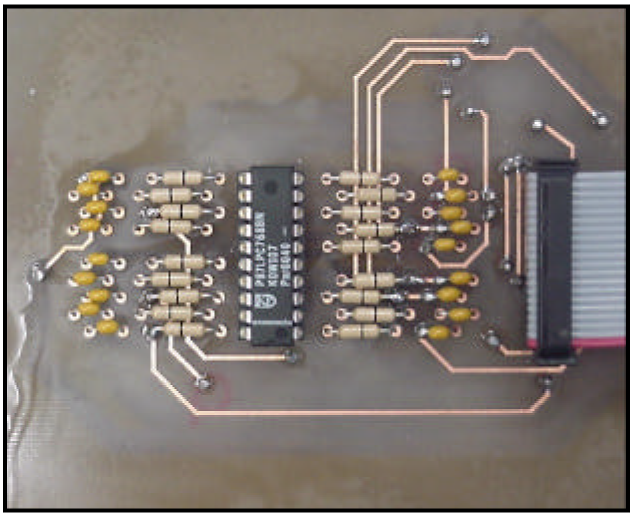


Figure 3.7 THE FINAL 87LPC768 MICROCONTROLLER BOARD.

3.6 LEVEL SHIFTER BOARD

The Level Shifter board translates the TTL outputs of the DAQ card and 87LPC768 micro into CMOS 0/15V levels for the Motor Driver card. The board uses two MC14504B hex non-inverting level shifters.

The MC14504B chip has six inputs and six outputs with two modes of operation. Mode one shifts TTL input logic levels to CMOS, and mode two shifts CMOS input logic levels to another CMOS level. Mode one is selected by connecting the V_{CC} pin to 5VDC and the V_{DD} pin to 15VDC. The DAQ card supplies the 5VDC, and the 15VDC comes from the Power Supply card. The ground of the Motherboard (and therefore the DAQ card) is referenced to the ground of the Power Supply card and Motor Driver card.

The Level Shifter board was made as compact as possible (refer Figure 3.8). Two 12-pin headers were used, one for inputs and the other for outputs, making testing simple. Heat-shrink is used to protect the connection between conductor and header-pin from shorts and breaks, and a ground plane helps to prevent noise from disrupting the signals.

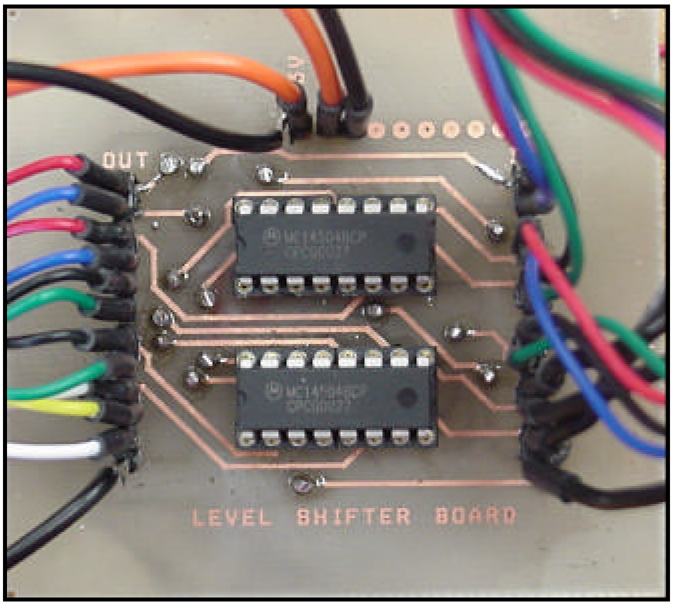


Figure 3.8 THE LEVEL SHIFTER BOARD

3.7 SENSORS

The ROV needs sensors to provide it with the ability to perform functions such as auto-depth and auto-heading. To allow for an auto-depth feature, the ROV has to have the ability to sense its current depth, hence requiring a sensor to measure the external water pressure. Likewise, an auto-heading feature relies upon the availability of information pertaining to the current course-direction of the ROV. If the ROV should be tipped or pushed over while underwater, it is essential to know the current attitude so it can be corrected for. To gather this information, the roll and pitch of the body must be known.

The two original sensors; the Compass and Pressure transducer provide simple navigational and depth information respectively. A Tilt sensor is added to the system to supply data concerning the roll and pitch of the ROV chassis.

3.7.1 Compass

The compass used in the DELPHINUS is shown in Figure 3.9.

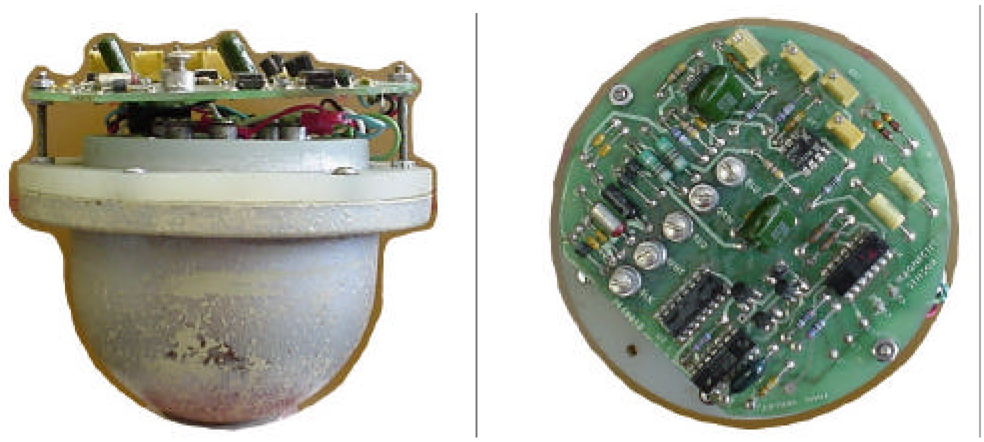


Figure 3.9 SIDE AND TOP VIEWS OF THE DC700 WESMAR FLUX-GATE COMPASS.

Upon salvage from the DART ROV, and after preliminary testing, the Compass proved to be in good working order, and was considered adequate for use in the new system.

Features of the DC700 Wesmar flux-gate Compass include:

- ? 1.5? accuracy
- “Saturable-core” all-electronic compass sensor
- Immediate response to directional change
- Automatic compensation for 80? pitch and roll
- Completely waterproof and lightweight

The flux-gate compass is a magnetic sensor that detects variations in the Earth’s magnetic field, and can convert these changes into various physical properties (including heading). Developed circa 1928, the flux-gate magnetometer is the most popular magnetic field sensing instrument. They have a wide range of applications including submarine detection, geophysical prospecting, and airborne magnetic field mapping.

3.7.1.1 Flux-Gate Theory

The Wesmar Compass uses a proprietary technique, but is likely to be very similar to the standard flux-gate sensing techniques. As shown in Figure 3.10, a primary coil and a secondary coil are wrapped around a high-permeability ferromagnetic core. When an external magnetic field is applied, the magnetic induction of the core changes. If a drive signal is applied to the primary winding, the core will oscillate between saturation points.

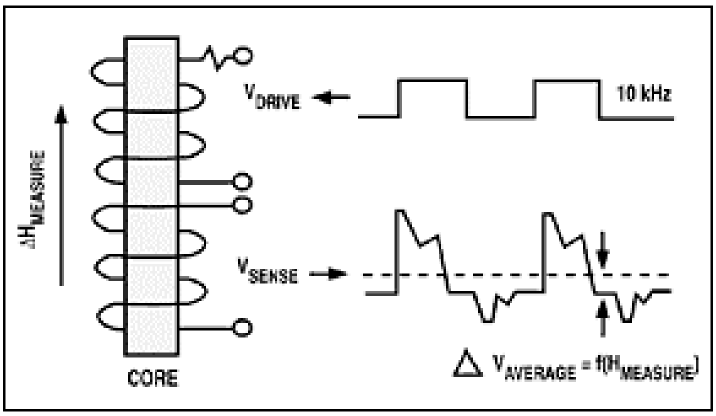


Figure 3.10 OPERATION OF A FLUX-GATE MAGNETOMETER [11].

Coupled through the core, the signal present on the secondary is affected by core permeability changes and this shows as a varying amplitude in the output of the sensing coil. The signal is then de-modulated and filtered to recover the value of the magnetic field.

3.7.1.2 Compass Power Supply

The Wesmar Compass uses a regulated ? 5VDC power source and has a maximum current consumption of 500mA. The analogue output signals are referenced to the Compass isolated ground of 0V [12]. Care must be taken NOT to connect the isolated ground of the Compass to the ROV ground.

The 15VDC from the Power Supply card is input to the Compass Power Supply board and regulated to 12V using a 7812 12V regulator (refer Figure 3.11).

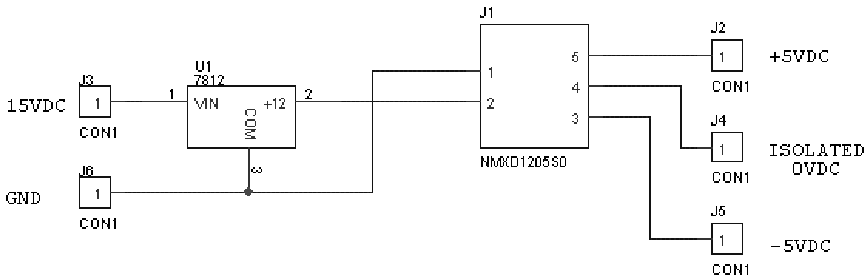


Figure 3.11 THE COMPASS POWER SUPPLY BOARD CIRCUIT.

A NMXD1205SO DC-DC Converter on the Compass Power Supply board converts the 12VDC to ?5VDC referenced to an isolated ground, and can supply up to 500mA. The NMXSO range of DC-DC Converters provide fully encapsulated DC supplies with 1kV isolation in a low-profile package. The Converter is short-circuit protected and no heat-sink is required, reducing the size of the board (shown in Figure 3.12).

The DAQ card is set up for eight single-ended analogue signals referenced to ROV ground (refer Section 3.3). Because the Wesmar flux-gate Compass uses an isolated supply, the output signals cannot be directly connected to the DAQ card.

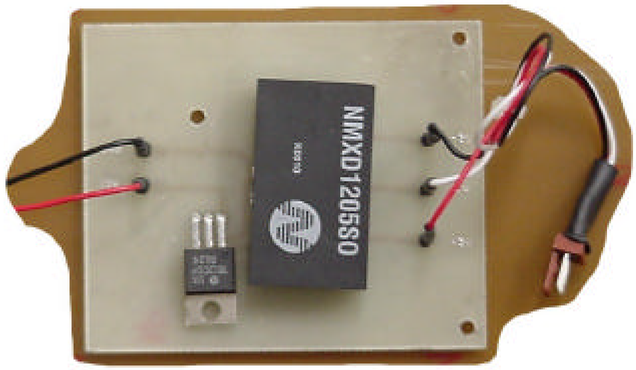


Figure 3.12 THE COMPASS POWER SUPPLY BOARD.

To allow the Compass outputs to be scanned by the DAQ card, a simple operational amplifier circuit is used (refer Figure 3.13). The Compass isolated 0V and cosine outputs are connected to the differential inputs of the first stage CA3240 BiMOS Operational Amplifier. The ?5VDC from the Compass Power Supply board allows the output of the amplifier to swing either positive or negative with respect to the ROV ground (GND).

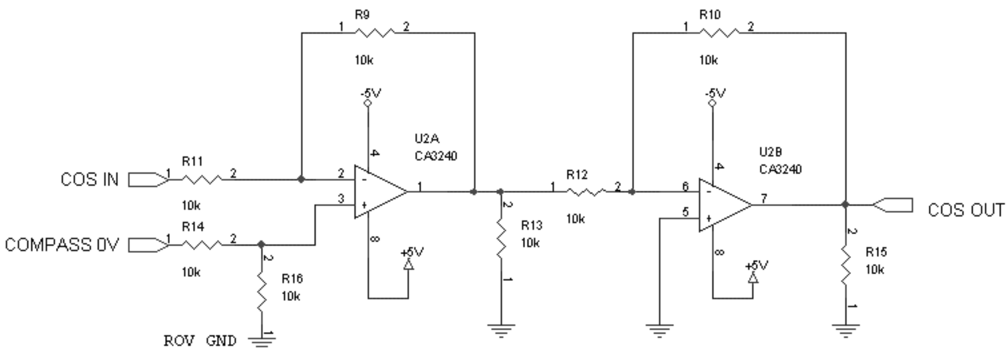


Figure 3.13 THE COMPASS OPERATIONAL AMPLIFIER CIRCUIT.

The difference between the two signals is presented at the output of the first stage amplifier. The inverting configuration of the amplifier means the output is 180? out of phase with the input, so a second stage is used to restore the original polarity of the Compass output signals.

An identical circuit is used for the sine output. The 10k? resistors restrict the gain to unity, and reference the Compass 0V output to GND. The complete circuit is made into a PCB board shown below in Figure 3.14. A ground plane reduces noise, and an eight-pin header connects ?5V, GND, cosine, sine and 0V, and allows the outputs to connect to the DAQ card.

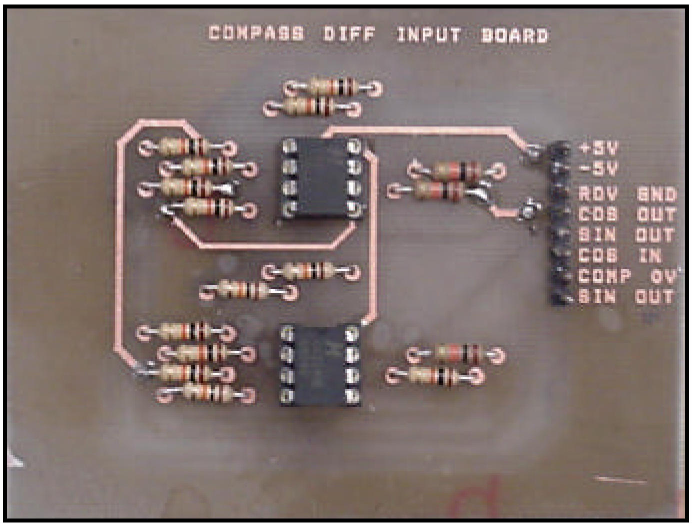


Figure 3.14 THE COMPASS DIFFERENTIAL INPUT BOARD.

3.7.1.3 Compass Calibration

The Wesmar Compass outputs two ? 1V analogue cosine and sine signals which allow the heading angle to be calculated. To ensure that the output voltages correspond to the correct heading, the Compass must be calibrated. By comparing the direction of the Wesmar Compass against the direction specified by a standard magnetic compass, adjustments can be made to the zero and span potentiometers of both the cosine and sine outputs to attain correct maximum and minimum measurements for the relevant directions.

Over 360?, the voltage of both the sine and cosine outputs are recorded at 10? intervals. The Compass is located at least 2m away from any metal object to reduce interference during testing. Results of these adjustments and measurements are shown in Figure 3.15. North direction corresponds to 0? and 360?, East to 90?, South to 180?, and West to 270?.

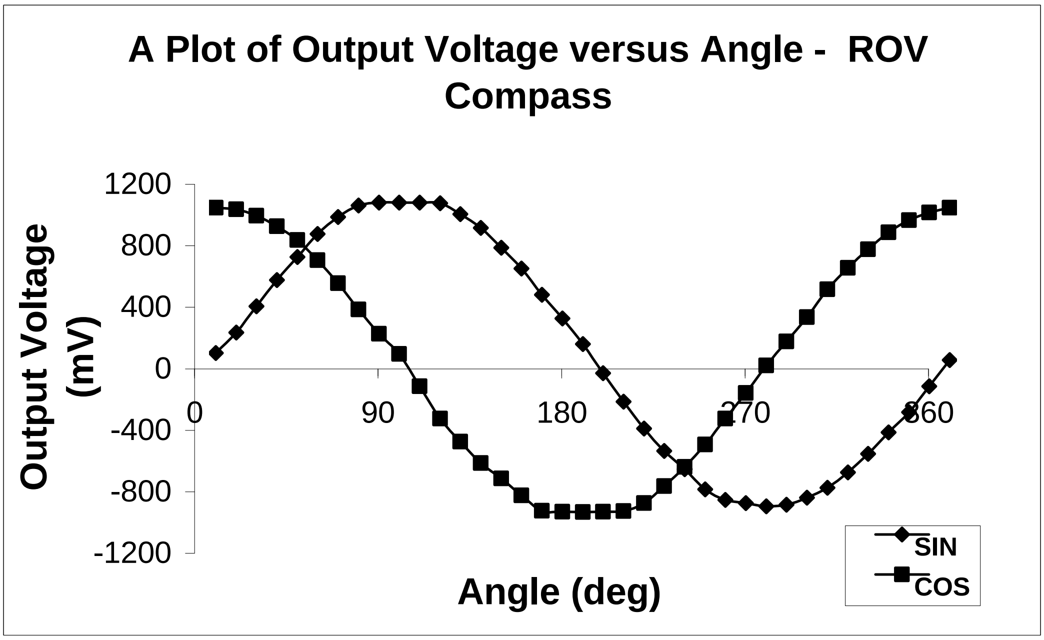


Figure 3.15 VARIATION OF THE SINE AND COSINE OUTPUTS OF THE DC700 WESMAR COMPASS WITH ANGLE.

The heading can be calculated from the sign of the output voltages as follows:

- cosine at 1 and sine at 0 means the heading is North
- cosine at 0 and sine at 1 means the heading is East
- cosine at -1 and sine at 0 means the heading is South
- cosine at 0 and sine at -1 means the heading is West

The exact angle of heading *H* is obtained by:

$$H = \tan^{-1}(abs(\frac{\sin}{\cos})) \qquad \textbf{EQUATION 3-1}$$

in the case when cosine is not equal to zero. If cosine is equal to zero, the angle is set to 90?. In both cases the angle must be converted into the correct quadrant based on the voltage sign (detailed in Section 4.2.2.1).

3.7.2 Pressure Transducer

The Bell & Howell High Output Pressure transducer (shown in Figure 3.16) was also a component of the original DART system, and is retained for use in the new system.

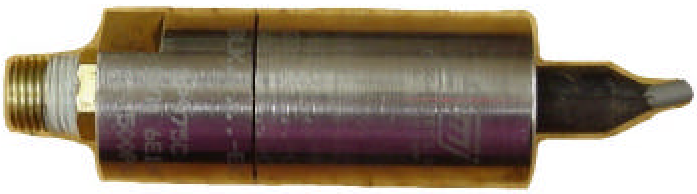


Figure 3.16 THE BELL & HOWELL HIGH OUTPUT PRESSURE TRANSDUCER.

Features of the transducer are:

- 0.25 % Accuracy
- 5VDC Full scale output
- 0 to 1000 PSI pressure range
- Stainless steel construction
- Temperature compensation
- Unregulated excitation from 12 to 30VDC
- 20mA Maximum current drain

The Bell & Howell transducer has the ability to sense pressure and transform it into an electrical signal, which is interpreted to give a depth reading in LabVIEW. The transducer also uses a proprietary technique, so an outline of the most common pressure sensing technique is given.

A stainless steel diaphragm internal to the sensor moves under the pressure of an external liquid. A diffused semiconductor beam is coupled to the diaphragm and on this beam is a four-arm strain gauge Wheatstone bridge which forms the sensing element [13]. To compensate for thermal transients, hysteresis, and nonlinearity, the semiconductor beam is isolated from the diaphragm by a force collector. A similar representation is shown below in Figure 3.17.

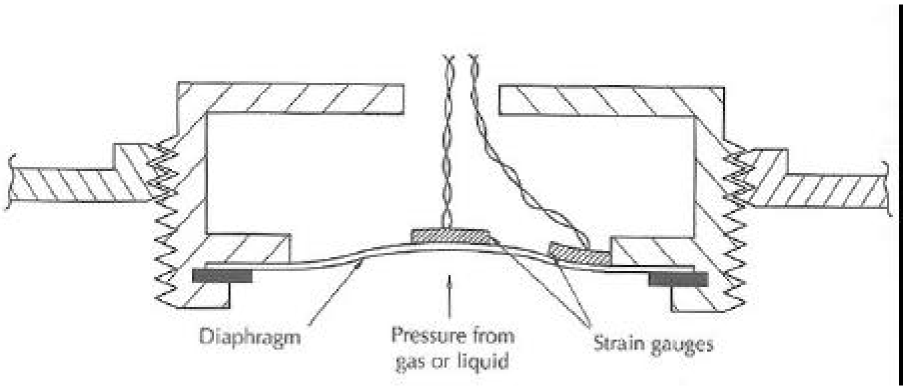


Figure 3.17 PRESSURE TRANSDUCER OPERATION [3].

3.7.2.1 Strain Gauge Theory

The strain gauge is an effective way of making precise measurements of small displacements [14]. This method uses the fact that the resistance in a simple cylindrical wire will change if a strain is applied to the wire within its elastic limit. The parameters (diameter, length, and resistivity) of a wire will change as strain is applied according to Equation 2-2.

A four-arm Wheatstone arrangement consists of four strain gauges in a bridge configuration. When an applied voltage excites the bridge, the pressure exerted deforms the four strain gauges and a changed output voltage can be measured due to the changing resistance of the bridge.

The bridge configuration has many useful features. Semiconductor devices are more sensitive than metal strain gauges, but they also are more vulnerable to temperature variation. A common method for temperature compensation is to use two gauges, one as the active measuring gauge, and one as a ‘dummy gauge’. Both gauges are under the same temperature conditions, but only one is under strain allowing temperature effects to be cancelled. The bridge configuration provides temperature compensation if all four gauges have the same coefficient of resistivity [14].

3.7.2.2 Pressure Calibration

The Pressure sensor is calibrated using the apparatus shown in Figure 3.18. The sensor is threaded into the left tube, and the kPa gauge is threaded into the opposite tube. In between is a reservoir of oil that, when compressed with the rotary handle at the front, provides the liquid that moves the diaphragm on the sensor. The same pressure is applied to the kPa gauge. The results of tests on the sensor are shown in Figure 3.19.

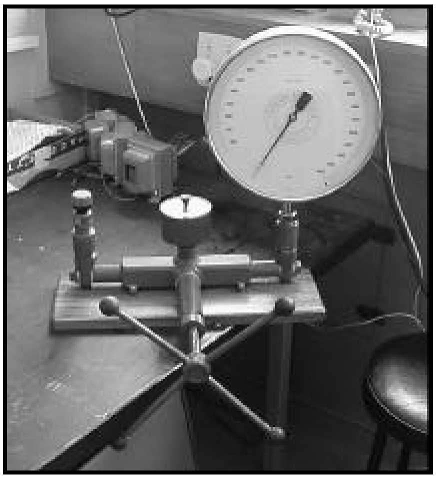


Figure 3.18 THE PRESSURE CALIBRATION APPARATUS.

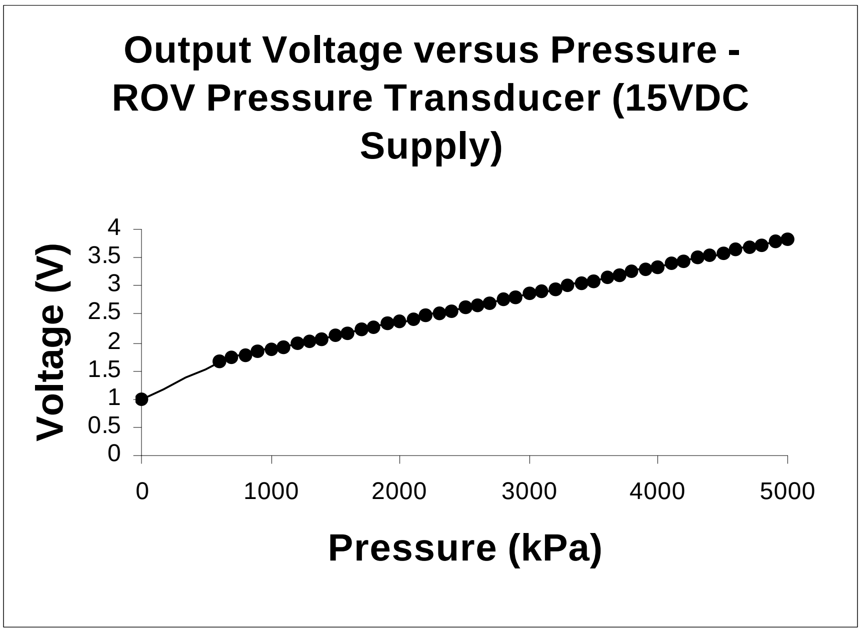


Figure 3.19 VARIATION OF THE BELL & HOWELL TRANSDUCER OUTPUT WITH PRESSURE.

The output voltage V of the transducer has a simple linear relationship with respect to pressure P in kilopascals as given by:

$$V \ ? \ mP \ ? \ C \qquad \textbf{EQUATION 3-2}$$

where:

m = gradient of Figure 3.19 = 5 ? 10^{-4} V/kPa
C = y-intercept of Figure 3.19 = 1.372 V

The pressure P is converted to a depth reading in Metres Undersea by [15]:

$$D \ ? \ \frac{(1000 \ ? \ P)}{9806.65} \qquad \textbf{EQUATION 3-3}$$

3.7.3 Tilt Sensor

The Crossbow CXTA02 Tilt sensor is a new sensor that has been added to the ROV system, and provides the ROV with roll and pitch information. The sensor is pictured below in Figure 3.20.

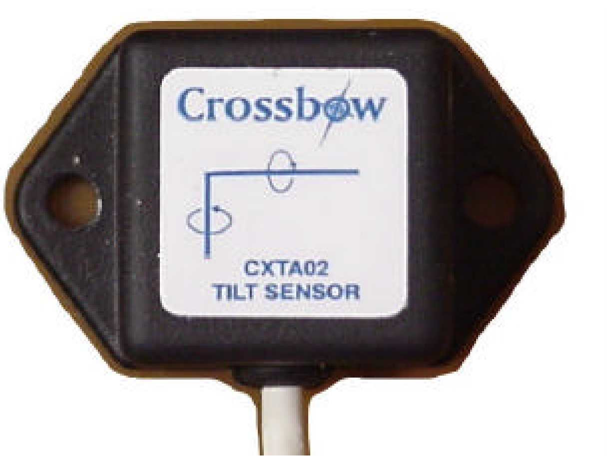


Figure 3.20 THE CROSSBOW CXTA02 TILT SENSOR.

Features of the CXTA02 include:

- 0.05?$_{rms}$ angular resolution
- ? 75? range over two axes
- Rapid response (0.2s settling time)
- Excitation voltage from 8 to 30VDC
- Fully conditioned analogue outputs
- Miniature dimensions: 1.91 ? 4.76 ? 2.54 cm

The Wesmar flux-gate Compass provides heading information for the ROV, also called yaw or the Z axis. The CXTA02 provides the ROV with information concerning the other axes of motion (X and Y), also called pitch and roll (refer Figure 3.21). The Crossbow sensor is chosen because it operates from a DC voltage, and requires no external signal conditioning components.

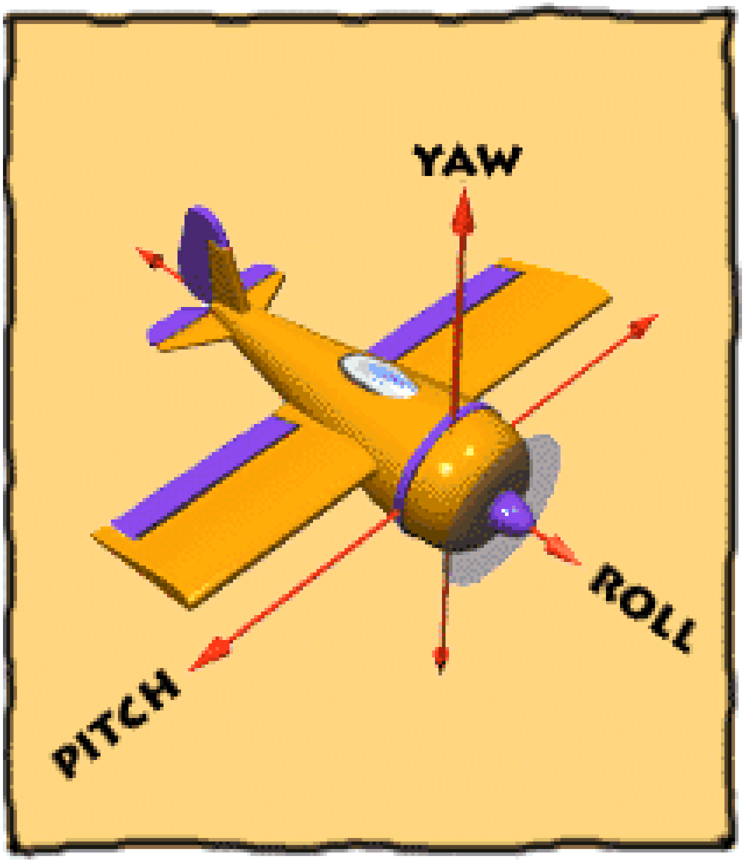


Figure 3.21 THE THREE AXES OF MOTION [15].

3.7.3.1 Principle of Operation

To measure the inclination of the sensor relative to gravity (refer Figure 3.22), a silicon micro-machined capacitive sensing technique is used.

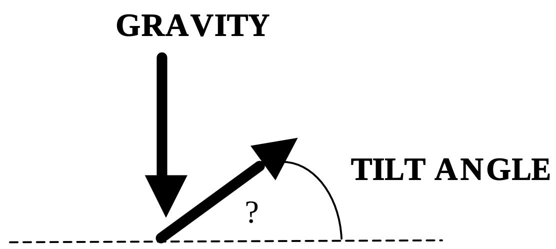


Figure 3.22 TILT ANGLE RELATIVE TO GRAVITY.

The CXTA02 uses a proprietary technique, but it is likely that internally the sensor is divided into two main parts, a micro-machined capacitive accelerometer, and custom integrated circuitry [17]. Inside the accelerometer a moving inertial mass is balanced, suspended by springs from a surrounding frame (refer Figure 3.23). A coating of metal is applied to the top and bottom surfaces of the mass, and the upper and lower surfaces of the frame. These four conductive surfaces produce a variable capacitance between them.

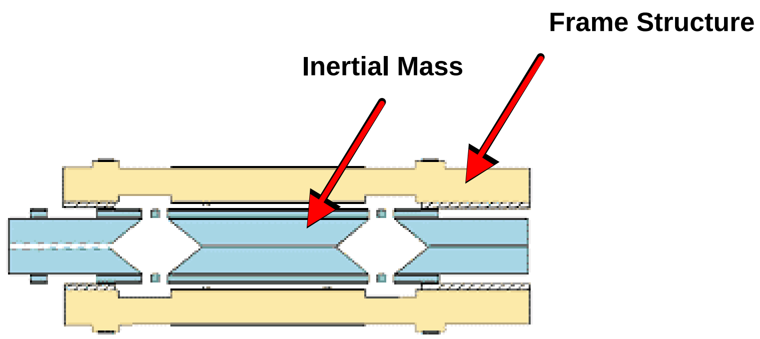


Figure 3.23 CROSS-SECTION OF A MICRO-MACHINED CAPACITIVE ACCELEROMETER [17].

The capacitance is varied by the magnitude of gravity parallel to the sensor. The changes in capacitance are sensed by the integrated circuitry, and conditioned into two signal voltages, roll and pitch. A restoring electrostatic force returns the mass to its original balanced position.

3.7.3.2 Tilt Calibration

The Tilt sensor is calibrated in the roll axis by measuring the angle of roll, with 0? being the point when the sensor is aligned with the roll axis. The sensor is tilted in positive 5? increments to the maximum tilt of 75? and the output voltage recorded. The sensor is also tilted in negative 5? increments from the zero axis to the maximum tilt of 75? and the output voltage recorded. The pitch axis is calibrated in a similar fashion. The results from testing the Tilt sensor are shown in Figures 3.24 and 3.25.

Documentation received with the sensor states that for angles less than 20?, there is a linear relationship between output voltage and tilt angle. An equation given allows the angle of roll and pitch to be calculated from the output voltages. For angles greater than 20?, the voltage response is proportional to the sine of the tilt angle.

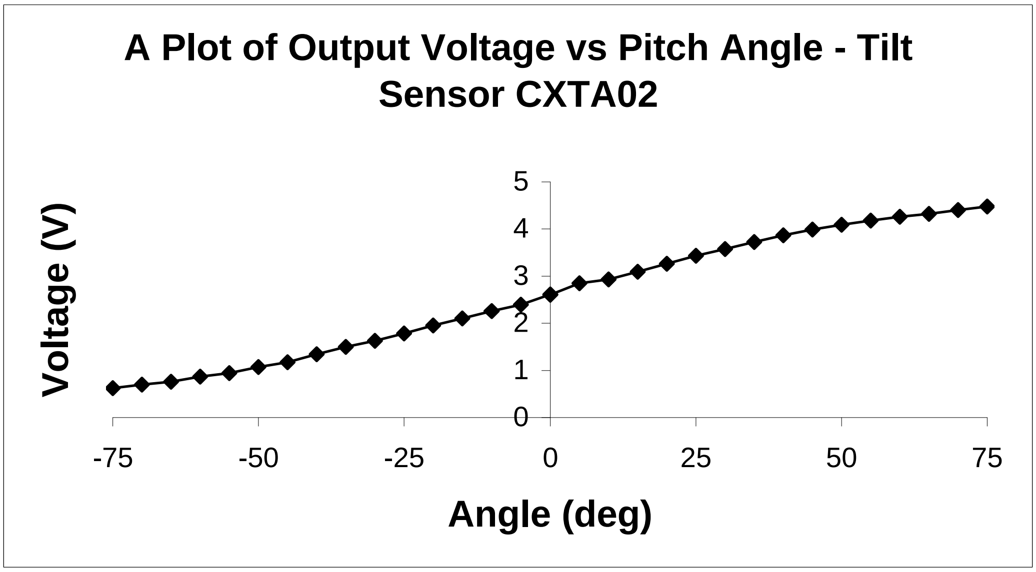


Figure 3.24 VOLTAGE RESPONSE OF THE CXTA02 SENSOR IN PITCH MOTION.

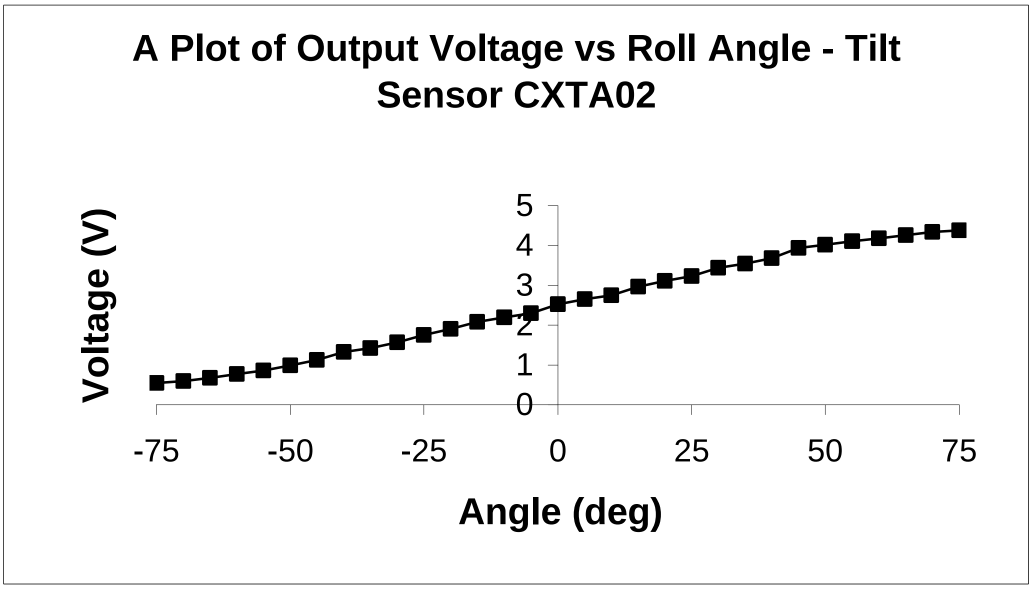


Figure 3.25 VOLTAGE RESPONSE OF THE CXTA02 SENSOR IN ROLL MOTION.

The tilt angle *T* in radians is given by:

$$T = \sin^{-1}\left(\frac{V_{out} - Z}{S}\right) \qquad \textbf{EQUATION 3-4}$$

where:

V_{out} = output voltage

Z = zero-angle voltage

S = sensitivity in V/rad

Exact values for the sensitivity and zero-angle voltage are obtained for each axis from the sensor documentation. The experimental results of Figures 3.24 and 3.25 agree well with the calculated values for pitch and roll.

3.8 CAMERA SYSTEM

At the heart of every ROV is a video camera. The pilot flying the ROV uses the video images to manoeuvre in a subsea environment. It also creates a record of work completed or undersea discoveries. To outline the advancements from the original video arrangement, it will be compared to the new system.

3.8.1 The Original Video System

Originally the main hull housed a Panasonic 1350A black and white video camera with Newvicon picture tube and automatic iris, all mounted within a pan and tilt unit.

The size of the camera meant it had to be disassembled into two parts. The camera lens, tube and video amplifier (refer Figure 3.26) were located in the main hull, while the camera control unit (refer Figure 3.27) was mounted in the port hull. A coaxial connection linked the video signal to the surface.

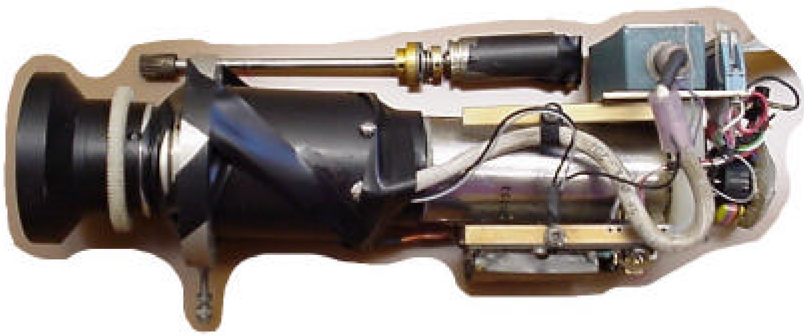


Figure 3.26 THE PANASONIC BLACK AND WHITE VIDEO CAMERA.

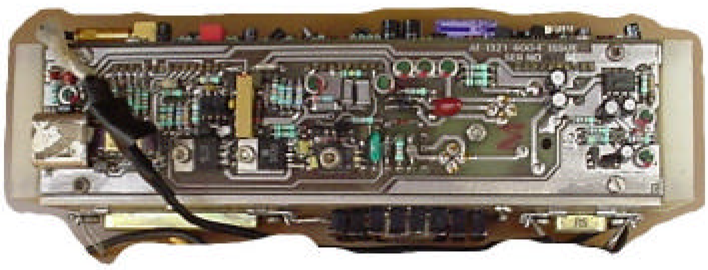


Figure 3.27 THE CAMERA CONTROL UNIT OF THE PANASONIC 1350A.

3.8.2 Original Pan and Tilt Control

The pan and tilt unit inside the main hull comprised two small ?8V DC motors in an aluminium frame. The pan motor turned a gear which rotated the aluminium frame left or right. The tilt motor worked similarly, but rotated a gear attached to a bracket, tilting the camera up or down. Potentiometers mounted on the pan and tilt unit provided feedback to the operator concerning camera orientation. The pan and tilt unit gave the camera a 75? conical viewing angle in two dimensions.

A 115V primary - 16V_{rms} centre-tapped secondary 8VA transformer situated in the port hull supplied power to the pan and tilt motors. The secondary was full-wave rectified to ?8VDC with respect to the centre tap. Positive or negative direction was controlled by one relay, and three other relays controlled which of the two motors was powered.

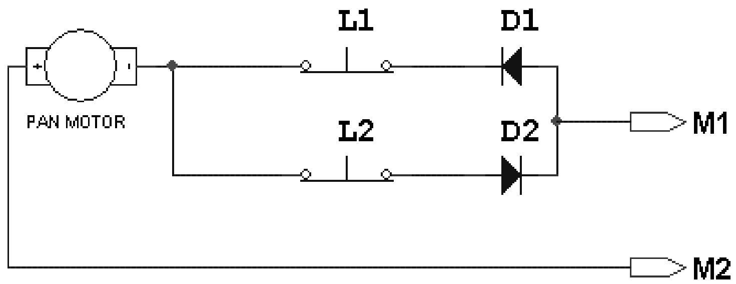


Figure 3.28 THE PAN MOTOR CIRCUIT TO PROTECT THE DC MOTORS.

The circuit shown in Figure 3.28 protected the pan motors from rotating too far. If M1 was positive with respect to M2, and current convention is used, the path of the current would flow through D1, L1 and the pan motor to M2. Once the maximum displacement was reached in that direction, the normally closed limit switch L1 was forced open, cutting off the current to the motor and stopping the movement. Two metal rods attached to each frame rotated with the camera pan and tilt unit and activated the limit switches.

Once the polarity of M1 and M2 were switched, the motor would begin to rotate in the opposite direction, releasing L1 to return to its normally closed position. Current now flowed back through the pan motor through L2 and D2 to M1 until the maximum displacement was again reached. The tilt motor had a similar circuit.

The limited size of the main hull ensures that components must be chosen to optimise space. A colour Philips USB camera is minute in size and weight, and provides the ideal replacement for the much larger original video system.

3.8.3 The New Video System

The new video system is greatly simplified with the use of a USB CCD camera. The camera output is connected directly to one of the four USB ports on the Motherboard, with the video displayed to the operator using Windows NetMeeting software. The camera is sensitive to a wide range of light levels, an essential feature in varying underwater lighting conditions.

Relevant specifications of the Philips USB camera are:

- ¼” CCD
- 640(H) ? 480(V) pixels
- 1 – 5000 Lux sensitivity
- Variable framerate
- Automatic image enhancement features; contrast, brightness, gamma, colour on/off, mirror image, backlight compensation, white balance, exposure control.

The Panasonic 1350A was dismantled and removed from the gold support bracket seen in Figure 3.29. This involved completely deconstructing the pan and tilt unit and video camera from the black aluminium hull cap. While the unit was apart, the gears used by the pan and tilt motors were cleaned and greased. The wiring between the potentiometers, limit switches and pan and tilt motors was replaced as the connections were deemed to be aged and unreliable. Heat-shrink was added to all connections for electrical protection and to give the wires mechanical strain relief.

The new wiring from the pan and tilt frame was collected at two points near the two potentiometers (refer Figure 3.29). A loop of wire was created to allow the frame to move in each direction to its maximum displacement. All the wiring was gathered into wire-wrap to ensure no wires were loose, and could be caught in the moving frame. The four potentiometer wires and the four motor wires were brought out to an 8-pin plug which connects to the new Camera Pan/Tilt Control board.

To mount the USB camera inside the pan and tilt unit, it was removed from its plastic outer shell to save space inside the hull. Due to the removal of the case, a new mounting system was designed to provide adequate protection to the uncovered electronics of the camera, and to hold the camera tightly in the gold frame when moved by the pan and tilt unit.

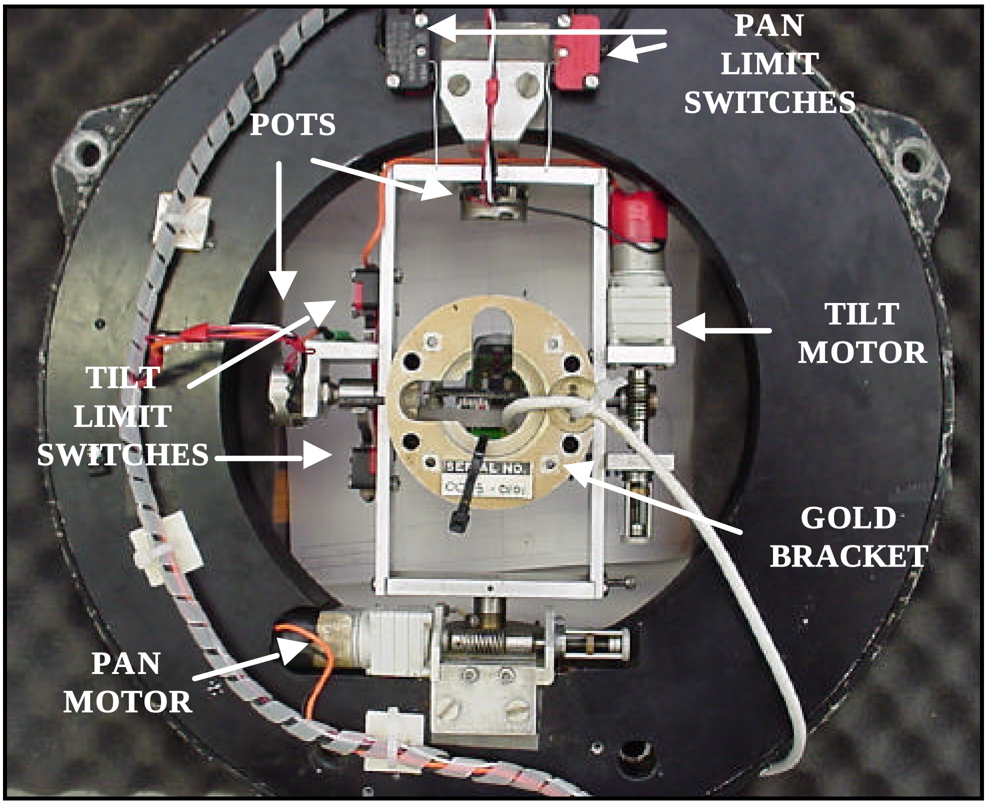


Figure 3.29 A REAR VIEW OF THE CAMERA PAN AND TILT UNIT.

A Perspex sheet was cut to fit in the slots of the existing gold bracket (refer Figure 3.30), and secured in place. The Perspex was shaped to fit the camera deep into the frame, with a hole cut to allow the USB cable to run out to the Motherboard.

The electronic board from inside the USB camera was drilled in three corners. These holes were fitted with nylon screws cut on an angle to isolate the board from the gold bracket, and secure it tightly for protection from vibrational disturbances in the video signal. The camera is shown in Figures 3.29 and 3.31 mounted in the frame. The motors and gears, limit switches and potentiometers of the camera pan and tilt unit are pictured in Figure 3.29.

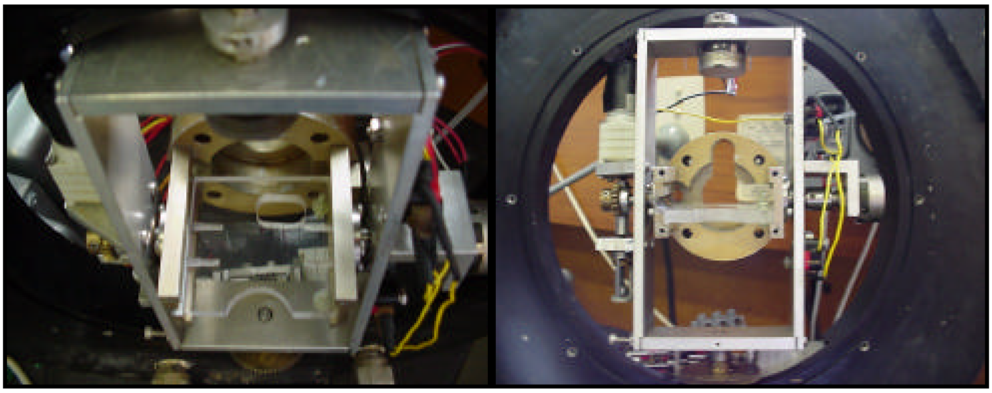


Figure 3.30 TWO VIEWS OF THE PERSPEX MOUNTING SYSTEM.

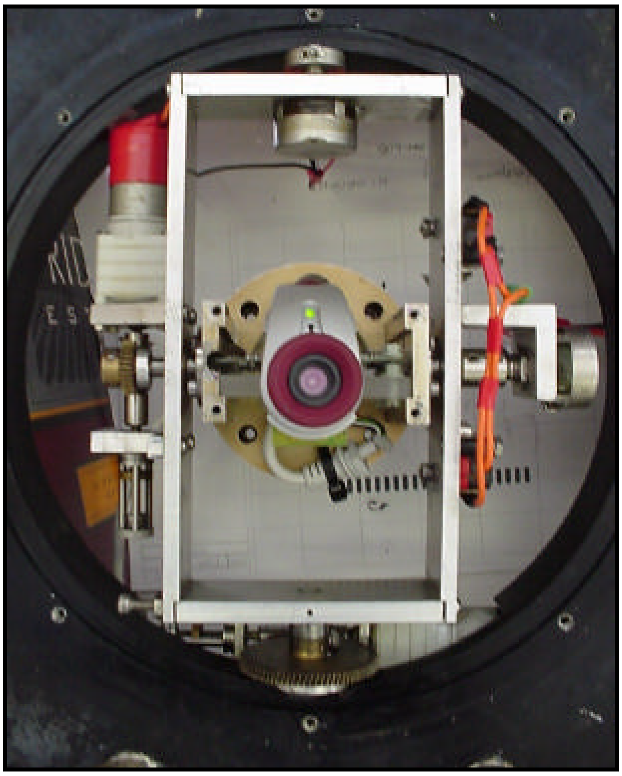


Figure 3.31 THE PHILIPS USB CAMERA MOUNTED IN THE PAN AND TILT FRAME.

3.8.4 New Pan and Tilt Control

An onboard system requires that the pan and tilt unit must be operable from digital signals. Specifically four digital signals are required to control up, down, left and right motion. The protection circuitry for the pan and tilt motors (refer Figure 3.28) remains in place.

Two L6203 DMOS Full-Bridge Drivers are chosen to control the direction of each motor. They are specifically designed for motor control applications of up to 48V at 4A, and have a TTL compatible drive.

Additional features of the L6203 Full Bridge Driver are:

- Cross conduction protection
- High efficiency
- Thermal shutdown

Within the internal circuitry of each of the L6203 Drivers are four power transistors in a bridge configuration. An internal charge pump maintains the charge on the bootstrap capacitors (refer C1 and C2 in Figure 3.32) allowing continuous operation of the high-side transistors. An enable line controls whether the driver is active, and two output pins allow the load (in this case the pan motor) to be attached.

If the driver is always enabled, a digital signal on the IN1 pin will cause the motor to turn in one direction. If the signal on IN1 is removed and applied to IN2 the motor will rotate in the opposite direction.

The pan motor circuitry is shown in Figure 3.32. Two digital signals from the DAQ card control the direction of the pan motor if the L6203 Driver is always enabled. The current drawn by each motor in the pan and tilt unit when moving the USB camera is approximately 300mA. To use the 15VDC supply from the Power Supply card, resistors are placed in series with the motors to limit the current to 300mA.

This circuit was constructed and tested for correct operation. An identical circuit was built for the tilt motor and both the pan and tilt circuits were incorporated into the Camera Pan/Tilt control board shown in Figure 3.33. A plug was used to connect the inputs, allowing easy removal of the card if a fault should occur.

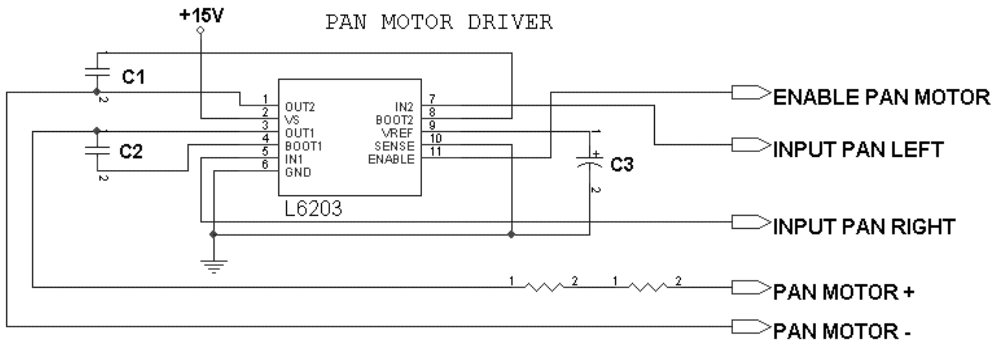


Figure 3.32 THE PAN MOTOR CONTROL CIRCUITRY.

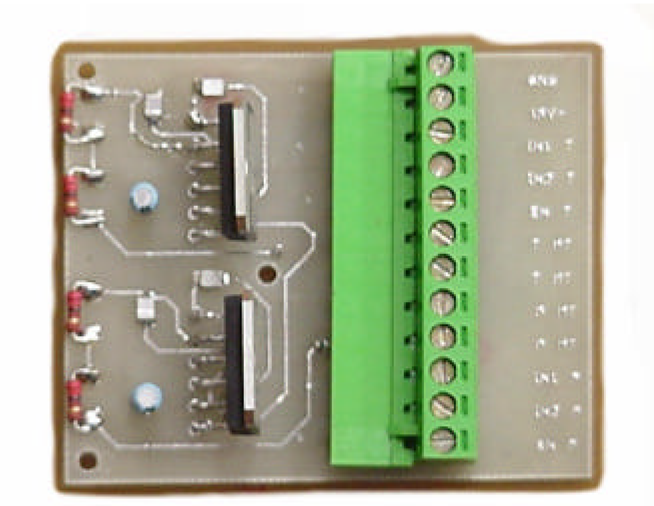


Figure 3.33 THE CAMERA PAN/TILT BOARD.

The new design of the pan and tilt control offers the following advantages over the original system:

✍✍Small robust design with few components.

✍✍Operates from the standard 15VDC supplied by the Power Supply card (a single central supply for all the electronics keeps the ROV system as simple as possible).

✍✍The Pan and tilt motors are easily controlled by four digital outputs from the DAQ card.

✍✍The PCB board is easily removable from the ROV

3.9 SURFACE COMPUTER

To communicate with the DELPHINUS ROV, a Toshiba laptop with a coaxial compatible network card is used. As the ROV is completely isolated from the mains, the surface computer must also be isolated.

Figure 3.34 THE TOSHIBA LAPTOP USED AS THE SURFACE COMPUTER.

A laptop provides a portable interface between the ROV and operator. The only software required for the surface computer is WinVNC virtual networking, which provides the link to the ROV onboard computer. Any changes to the LabVIEW software on the ROV computer can be directly implemented in the field through the laptop. The surface computer is pictured in Figure 3.34 running the DELPHINUS front panel (refer Section 4.2.1) of the ROV. The coaxial network connection can be seen situated to the left of the machine.

4. SOFTWARE

4.1 SOFTWARE OVERVIEW

Software must be developed to display the data from the sensors, and control the thruster motors and camera pan/tilt unit from the surface. This software must be alterable via the coaxial umbilical connection, allowing changes to be made while the ROV is in operation. The choice of software is important, as the display and control of the sensors, camera and motors must be easy to interpret and use.

The software environment LabVIEW? specialises in data acquisition, instrument control, and data logging, analysis and display. These features enable LabVIEW to provide the ideal control system for this application, the key advantage being the ability to build Virtual Instruments (VI), which can be used to replicate the physical appearance of controls and sensors.

LabVIEW uses a graphical programming language called ‘G’. Block diagrams are linked together to form programs instead of writing lines of code as in text-based languages. Extensive function and subroutine libraries are available for universal software development and support. Specially designed to build software in a modular fashion, each function can be developed separately and made into a sub-VI, for inclusion in a main control diagram. The DELPHINUS LabVIEW software is thus developed in sections: sensors, motor control and camera control.

The analogue voltages from each sensor are read by the analogue to digital converter of the DAQ card, converted into a calibrated value and displayed to a front panel. The sensor software is then built upon to include control of the four thruster motors.

On/Off control, and propeller direction and speed must be able to be manipulated from the front panel. The On/Off and Direction controls utilise eight DAQ digital outputs, and via the Level Shifter board (refer Section 3.6) are input to the Motor

Driver card. The speed of each thruster is output to the 87LPC768 microcontroller as four multiplexed 11-bit words, via eleven digital outputs on the DAQ card (refer Section 2.8.2). The four digital camera controls use a further four outputs (refer Figure 3.4).

The final stage of software development is for the 87LPC768 microcontroller. To read in and interpret the 11-bit words to control each of the four PWM output channels, software is developed in ‘C’ via a P8xLPCx emulator. The software is downloaded into an actual 87LPC768 microcontroller via a P8xLPC76x programmer. The four PWM outputs of the 87LPC768 (via the Level Shifter board) are input to the Motor Driver card to switch the main power to the thrusters.

4.2 DELPHINUS LABVIEW SOFTWARE

The software control system is explained in a top-down approach, beginning with the front panel used to control and monitor the ROV. The front panel is the display for the readings from the sensors, video, and the controls for camera direction and thruster motors.

4.2.1 The Front Panel

The DELPHINUS front panel (shown in Figure 4.1) is created in software and is the interface the ROV operator sees and interacts with. The sensors are displayed on the left; the **Depth** indicator moves a slider up or down depending on the depth of the ROV, the **Heading** indicator displays the current direction and the **Roll** and **Pitch** indicators display the attitude of the vehicle (the needles are centred when the ROV is balanced).

The four arrow shaped buttons, located above the video image from the USB camera, control the camera pan and tilt. They turn green when pressed, return to a red colour if released, and are active only when green. This action allows the operator to adjust the viewing angle of the camera to point in any direction.

Microsoft Windows NetMeeting displays the video image from the camera; the image window is set to remain "always on top" so it does not disappear when the panel controls are changed.

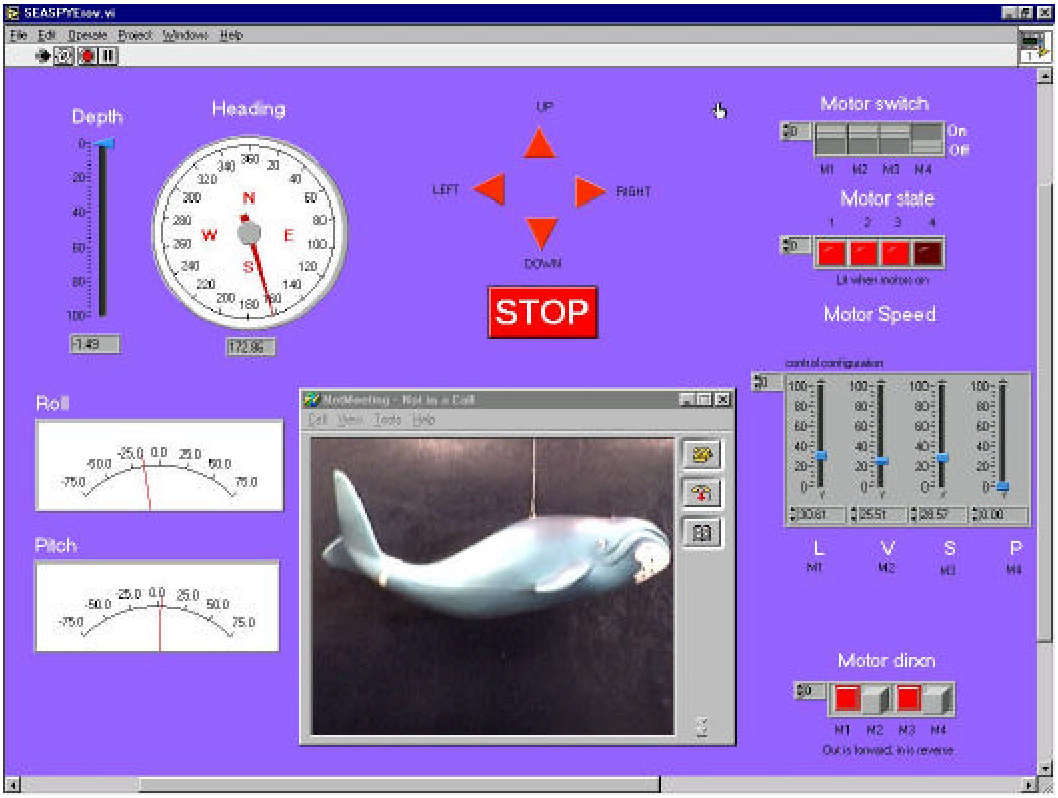


Figure 4.1 THE DELPHINUS FRONT PANEL.

The ROV thrusters are controlled by eight switches and four sliders located on the right side of the panel. The four switches labelled **Motor Switch** control the on/off status of each motor. If a switch is turned on, 5V is output by the DAQ card on the respective line of an output port. The LEDs labelled **Motor State** reflect the status of the switches.

The four sliders labelled **Motor Speed** control the duty cycle of each PWM output on the 87LPC768 microcontroller, 0 being equivalent to a 0% duty cycle and 100 being 100%. The **Motor Dirxn** buttons toggle the direction of each motor.

To develop an overall control system, the software is developed in sections. Separate programs are developed to read in the analogue voltages from the

Compass, Pressure sensor and Tilt sensor and translate each into a meaningful form.

4.2.2 Sensor Software

The development of software for the DELPHINUS ROV began with the creation of Virtual Instruments (VI) to read and display the analogue data from the sensors onboard the ROV.

The Data Acquisition (DAQ) card provides either eight single-ended (referenced to ROV ground), or four differential analogue inputs as detailed in Section 3.3. Although differential inputs are preferred for common-mode rejection of noise, five differential inputs would be needed to read in the two Compass outputs, the two Tilt outputs and the Pressure sensor. Therefore the signals are all referenced single-ended. The sensors are located within the port hull and junction box of the ROV to reduce the interference of noise (refer Sections 5.3.3 and 5.4.1), so it is deemed unnecessary to use differential inputs for sensors other than the Compass.

4.2.2.1 Wesmar Flux-Gate Compass

The hardware configuration of the Wesmar flux-gate Compass is shown in Figure 4.2. The Power Supply card provides 15VDC to the Compass Power Supply board. The Compass Power Supply board supplies the Compass with ?5V with respect to an isolated 0V. The isolated signals from the Compass are referenced into analogue Channels 2 and 3, through a Differential Input board (refer Section 3.7.1.2).

As discussed in Section 3.7.1.3, the DC700 Wesmar flux-gate Compass outputs two ?1V analogue signals: cosine and sine. The DAQ card reads in the sine and cosine voltages, which are accessed via LabVIEW. The software algorithm to convert the two voltage signals from the Compass into a heading angle is adapted from [12] and is given in Figure 4.3.

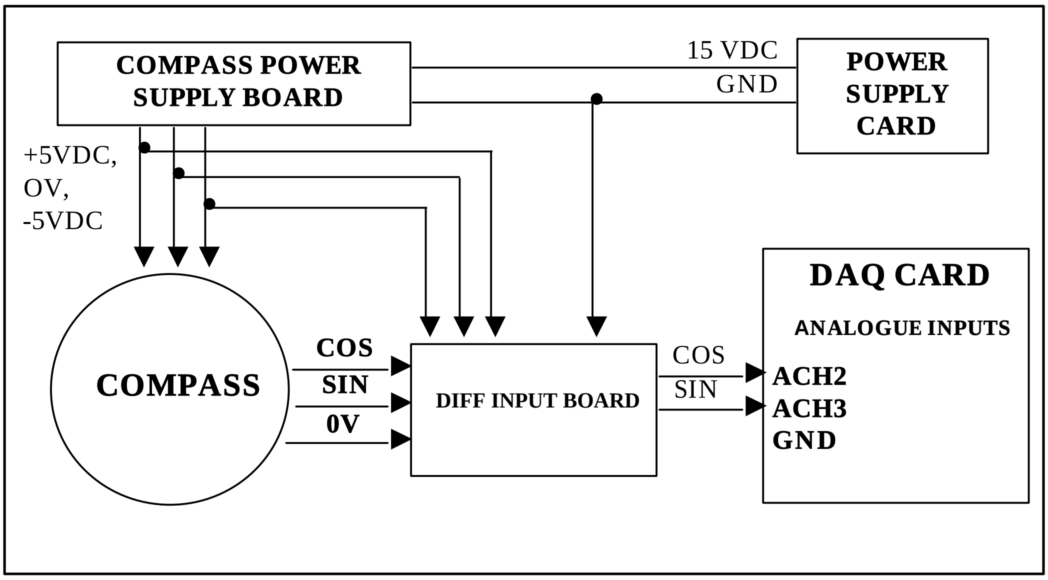


Figure 4.2 COMPASS SENSOR HARDWARE CONFIGURATION.

In LabVIEW the equivalent software routine is implemented and shown in Figure 4.4. Inside the program three Case-structures are used. The Case structure executes different code based on a Boolean true or false input parameter, equivalent to the if-else statements of the text-based code in Figure 4.3.

The two values `SIN` and `COS` are input to both Case-structures 1 and 2. Case-structure 1 is the equivalent of lines 1 through 5 of the C-code. It will output one of two values to Case-structure 3; if `COS` is equal to zero, the true case will execute (not shown) and output the value 90. If `COS` is not equal to zero, the value output is equal to the inverse tangent of the absolute value of `SIN` divided by `COS`.

Case-structures 2 and 3 implement lines 6 through 18 of Figure 4.3, finding which quadrant the Compass heading is in based on the sign of the signal.

If `SIN` is greater than zero, the true case (not shown) checks whether `COS` is greater than zero. If so, Case-structure 3 will pass the value from Case-structure 1 directly to the output `COMPASS`. If the value of `COS` is less than zero, the output of Case-structure 1 is subtracted from 180, before passing to the output variable `COMPASS`.

```
If Cosine <> 0 Then //Convert Sine & Cosine to an Angle 0-360
    Angle = Arctan(Abs(Sine/Cosine))
Else
    Angle = 90.0
End

If Sine > 0 Then //Convert into the correct quadrant based on sign
     If Cosine > 0 Then
         Angle = Angle + 0
     Else
         Angle = 180 – Angle
     End
Else
     If Cosine > 0 Then
         Angle = 360 – Angle
     Else
           Angle = Angle + 180
     End
End
```

Figure 4.3 THE COMPASS ALGORITHM IN C CODE.

If `SIN` is less than zero, `COS` is checked to determine if its value is greater than zero, if it is, the value output by Case-structure 1 is subtracted from 360. If not, 180 is added to the value before being output to `COMPASS`.

The algorithm for the compass is made into a sub-VI (the equivalent of a sub-routine) called **COMPASS** (shown in Figure 4.5). It has two inputs (`SIN` and `COS`) and one output (`COMPASS`).

A front panel indicator **Heading** is custom made to display the output of the COMPASS sub-VI, as shown in the front panel of Figure 4.1.

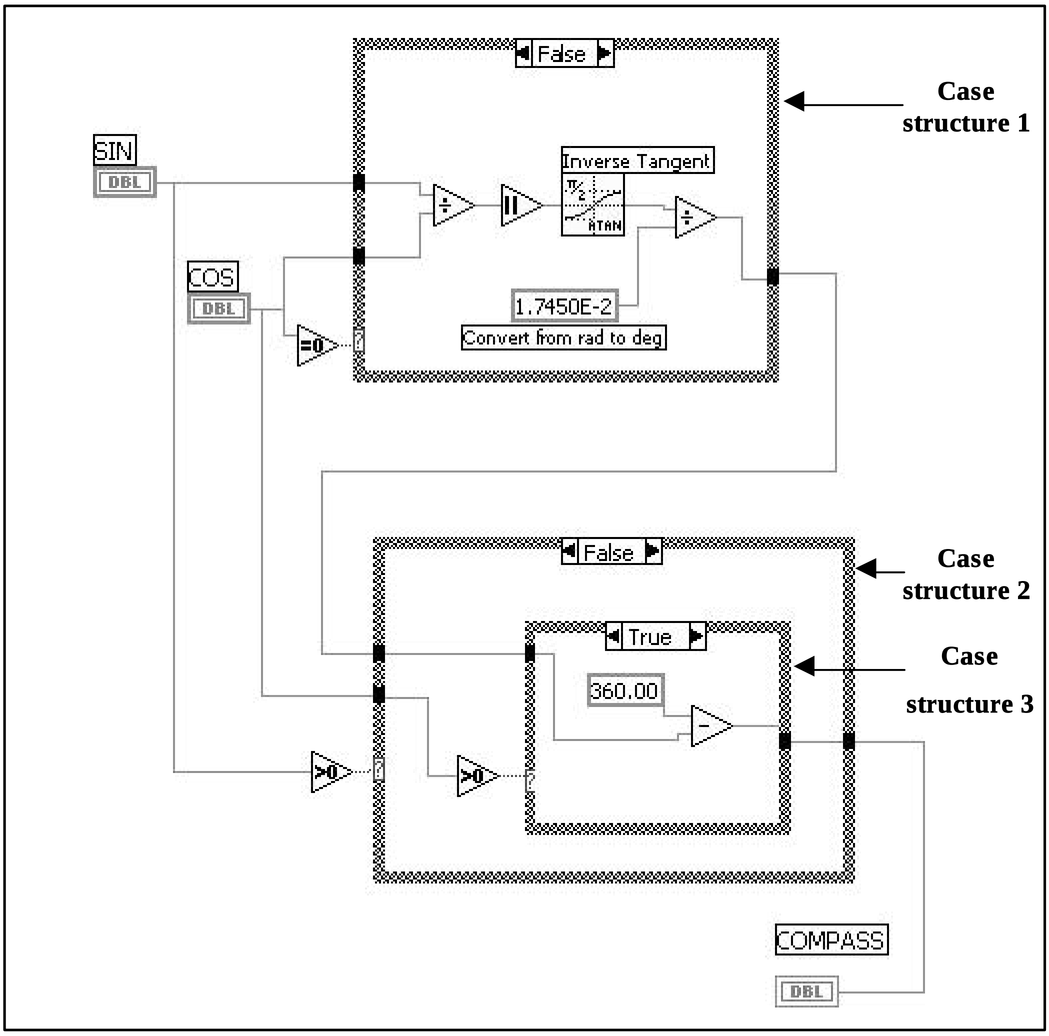


Figure 4.4 THE LABVIEW PROGRAM FOR THE WESMAR COMPASS.

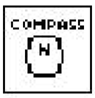


Figure 4.5 THE COMPASS VI.

4.2.2.2 Bell & Howell Pressure Transducer

The hardware configuration of the Bell & Howell Pressure transducer is outlined in Figure 4.6.

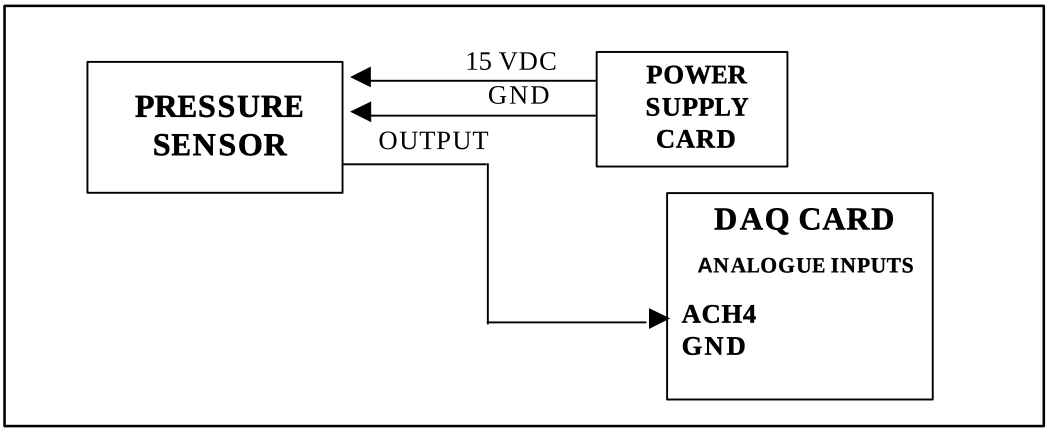


Figure 4.6 PRESSURE SENSOR HARDWARE CONFIGURATION.

The Power Supply card provides the Pressure transducer with a 15VDC excitation voltage, and the output signal is connected directly to analogue Channel 4 of the DAQ card. Data from the calibration results of Section 3.7.2.2 are used to develop the program shown in Figure 4.7.

The pressure algorithm uses a single Case-structure. At one atmosphere pressure (the ROV at the surface), the Pressure transducer outputs approximately 1V (refer Figure 3.19). If the output voltage of the Pressure transducer is less than or equal to 1V, the true case (not shown) outputs the value zero.

If the voltage is greater than 1, the false case computes the pressure P in kilopascals which is given by:

$$P = \frac{(V - 1.372)}{5 \times 10^{-4}} \qquad \textbf{EQUATION 4-1}$$

as detailed in Section 3.7.2.2.

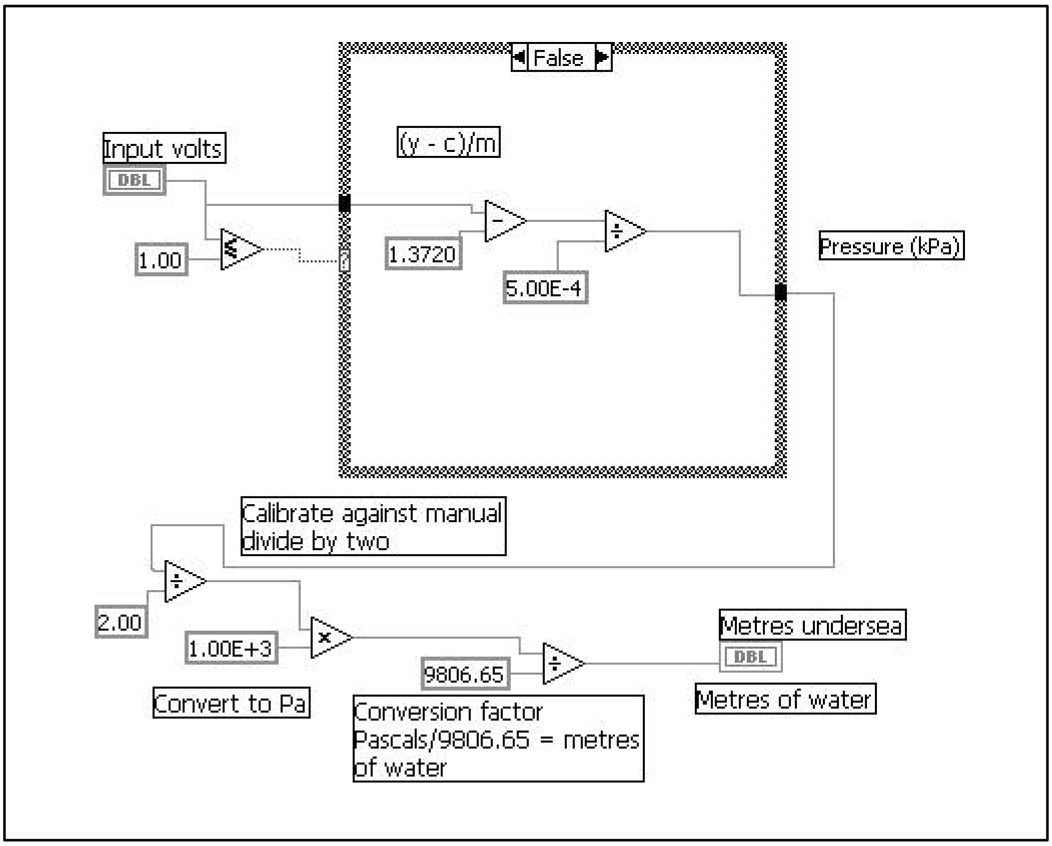


Figure 4.7 **THE LABVIEW PROGRAM DEVELOPED FOR THE PRESSURE TRANSDUCER.**

To calibrate with expected depth values for the Bell & Howell transducer from [13], the output from the Case structure is divided by two, and converted from kPa to Metres Undersea (refer Equation 3-3). The algorithm for the Pressure transducer is made into a sub-VI called **DEPTH** (shown below in Figure 4.8). It has one input (`Input volts`*)* and one output (`Metres undersea`).

Figure 4.8 **THE DEPTH VI.**

A front panel indicator **Depth** is made to illustrate the current depth of the ROV and is shown in Figure 4.1.

4.2.2.3 CXTA02 Tilt Sensor

The hardware configuration for the CXTA02 Tilt sensor is shown below in Figure 4.9.

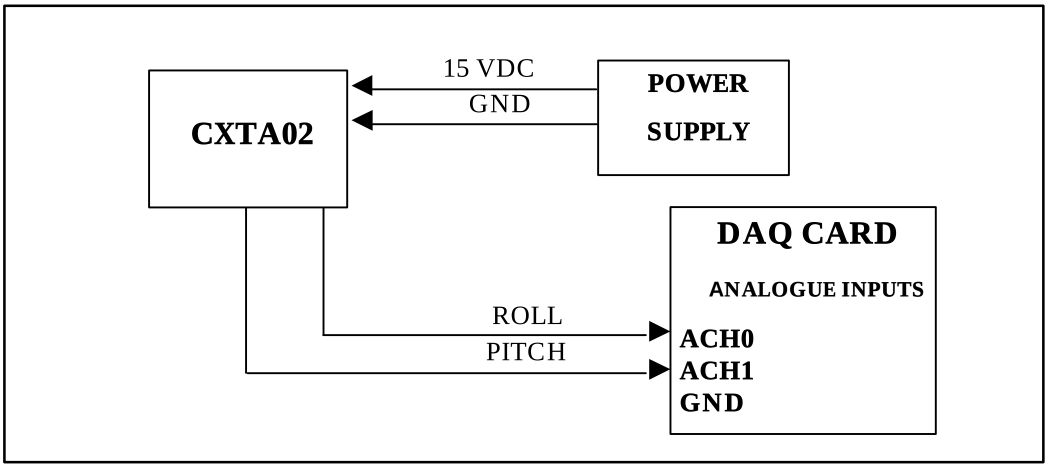


Figure 4.9 **TILT SENSOR HARDWARE CONFIGURATION.**

The CXTA02 Tilt sensor outputs two voltages, Roll and Pitch. These outputs are connected to analogue Channels 0 and 1 respectively, with each voltage proportional to the sine of the tilt angle (refer Section 3.7.3.2).

The program developed in LabVIEW is shown in Figure 4.10. A formula node is used to execute the required mathematical formulas, for the roll angle and the pitch angle.

A calibration sheet received with the CXTA02 gives exact values for the zero-angle voltage and the sensitivity for both the pitch and roll axes. Every variable used in the equations is input to the formula node. The angle in radians for both axes are computed and then multiplied by 180/? to convert to degrees.

This program is made into a sub-VI called **TILT SENSOR** shown in Figure 4.11. It has two inputs (`Pitch`, and `Roll`) and two outputs (`Pitch 2`, and `Roll 2`).

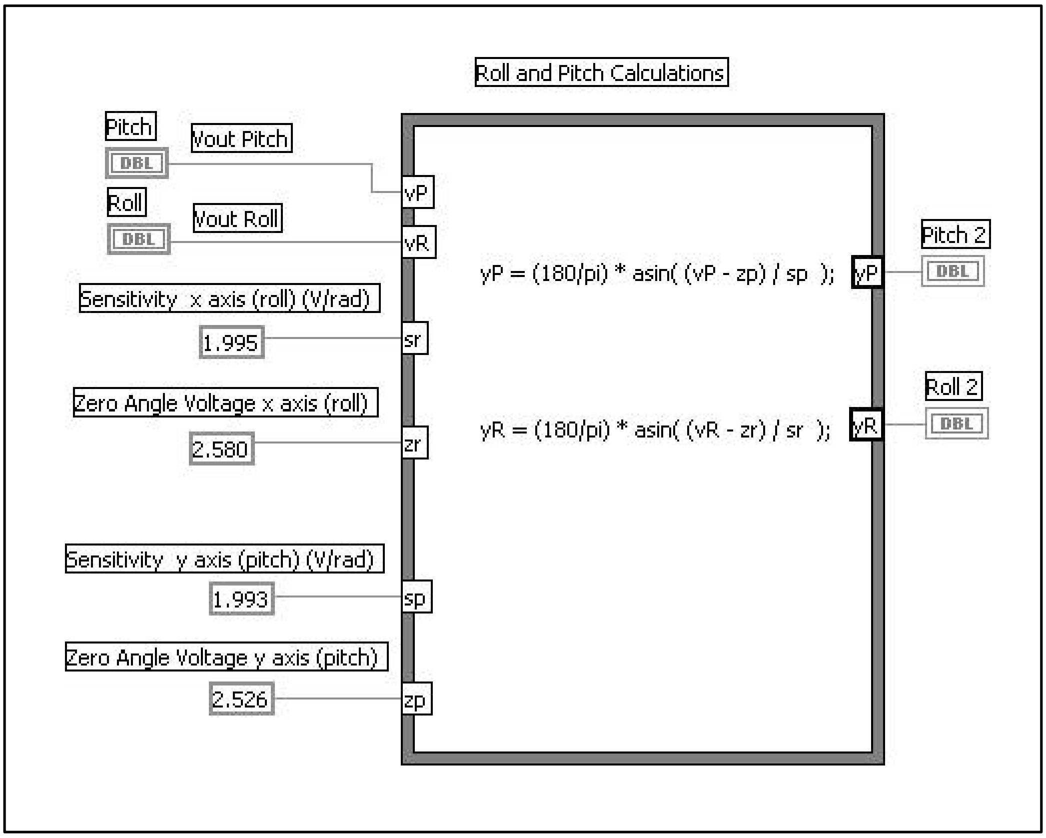


Figure 4.10 THE LABVIEW PROGRAM DEVELOPED FOR THE CXTA02 TILT SENSOR.

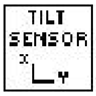


Figure 4.11 THE TILT SENSOR VI.

Two front panel indicators, **Roll** and **Pitch**, display the attitude of the vehicle and are shown in Figure 4.1.

4.2.3 Motor Software

To control each of the four ROV motors; four digital On/Off bits, four digital Direction bits and four multiplexed 11-bit words must be created and controlled by the front panel (refer Section 2.8).

4.2.3.1 Motor Direction and On/Off Control

Eight switches on the front panel (refer Figure 4.1) labelled **Motor Dirxn** and **Motor Switch** control the Direction and On/Off bits respectively for each motor. An LED panel called **Motor State** indicates which motors are on by illuminating the respective virtual LEDs.

The LabVIEW main program contains a while loop (refer Figure 4.12) which continues to run until the **STOP** button on the main panel (refer Figure 4.1) is pressed. Outside of the while loop a sub-VI called **Port Config** is used to establish a channel-configuration for port 0 (Digital Port A of Figure 3.4), which is an 8-bit port used to write the motor On/Off and Direction controls to the Motor Driver Card. **Port Config** only runs once to set up the port to write and tell the computer the memory location of the DAQ card.

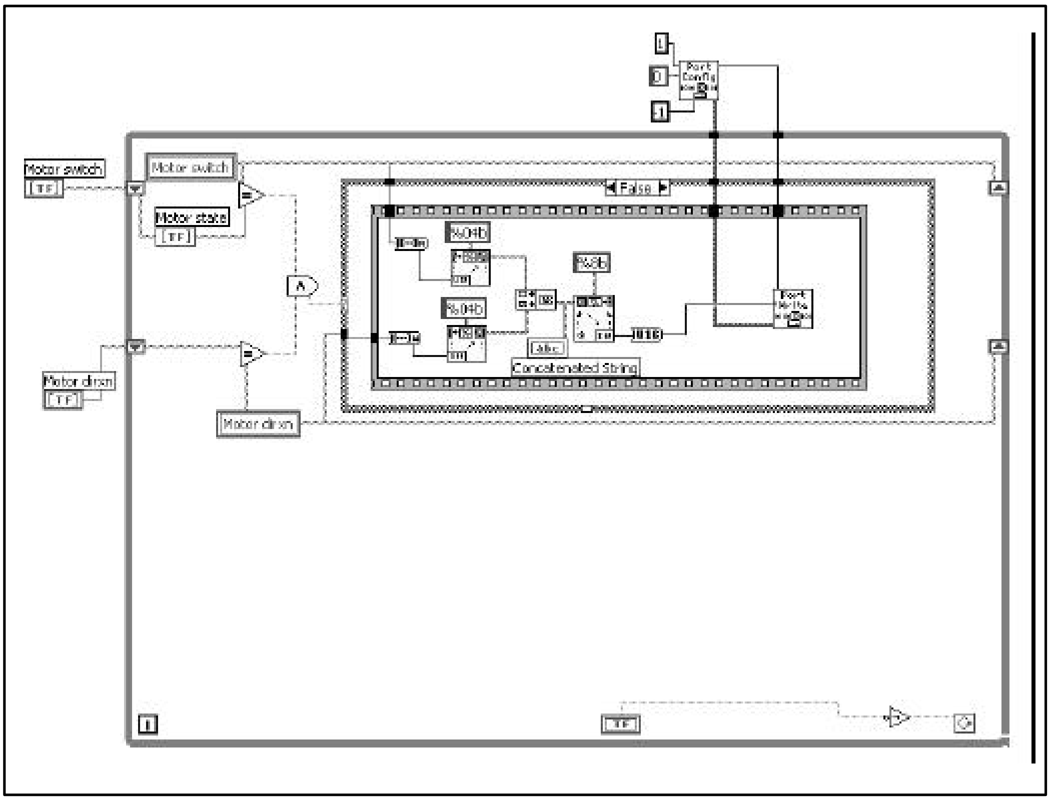


Figure 4.12 DIRECTION AND ON/OFF CONTROL SOFTWARE.

During the first iteration of the loop, the saved configuration of each switch from the **Motor Switch** and the **Motor Dirxn** front panel controls are stored in two arrays called **Motor Switch** and **Motor Dirxn** respectively. These arrays each contain four Boolean values relating to whether each switch is on or off (TRUE OR FALSE). The **Motor Switch** array is displayed by the **Motor State** LEDs on the front panel.

Each array is also stored in a shift register, which transfers the values from the completion of one iteration of the loop to the start of the next. At the start of every loop the array is compared with the values from the last iteration. If they are not equal, the case structure inside the while loop executes the false case.

In the false case, each array is converted from four Boolean values into a four-bit binary string. The two binary strings are then concatenated into an eight-bit binary string, converted into an unsigned integer and written to Digital Port 0.

In the true case when none of the **Motor Dirxn** or **Motor State** switches have been toggled, Port 0 will hold the values previously written.

4.2.3.2 Motor Speed Control

Four sliders on the front panel are used to control the speed of each thruster motor (refer Figure 4.1).

The LabVIEW main program incorporates another case structure inside the while loop (shown in Figure 4.13). The On/Off and Direction control Case-structure is removed for simplicity. Outside of the loop, Ports 1 and 2 (Ports B and C in Figure 3.4) are configured to write by using the **Port Config** sub-VI. Port 1 is an eight-bit port used to output the PWM duty cycle. Port 2 outputs the two Motor ID bits, the Valid Data bit and the four digital camera control bits.

Control Configuration contains four integer values in an array corresponding to the value of each slider. This array is also stored in a shift register. A Not-Equal operator compares the array from the last iteration with the current array and creates an array called **Motor?** consisting of four Boolean values with each element set to TRUE if they are not equal.

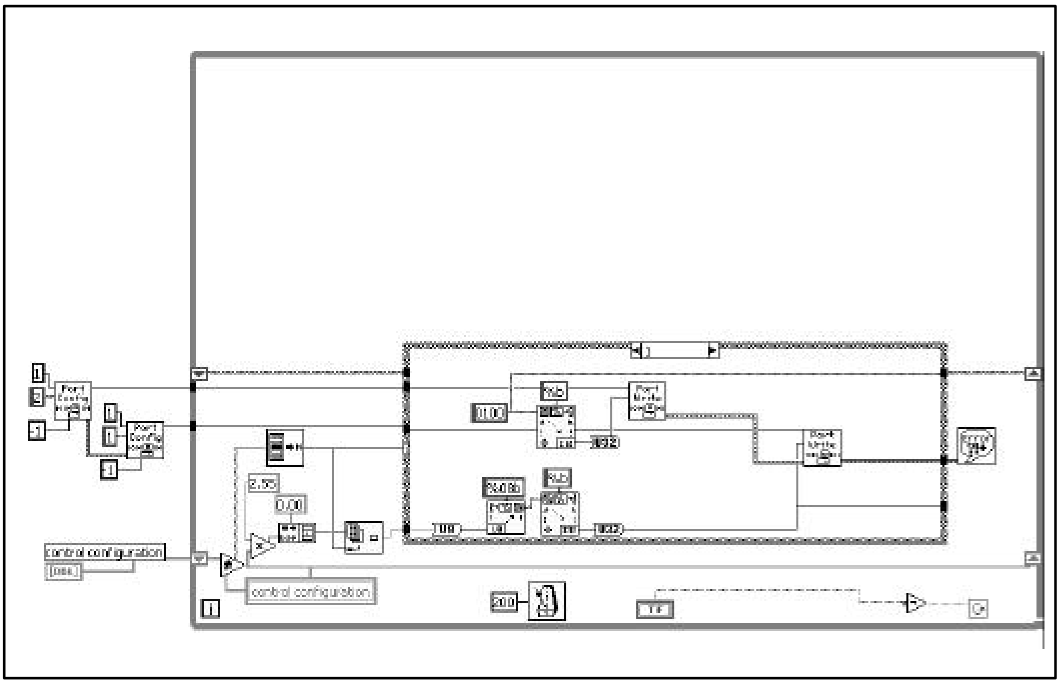


Figure 4.13 THE MOTOR SPEED CONTROL PROGRAM.

A sub-VI called **Which Button** searches through the **Motor?** array and returns the ordinal number of the first element set to TRUE (the motor that has changed speed). If the first motor has changed speed, **Which Button** will return **1**, if the second motor has changed it will return **2**, etcetera, returning **0** if none are true. The index of the motor value set to true is input to an index-array function and the case structure. The case structure has five different cases to execute depending on this value.

The **Control Configuration** array is multiplied by 2.55 to increase the range from 0? 100 to 0? 255, and has the value 0 appended to the start of the array. This is done so the element number returned by the **Which Button** sub-VI will cause the index-array function to access the correct element in the **Control Configuration** array. The value in the element specified is passed to the case structure.

If the lateral motor (L or motor 1) slider has been changed, the value **1** will be returned by **Which Button** and input to the case structure, which will execute Case 1.

Case 1 converts the value from the **Control Configuration** array accessed by the index-array function, into an 8-bit unsigned long integer which is input to the **Port Write** sub-VI and written to Port 1. A null bit, the Valid Data bit and the Motor ID number (in this case the sequence 0100) is concatenated with the four bits used to control the camera direction (refer next Section), and is converted to an 8-bit unsigned long integer before being written to Port 2.

Case 2, 3 and 4 control the vertical, starboard and port motors respectively. They function identically except for the changed Motor ID bits.

In the case where no speed change has been made to any motor, the **Which Button** sub-VI will return the value zero as explained earlier. This causes the case structure to execute Case 0, as shown in the lower region of Figure 4.14. Case 0 (the default case) controls the direction of the camera, and reads in the analogue sensor data.

4.2.4 Camera Control and Sensor Display

The four arrow buttons on the front panel manipulate the camera direction control (refer Figure 4.1). The four buttons become TRUE when pressed, and FALSE when released. All four are concatenated in an array before conversion to a four-bit binary string, and are concatenated with the null bit, Valid Data bit and Motor ID bits. The concatenated 8-bit string is converted to an unsigned 8-bit integer and written to Port 2.

The analogue input port is configured outside of the loop by the **AI Config** sub-VI, which specifies the memory location of the DAQ card, and allocates a buffer for the analogue information from channels 0 to 4. The **AI S-Scan** sub-VI performs a single scan of the channels into an array. Five index-array functions are used to access the five data values which are input to the respective sensor sub-VIs and displayed on the front panel.

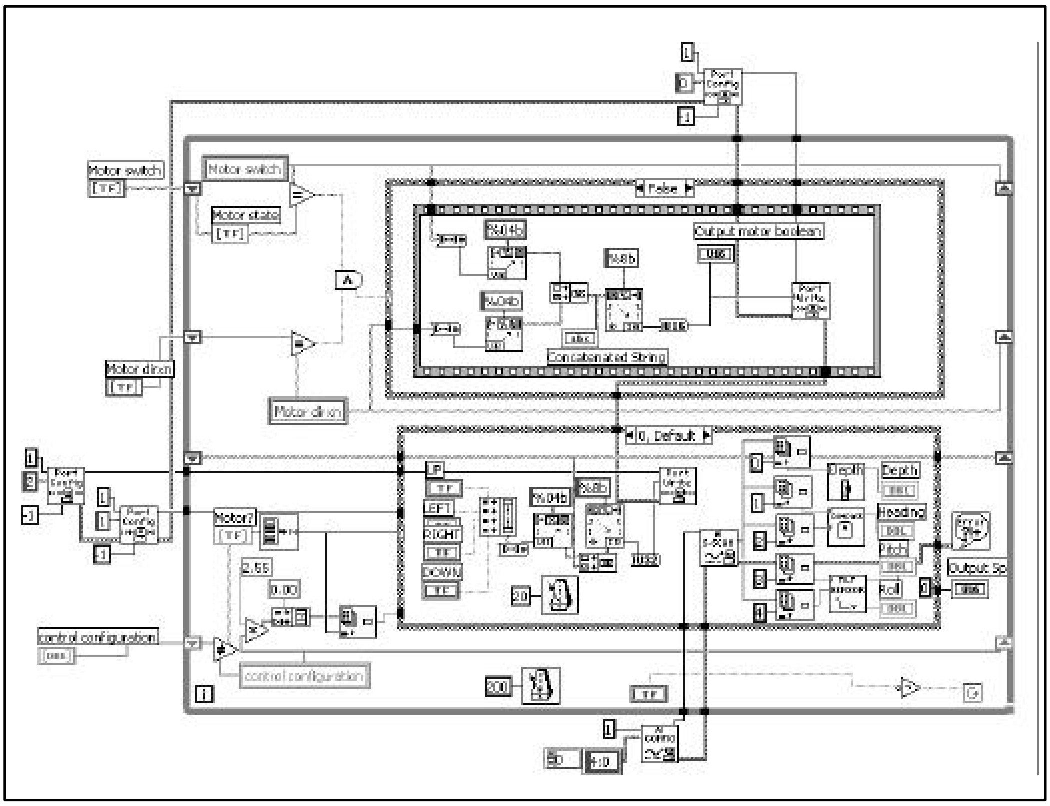


Figure 4.14 THE DELPHINUS MAIN PROGRAM.

To improve the performance of the program, delay timers are added inside the lower Case-structure 0 and inside the while loop of the main program. When **AI S-Scan** is called, the sub-VI waits until the next scan of the specified channels is acquired before returning. This action ties up CPU time, and the other VI's that are running will be slowed down or perform intermittently. A delay timer reduces this problem and allows the other sub-VI's to execute normally during the delay time [18].

A general error handler sub-VI **Error** tells the operator if, what, and where an error has occurred within the **Port Config**, **Port Write**, **AI Config** and **AI S-Scan** sub-VIs.

Central to the front panel, a major **STOP** button is located. This writes all the digital output lines to zero after the while loop completes the current iteration (not shown in Figure 4.14).

To control the motors, the four multiplexed 11-bit words must be converted into four PWM signals. To achieve this, the 87LPC768 microcontroller is programmed to read in the words and convert them into four individual PWM duty cycles.

4.3 87LPC768 SOFTWARE

The 87LPC768 microcontroller translates the 11-bit multiplexed digital words from the DAQ card (refer Figure 3.4) into four individual PWM outputs. The 11-bit words are read into the micro via eleven digital inputs on two ports. Each 11-bit word (refer Figure 2.24) contains information on the duty cycle for one of its four PWM output channels.

The 87LPC768 is a One Time Programmable (OTP) microcontroller. To limit the wastage caused by programming chips with defective code, and to decrease development time, a P8xLPC76x emulator is used to develop the necessary software (refer Section 3.5.2).

The 87LPC768 micro has a total of three I/O ports, Port 0, Port 1 and Port 2. Ports 0 and 1 are 8-bit ports and Port 2 is a 2-bit port.

To read in the 11-bit word from the DAQ card, the digital I/O port bits are assigned as shown in Figure 4.15. There are four motors to control on the ROV and therefore all four PWM channels will be used. This leaves a total of three unused I/O pins; Port 2, bit 1 (P2.1), P2.0 and P1.0. The valid data bit is read by P0.2, the Motor ID bits are read by P0.2 and P0.4. The MSB of the PWM value is read by P0.5, proceeding to the LSB which is read by P1.5.

VD	MID		PWM							
			7	6	5	4	3	2	1	0
P0.2	P0.3	P0.4	P0.5	P0.6	P0.7	P1.1	P1.2	P1.3	P1.4	P1.5

Figure 4.15 ASSIGNMENT OF THE ELEVEN BIT WORD.

The 87LPC768 microcontroller has many features as described in Section 3.5.1. To perform digital to PWM conversion, the 87LPC768 is configured in software.

4.3.1 Configuring the 87LPC768

Internal to the 87LPC768 micro, the configuration of the UCFG1 register controls the following functions:

- CPU clock rate selection (6 or 12 CPU clocks per machine cycle)
- Watchdog enabled/disabled
- External reset pin enabled/disabled
- Port rest state high/low
- Brown out voltage
- Oscillator selection, external 20kHz to 20MHz or internal 6MHz

In the device set-up inside the emulator software, the 87LPC768 micro is selected and the UCFG1 register set to:

- A clock rate of 6 CPU clocks per machine cycle. This allows the program to be executed as fast as possible to read in the multiplexed words from the DAQ card.
- Watchdog enabled. The external reset pin is used as a digital input so a reset must be activated by software. A reset is essential if the program should fail for any reason.
- External reset disabled. See above explanation.
- Ports reset high. The quasi-bidirectional output is driven weakly when high, so if the DAQ card writes the input pins low, the micro is safely pulled low.
- Brown-out detect voltage at 2.5V.
- Internal RC oscillator, 6MHz.

4.3.2 87LPC768 Program Code

The 87LPC768 program first declares the special function register addresses and variables used in the code. The special function registers include:

- ✍✍I/O Ports 0 to 2
- ✍✍Counter shadow registers 0 to 4
- ✍✍Compare shadow registers 0 to 4
- ✍✍PWM control registers 0 and 1
- ✍✍Clock divide register DIVM
- ✍✍Watchdog timer control and reset registers

Once the special function registers are declared, the next task is to set the value of the PWM frequency of the microcontroller.

4.3.2.1 Setting the PWM Frequency

The 87LPC768 micro creates four individually controlled duty cycles for the Motor Driver card. The Motor Driver card is designed for a PWM frequency of 50Hz. To achieve correct switching of the Motor Driver card, the PWM frequency of the micro must be set to 50Hz.

The PWM frequency of the 87LPC768 is given by:

$$f_{PWM} \ ? \ \frac{F_C}{(CNSW \ ? \ 1)} \qquad \textbf{EQUATION 4-2}$$

where:

F_c = CPU clock frequency

$CNSW$ = value of the Counter Shadow registers

CNSW is a 10-bit register, therefore the maximum value it can be is 1023. If *CNSW* is set to its maximum value and f_{PWM} is to be 50Hz, F_c must be equal to 51200Hz, which rounds up to 52kHz.

The internal RC oscillator set by the UCFG1 register sets F_c to be 6MHz. The DIVM register internal to the micro is able to divide the CPU clock by:

$$2 ? (N ? 1) \qquad \textbf{EQUATION 4-3}$$

where *N* is the value of the DIVM register. The value of the DIVM register is set to 56 by:

```
DIVM = 0x38;  // Set CPU clock to be divided down to 52kHz
```

The value of CNSW is contained in two 8-bit registers. Bits 0 to 7 are located in the CNSW0 register, and bits 8 and 9 are located in register CNSW1. The counter value is set to 1023 by:

```
CNSW0 = 0xFF;    // Set shadow counter register
CNSW1 = 0x03;    // to maximum
```

4.3.2.2 Watchdog Control

To ensure the program code never stalls the micro, utilising the watchdog function allows for a reset option. The watchdog is initialised by:

```
WDRST = 0x1E;    // first part of watchdog feed sequence
WDRST = 0xE1;    // second part of watchdog feed sequence
WDCON |= 0x07;  // set 2.1 sec watchdog delay
```

This code sets the watchdog to the maximum value of 2.1 seconds before the program is reset. The delay value of 2.1 seconds is chosen to ensure the program has enough time to execute before any reset is enabled.

The program must continually poll the eleven input pins to read the multiplexed values of the duty cycle for each channel. To perform the digital to PWM conversion and continually poll and change the PWM values as required, the inputs must be read and written inside a while loop.

4.3.2.3 Digital to PWM Conversion

A while loop is used to read in the values of the eleven input pins. If the valid data bit is high, the micro will place the 8-bit PWM duty cycle into the appropriate Compare Shadow register specified by the Motor ID bits. The value of the valid data bit is read in by:

```
valid_data = (P0 & 0x04);
```

This sets an unsigned char variable `valid_data` to the value of P0.2 by performing an AND operation between port 0 and the hex value 4, with `valid_data` taking the value 4 if P0.2 is high. If the `valid_data` bit is high, the program will execute code to read in the values of the Motor ID pins and the PWM duty cycle. If `valid_data` is low, the program will continuously feed the watchdog.

In the case when `valid_data` is high, the code in Figure 4.16 concatenates the 8-bit PWM value from the digital inputs of the micro into two unsigned chars, `PWM_1` and `PWM_2`.

```
PWM_1 = (((P0 & 0x20) >> 4)+ ((P0 & 0x40) >> 6));
PWM_2 = ( (P0 & 0x80) + ((P1 & 0x02) << 5)+ ((P1 & 0x04) << 3)
        + ((P1 & 0x08) << 1)+ ((P1 & 0x10) >> 1)
        + ((P1 & 0x20) >> 3));
```

Figure 4.16 CODE TO READ IN THE PWM DUTY CYCLE.

PWM_1 stores the most significant bits of the PWM value (refer Table 4-1). An AND operation between the hex value 20 and port 0 accesses P0.5. This value is shifted by 4 bits to place it in bit 1 of PWM_1 (refer line 5, Figure 4.16).

Similarly P0 is ANDed with the hex value 40 to access P0.6, the value of P0.6 is then shifted by 6 bits to place the value in bit 0 of PWM_1.

PWM_1: Bits 7-6 of PWM duty cycle

7	6	5	4	3	2	1	0
unused	unused	unused	unused	unused	unused	P0.5	P0.6

Table 4-1 PWM_1 CONTENTS.

PWM_2 stores bits 0-5 of the PWM value. Each bit is read in and stored as described above (refer lines 6-8 in Figure 4.16) to fill PWM_2 with the values of the input pins as shown in Table 4-2.

PWM_2: Bits 5-0 of PWM duty cycle

7	*6*	*5*	*4*	*3*	*2*	*1*	*0*
PO.7	P1.1	P1.2	P1.3	P1.4	P1.5	unused	unused

Table 4-2 PWM_2 CONTENTS.

The 8-bit PWM value must then be read into one of the four PWM Control registers, the selection of which is specified by the Motor ID bits.

To read into a specific PWM Control register, the value of the duty cycle must be stored in the appropriate Compare Shadow register. The value in each Compare Shadow register is transferred to the relevant PWM control register when an underflow occurs in the counter.

The 87LPC768 microcontroller has four PWM channels with 10-bit resolution. To obtain the maximum possible range using 8-bits from the DAQ card, the 8-bit value must be placed into the MSB of each PWM Control register. Due to the resolution difference between the DAQ card output and the PWM output, the 2 LSBs of each PWM control register are not used. This gives a range of 0 to 1020 in steps of 4.

The 10-bit PWM value for each channel is stored in Compare Shadow registers 0-4. Bits 0-7 for each PWM channel are stored in Compare Shadow registers CPSW0-3, and bits 8 and 9 for each PWM channel are stored in CPSW4 (refer Table 4-3).

PWM outputs 0-3 are controlled by the values in Compare Shadow registers 0-4. The Motor ID bits are used to place the PWM value in the appropriate Compare Shadow register.

Figure 4.17 shows the code to transfer the value of the duty cycle into the relevant motor PWM Compare register. Line 9 checks whether the Motor ID bits are the same. To compare them, the value of P0.3 is shifted left by 1 bit to place it in the same position as P0.4. If the Motor ID bits are equal they are polled to determine if P0.3 is 0 or 1.

If P0.3 is 0 (Motor ID 00) the code executes lines 13 and 14, and places the PWM value into the Shadow registers controlling PWM0. This is achieved by performing an AND operation on CPSW4 with the hex value FC, and adding `PWM_1`. The AND operation allows the bits not relating to PWM0 to remain the same, and adding `PWM_1` sets bits 0 and 1 of CPSW4 to the MSB of the PWM value. CPSW0 is set to the value of `PWM_2`.

If P0.3 is 1 (Motor ID 11) the code executes lines 18 and 19, which will place the PWM value into the Shadow registers controlling PWM3. The AND operation again allows the bits not relating to PWM3 in CPSW4 to remain the same, and `PWM_1` is added to set bits 6 and 7 of CPSW4 to the MSB of the PWM value. CPSW3 is set to `PWM_2`.

CPSW0: Compare Shadow Register 0

7	6	5	4	3	2	1	0
CPSW07	CPSW06	CPSW05	CPSW04	CPSW03	CPSW02	CPSW01	CPSW00

CPSW1: Compare Shadow Register 1

7	6	5	4	3	2	1	0
CPSW17	CPSW16	CPSW15	CPSW14	CPSW13	CPSW12	CPSW11	CPSW10

CPSW2: Compare Shadow Register 2

7	6	5	4	3	2	1	0
CPSW27	CPSW26	CPSW25	CPSW24	CPSW23	CPSW22	CPSW21	CPSW20

CPSW3: Compare Shadow Register 3

7	6	5	4	3	2	1	0
CPSW37	CPSW36	CPSW35	CPSW34	CPSW33	CPSW32	CPSW31	CPSW30

CPSW4: Compare Shadow Register 4

7	6	5	4	3	2	1	0
CPSW39	CPSW38	CPSW29	CPSW28	CPSW19	CPSW18	CPSW09	CPSW08

Table 4-3 THE 87LPC768 COMPARE SHADOW REGISTERS.

If the Motor ID bits are not the same, the code will execute lines 22 to 34. The `else` structure checks whether P0.3 is 0 or 1, and places the PWM value in the Shadow registers controlling PWM1 or PWM2 respectively.

Once the appropriate Shadow Compare register holds the PWM value, the code in Figure 4.18 is executed. PWMCON0 is the PWM Control register 0. Setting it to the hex value F6 (line 35) enables the counter to run and sets the transfer bit high, allowing the contents of the shadow registers to be transferred to the control registers at the next underflow. The PWM outputs 0-3 are inverted to allow the duty cycles to mirror the values set by the sliders on the front panel.

```
if  (((P0 & 0x08) << 1) == (P0 & 0x10))
{
        if ( (P0 & 0x08) == 0 )
        { //write to PWM0 compare register for motor 1
                CPSW4 = ((CPSW4 & 0xFC) + PWM_1);
                CPSW0 = PWM_2;
        }
        else
        { //write to PWM3 compare register for motor 4
                CPSW4 = ((CPSW4 & 0x3F) + (PWM_1 << 6));
                CPSW3 = PWM_2;
        }
}
else
{
        if ( (P0 & 0x08) == 0 )
        { // write to PWM0 compare register for motor 2
                CPSW4 = ((CPSW4 & 0xF3) + (PWM_1 << 2));
                        CPSW1 = PWM_2;
        }
        else
        { // write to PWM0 compare register for motor 3
                CPSW4 = ((CPSW4 & 0xCF) + (PWM_1 << 4));
                CPSW2 = PWM_2;
        }
}
```

Figure 4.17 CODE TO PLACE THE PWM DUTY CYCLE IN THE RELEVANT PWM CHANNEL.

```
PWMCON0 = 0xF6; // enable transfer and run of PWM data
   while ((PWMCON0 & 0x40) != 0); // poll transfer bit
               /* wait */;

WDRST = 0x1E; // first part of watchdog feed sequence
WDRST = 0xE1; // second part of watchdog feed sequence
```

Figure 4.18 CODE TO RUN THE PWM AND RESET WATCHDOG.

Line 36 polls the transfer bit. When a transfer from the shadow registers to the control registers has taken place, the transfer bit is reset to zero. Until the transfer occurs, the program waits. Once the PWM value has been written to the appropriate register, the watchdog is fed to ensure it will not reset the program (lines 37 and 38).

The entire control loop will continue to run as long as the 87LPC768 micro is active, polling the inputs and writing to the appropriate PWM Compare register, or resetting the watchdog.

5. SUBMERGING THE ROV

A substantial number of alterations and improvements must be made before the DELPHINUS ROV can be launched underwater. The key considerations are:

- Mechanical alterations to the hull
- Protecting the chassis from corrosion
- Installing the electronics inside the ROV
- Protecting the ROV from water leaks over the intended pressure range
- Connecting the surface to the ROV
- Ensuring the ROV is electrically safe

The ROV can then be reconstructed and sealed for submersion.

5.1 MECHANICAL ALTERATIONS

In operation, it is advantageous to be able to access each hull individually. This allows fast fault diagnosis and alterations, and reduces the downtime due to repairs. To be able to achieve this, modifications must be made to the original hull design.

In the original system, access to the internals of the ROV meant removing all three hull caps as one unit, due to the stainless-steel Swage-Loc tubing inter-connected between them (refer Figure 1.5). It was difficult to remove them in this manner, as all three had to be pulled evenly to prevent damage to the sealing edges. This process was also extremely time consuming.

To allow access to each hull individually, mechanical alterations were made to the structure of the DELPHINUS. Two marine-grade aluminium conduits were added from the main hull to each of the port and starboard hulls, allowing power and signal wires to run in separate pipes (refer Figure 5.1). Since the ROV hulls are also made of marine-grade aluminium (refer Section 1.4), fabricating the conduits from the same material prevents corrosion caused by the contact of dissimilar metals.

5.2 PROTECTING THE CHASSIS

The underwater environment is a hazardous place for metal. To protect the ROV from water leaking in any holes or pits in the new welds, and to protect the chassis from corrosion, the motors were removed and the body of the ROV was sprayed with standard matt-black paint. The disassembled and painted chassis is shown in Figure 5.1. The thrusters were also disassembled and the frame of each was painted.

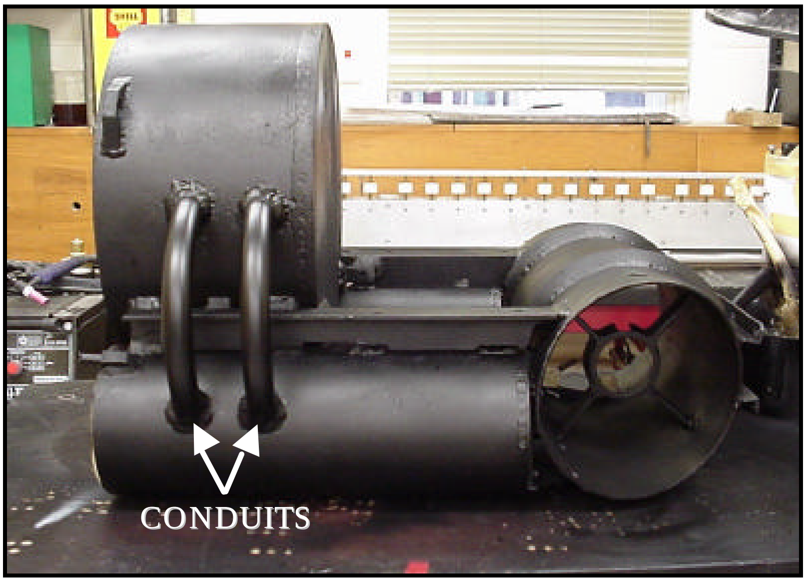


Figure 5.1 **THE NEWLY PAINTED CHASSIS.**

5.3 INSTALLING THE ELECTRONICS

During development, each hardware component is selected for a specific position inside each hull. Each active component must be kept cool, and the connections between the hulls established.

The electronics are installed inside the main, starboard and port hulls, and the junction box (refer Figure 5.2). The main hull contains the computer hardware and power supply, the starboard hull contains all of the motor driver components and the power supply for the electronics, and the port hull holds all of the sensors (except the Pressure transducer). All components are designed to be easily removed for quick replacement should a fault occur. The junction box provides the connection point from the surface to the ROV, and is a convenient place to mount the Pressure transducer.

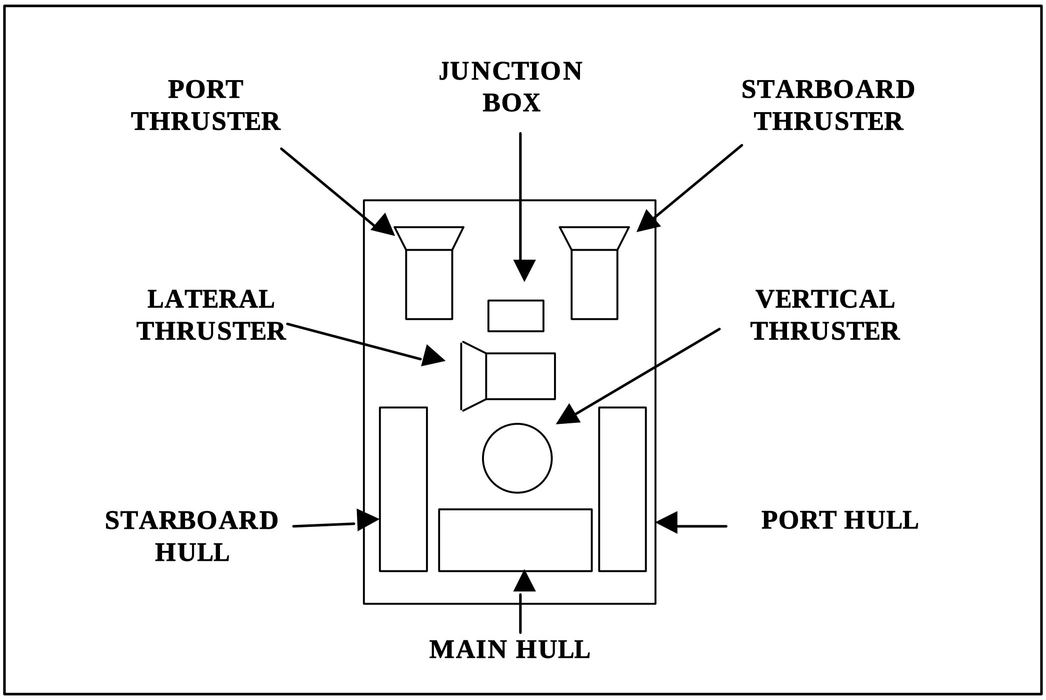


Figure 5.2 A TOP VIEW OF THE ROV.

5.3.1 The Main Hull

Inside the main hull the following components are located:

- GA-V5VMM Motherboard and hard drive
- Lab-PC+ Data Acquisition card (DAQ)
- DE-528 Series Network card
- Computer power supply and fan
- 87LPC768 Microcontroller board
- DAQ I/O input card
- Level Shifter board
- USB Camera
- Pan and tilt unit

The Motherboard is attached as high as possible to allow the computer power supply to sit underneath, and permit wiring to run over the top of the computer housing. The hard drive of the computer is attached to the computer housing by three screws, each drilled from the back of the Perspex which mounts the Motherboard to the hull (refer Section 3.2.2). The screw holes are countersunk, allowing the Perspex to sit flat against the rear wall.

The DAQ card and Network card are placed into the ISA and PCI slots of the Motherboard respectively. The Network card is placed in the highest PCI slot to allow the camera pan and tilt unit sufficient freedom of movement.

The computer power supply outer case is cut down to provide only a base. The remainder of the housing is removed to allow the power supply to fit inside the hull, and Velcro strips mount the power supply underneath the Motherboard. Mylar film insulates the high voltages of the power supply in place of the removed casing. The power supply fan is bolted to the computer housing, and holes are drilled in the housing to allow air to circulate through the fan and over the power supply.

Two strips of Velcro mount the 87LPC768 microcontroller board to the right-hand wall of the computer housing. The header pin is orientated at the top, so that the ribbon cable can exit through an unused card slot into the right-hand side of the computer housing and connect to the DAQ I/O card.

The DAQ I/O card is mounted to the right of the computer power supply, on the other side of the computer housing. The Level Shifter board is mounted on top of the DAQ I/O card. The USB camera and pan/tilt unit is mounted in the main hull cap as described in Section 3.8.3. The wiring in the hull is gathered with cable ties and cable-tie mounts.

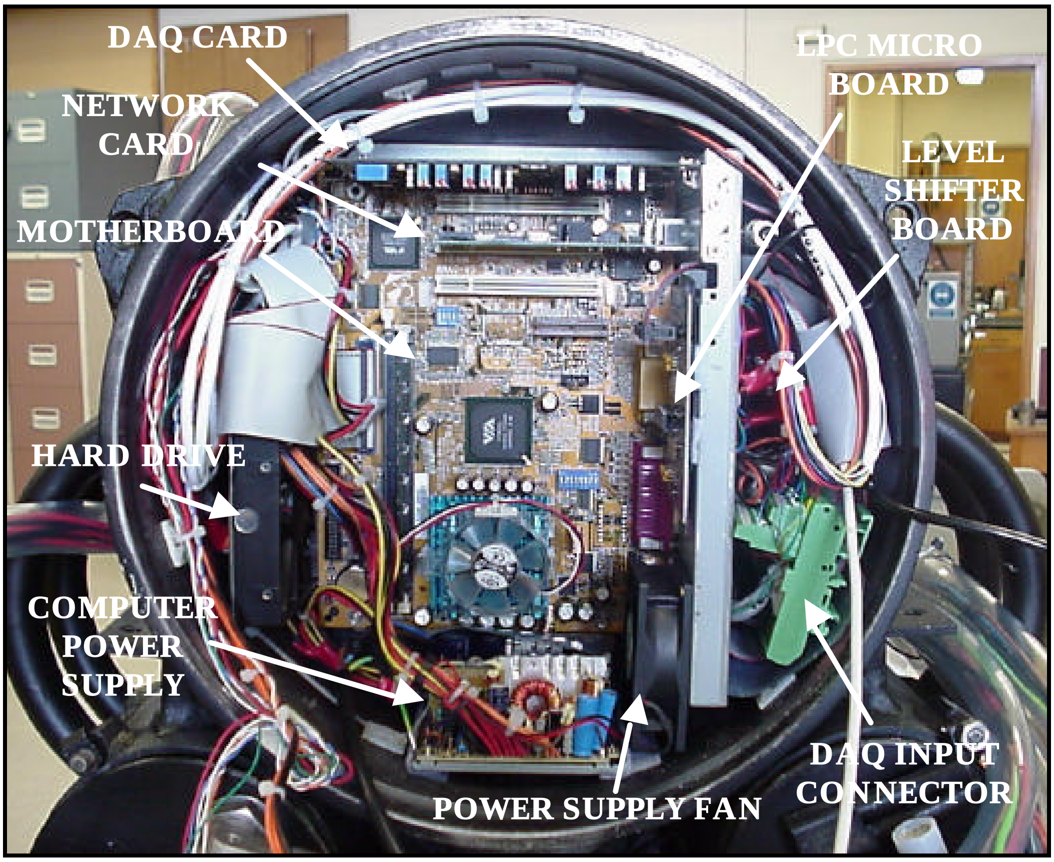


Figure 5.3 THE MAIN HULL OF THE ROV.

The following connections are made through two Swage-Loc fittings on the main hull cap:

- 230VAC for the computer power supply
- Coaxial network cable
- Power and reset control wires for the computer
- 15VDC, GND and signal output for the Pressure transducer
- One spare single-core shielded cable

The 230VAC and the coaxial cable are connected to the junction box by one Swage-Loc fitting and a length of flexible hose (refer Section 5.4.2). The power and reset switches for the computer are reed switches located in the junction box, allowing the sealed computer to be powered and reset by a magnet placed near the relevant switch. The wires to connect the Motherboard to the reed switches are run with the connections for the Pressure transducer and the spare shielded cable, through the remaining Swage-Loc fitting and flexible hose to the junction box.

The wires from inside the hull are potted into lengths of Nylon tubing with sufficient slack inside the hull to allow the main hull cap to be removed from the ROV.

5.3.2 The Starboard Hull

The electronic components for the starboard hull are mounted into a canister which slides inside the hull.

Inside the starboard hull the following components are located:

- Electronics Transformer
- Motor Driver card
- Power Supply card

The Electronics Transformer is bolted upside down into the enclosed front section of the canister (refer Figure 5.4). The five centre-tapped outputs of the transformer (as described in Section 2.9.3) are threaded through a hole in the wall of the enclosed section. Each output is extended and soldered to the respective pin on the PCB connectors for the Motor Driver card (refer Figure 5.5) and Power Supply card. Two 6-core colour-coded cables connect to the four PWM, four On/Off and four Direction inputs of the Motor Driver card.

All the cables are captured into plastic wire-wrap, which confines them underneath the PCB connectors, and prevents any of the cables from catching when the canister is removed from the hull. The cables are tied to the canister to provide strain relief, and are long enough so the starboard canister can be completely removed from the hull. The cables are fed up through one of the side conduits into the main hull.

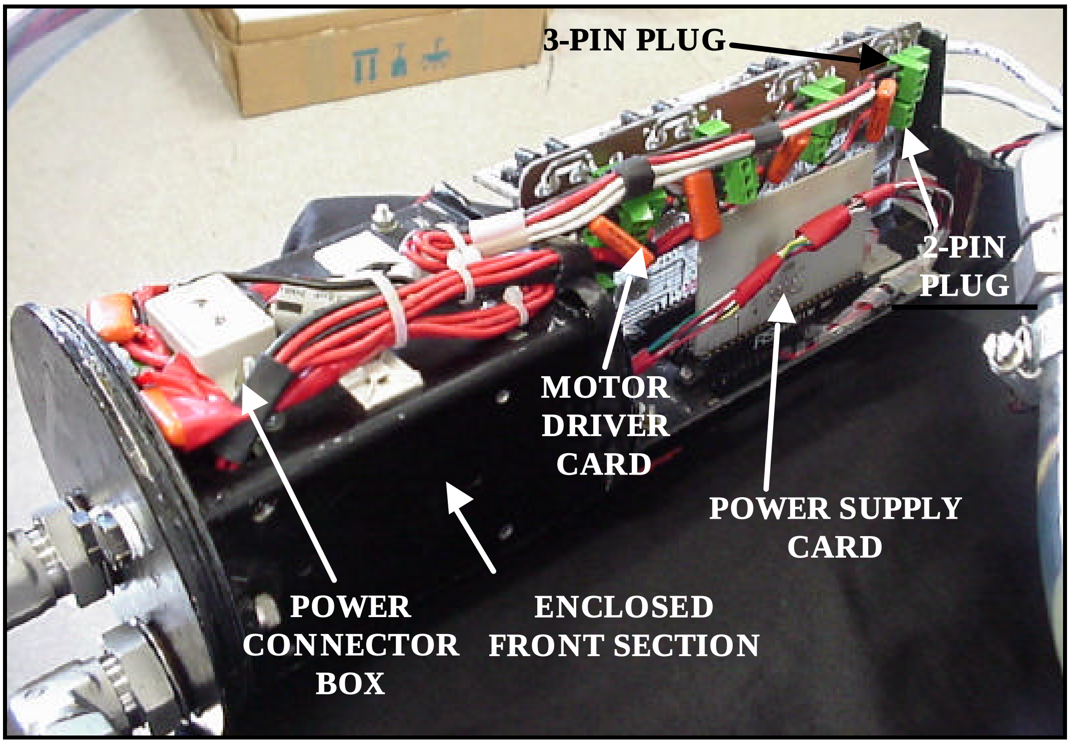


Figure 5.4 THE STARBOARD CANISTER.

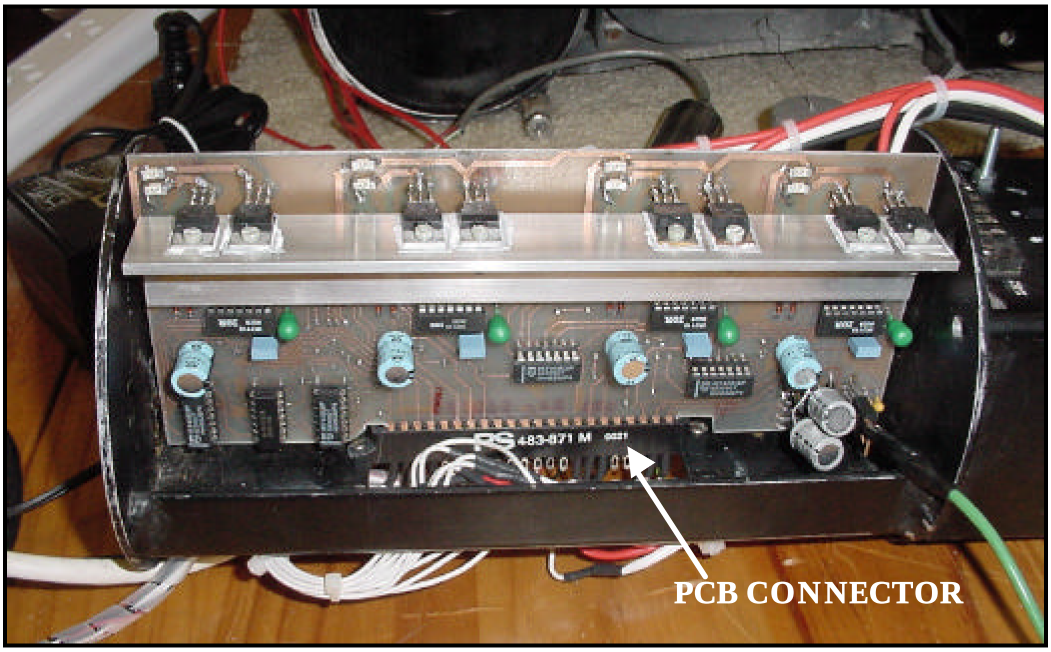


Figure 5.5 THE MOTOR DRIVER CARD INSERTED IN THE PCB CONNECTOR.

The two 6-core cables are tied to the top of the main hull and connect to the outputs of the Level Shifter board. The GND and 15VDC connect into a connector block mounted to the side of the main hull, with the ground of the Power supply card connected to the DAQ card ground.

The following connections are made through two Swage-Loc fittings on the starboard hull cap:

- 230VAC for the Electronics Transformer primary
- The centre-tapped supply from the Motor Transformer
- Four pairs of motor conductors from each half-bridge motor driver

The 230VAC and the centre-tapped supply are input to the starboard hull via one of the two Swage-Loc fittings. The other Swage-Loc fitting outputs the eight motor cables. Internal to the canister, the eight motor cables are connected to the four half-bridge circuits by four 2-pin plugs on the Motor Driver card (refer Figure 5.4). A Power Connector box attaches the centre tapped supply of GND, +70VDC and +140VDC from the Motor Transformer to each half-bridge circuit, via four 3-pin plugs (refer Section 2.8.1).

The conductors are run separately to each of the half-bridge circuits to ensure they will carry the maximum current of 10A.

5.3.3 The Port Hull

The electronic components for the port hull are mounted in the canister which slides inside the hull. All but one of the sensors are incorporated into this hull, to minimise the noise interference from the power circuitry in the starboard hull.

Inside the port hull the following components are located:

- Wesmar flux-gate Compass
- Compass Power Supply board
- Tilt sensor
- Camera Pan/Tilt board
- Differential Input board

Power is supplied to the components in the port hull by 15VDC and GND wires run from the connector block in the main hull, via a side conduit to another connector block on the canister.

The Compass is placed in the same location as in the original DART ROV, and is seated in a circular frame (refer Figure 5.6). The outputs from the Compass are rewired with a shielded cable, which is wound around the Compass to provide spare length. A 5-pin plug is connected to the end, and an equivalent 5-pin socket attaches the isolated supply from the Compass Power Supply board to the Compass, and the sine, cosine and 0V outputs of the Compass to the Differential Input board.

The Compass Power Supply board and Camera Pan/Tilt board are each mounted to the canister with three nylon screws. The Differential Input board is mounted on the opposite side of the canister with two Velcro strips (refer Figure 5.7) and insulated from the chassis using Mylar film. The four inputs of the Camera Pan/Tilt board (refer Section 3.8.4) are connected to the respective outputs on the DAQ card by a separate shielded cable.

A length of aluminium bent at a 90? angle attaches the Tilt sensor to the canister, which is mounted so the roll and pitch axes of the sensor align with the roll and pitch axes of the ROV. A five pin plug attaches GND and 15VDC to the sensor, and outputs the roll and pitch voltages to the DAQ I/O card.

The signals from the Differential Input board and Tilt sensor are input to the DAQ I/O card by a shielded cable run through a conduit. In total, two shielded cables and the power lines are run through the conduits. One shielded cable is for the digital signals, and the other for the analogue data from the sensors. The cables are long enough to remove the port canister completely from the hull. There are no external connections to this hull, so the Swage-Loc fittings are plugged (refer next Section) for future use.

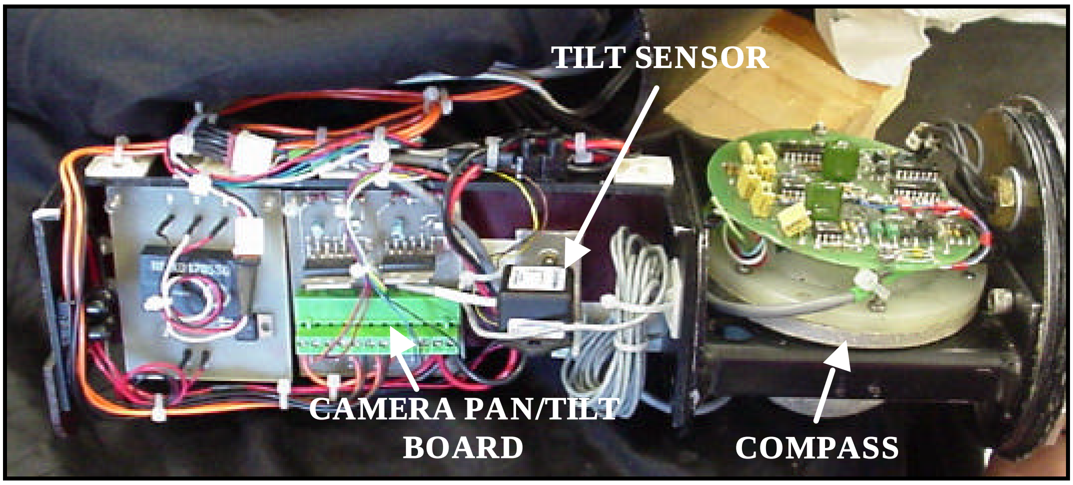


Figure 5.6 THE PORT CANISTER.

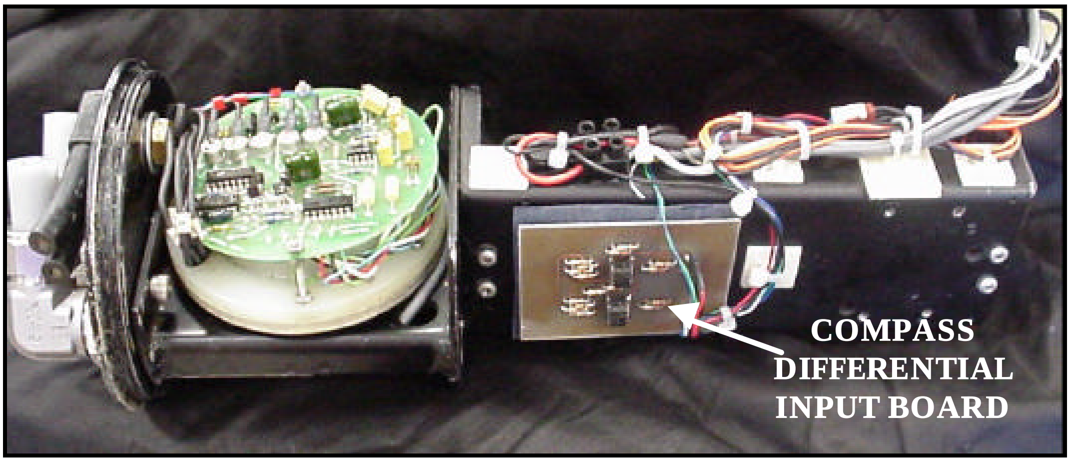


Figure 5.7 A REAR VIEW OF THE PORT CANISTER.

5.4 LEAK PROTECTION

The centre-tapped supply, 230VAC input and the coaxial cable from the surface require entry into the starboard and main hulls. One option is to use special underwater connectors, but this is very expensive due to the current and voltage ratings of the centre-tapped supply. The limited space on the front hull caps necessitates the need for an alternative solution. A junction box provides a low-cost way of connecting the umbilical to the two hulls.

5.4.1 The Junction Box

To prevent the junction box and hulls from leaking, the pressure experienced underwater must be equalised inside the box, and at the connection points into the hulls. To compensate for pressure differences, a standard aluminium box has holes drilled in the lid, and a sheet of neoprene rubber is laid underneath to form a movable diaphragm seal. The box is filled with oil (refer Figure 5.8).

When the box is submerged, the water enters the holes in the lid and pushes on the diaphragm (refer Figure 5.9). The oil inside is incompressible and pushes against the seals of the box, keeping the internal pressure the same as the ambient water pressure and preventing water from leaking in. The junction box also provides an ideal place to mount the Pressure transducer, as there is no appropriate space within the hulls. Because the Pressure transducer is encased in metal, the sensor is protected from noise interference.

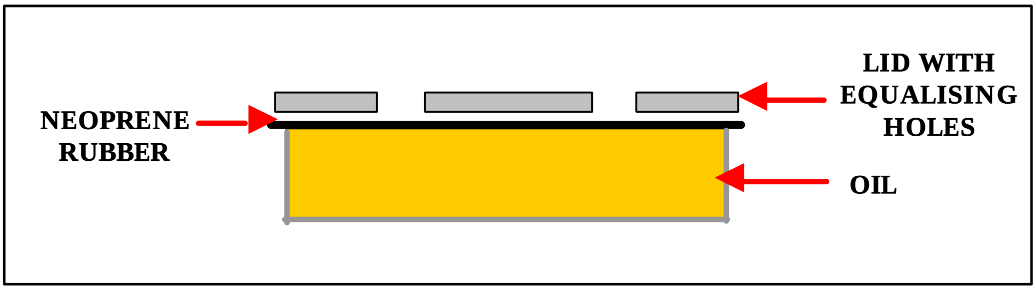


Figure 5.8 A CUT-AWAY VIEW OF THE JUNCTION BOX.

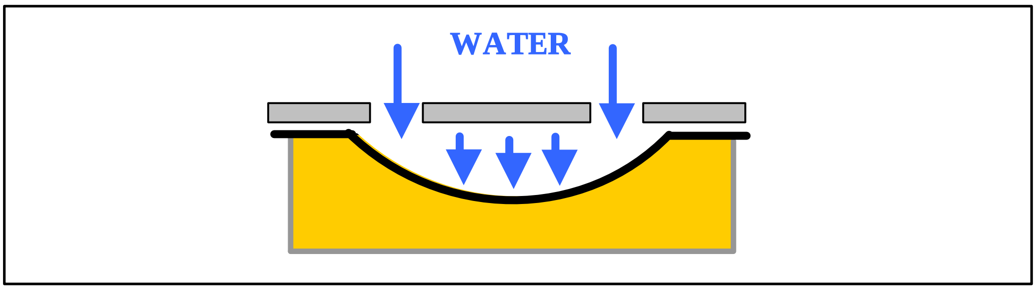


Figure 5.9 WATER COMPRESSING THE DIAPHRAGM.

To connect the surface to the hulls, four large holes are drilled in the base of the junction box, allowing one 32mm and three 25mm cable glands to bolt to the box.

The Pressure transducer is threaded into the junction box in the space between the glands (refer Figure 5.10) with the internal stainless steel diaphragm (refer Section 3.7.2) exposed to the outside of the box.

The cable glands provide an insertion point for oil filled cables. Two plugs on the right-hand side of the box become fill and bleed points for the oil (refer Figure 5.11). The box is painted to protect the metal from corrosion, and mounted to two aluminium brackets which are bolted to the ROV and shown in Figure 5.11. The junction box is mounted low enough to allow the yellow buoyancy block to sit in its original position.

Inside the junction box, the umbilical connects an isolated 230VAC supply to the starboard and main hulls, and the centre-tapped Motor Transformer output to the starboard hull. The two computer power/reset reed switches are located at opposite ends of the box.

5.4.2 Connecting Into Each Hull

Originally, connections into the hulls were made with EO underwater connectors and stainless steel tubing (shown in Figure 5.12). The female counterparts to the EO connectors did not arrive with the ROV, rendering them unusable. In the DELPHINUS system, the connection into each hull is made with Swage-Loc fittings and flexible tubing.

The EO connectors are removed from the starboard and port hulls. Each hull cap is sealed by tapping new thread in the holes left by the connectors, and inserting small end-plugs. Thread tape is wound around the end-plugs to ensure the seal is watertight. As space is not such a concern in the port hull, the EO connector on the front cap is left in its original position.

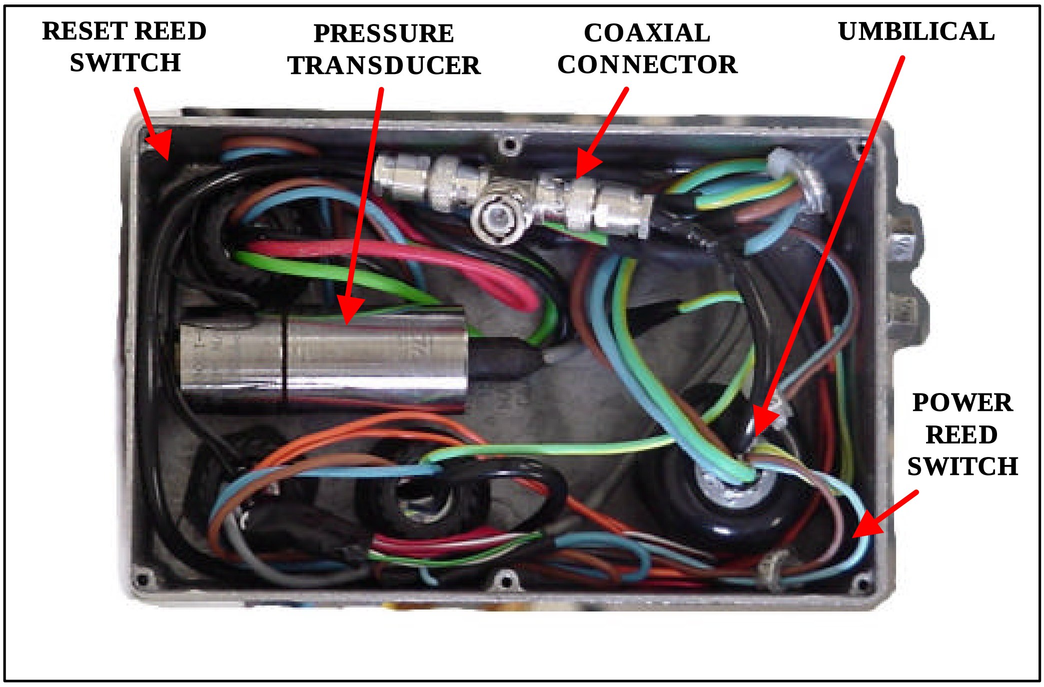


Figure 5.10 THE INSIDE OF THE JUNCTION BOX.

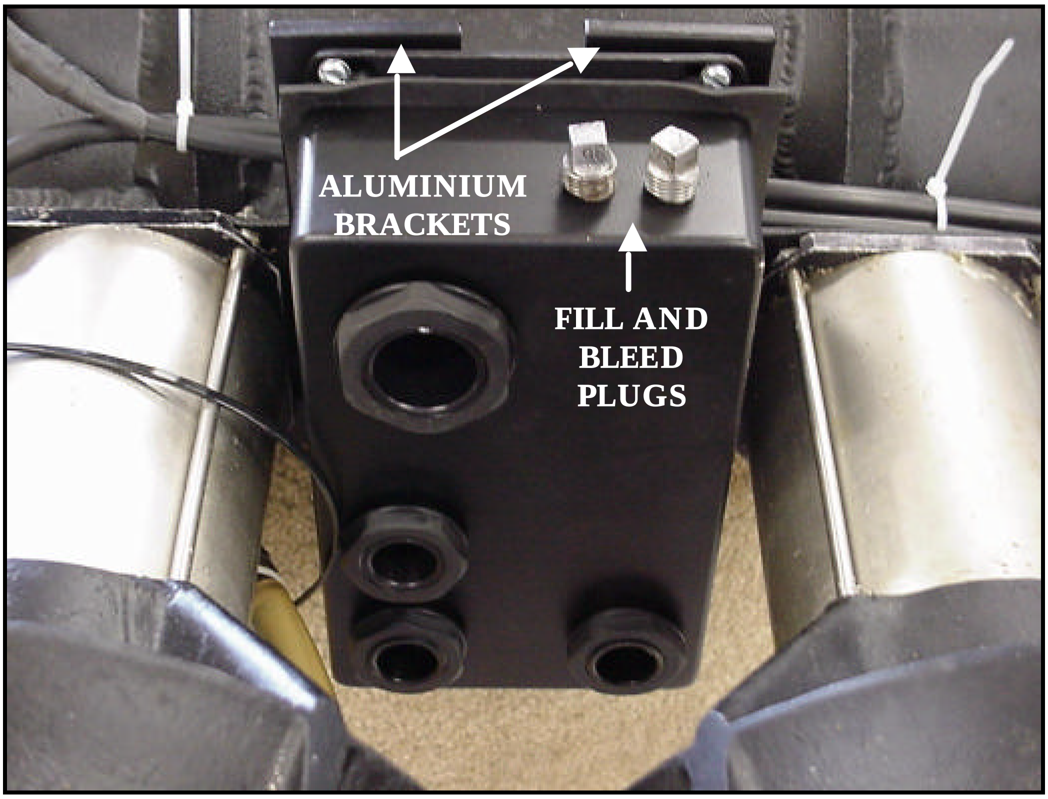


Figure 5.11 THE MOUNTING PLATES FOR THE JUNCTION BOX.

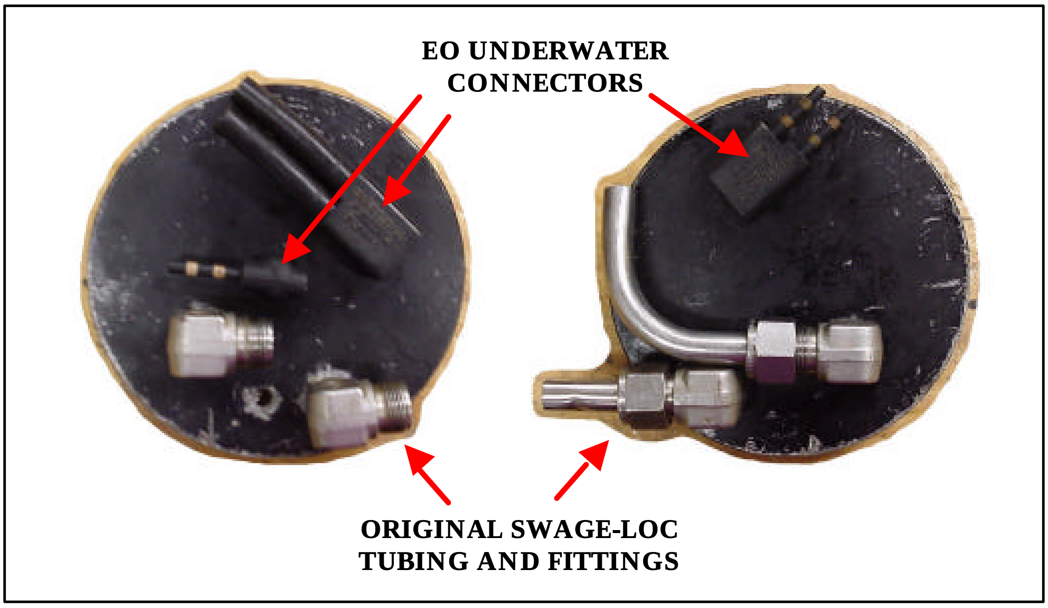


Figure 5.12 THE ORIGINAL LAYOUT OF THE HULL CAPS.

The stainless-steel tubing and Swage-Loc fittings were removed from the hull caps, as the conductors from the starboard hull cannot fit through them. The remaining holes were tapped to fit the thread of new ¾” Positionable Swage-Loc Elbow joints. The ¾” size of the Swage-Loc provides enough space for all eight motor conductors to exit the starboard hull. It was decided to replace all the Swage-Loc fittings, including those of the main hull, to make the system uniform and replacement easier.

To connect the wiring from each hull to the junction box, lengths of ¾’’ Nylon-tubing are used (refer Figure 5.13). The wires from each hull are placed through the tubing and sealed at the bottom with Blu-tac. A potting compound is poured into the tubing, and when dry, the Blu-tac is removed and the tube is fitted into the Swage-Loc. This forms a plug which seals the hull and provides strain relief to the wiring. Should new wiring be required, the plugs can be easily removed and replaced without damaging the Swage-Loc.

All the potting for the ROV uses a twin pack encapsulating system because it mixes together in an air-evacuated bag. This ensures no air is mixed into the compound which would cause bubbles in the mould. Bubbles form cavities and collapse under pressure allowing water entry to the hulls.

Flexible 19mm clear tubing is inserted over the Nylon plugs, cable clamped and the wiring pulled through. The tubes are clear to allow the conductors to be checked visually. Both tubes from the main hull and the tube from the starboard hull containing the mains and centre-tapped supply run alongside the port hull, attaching to additional pieces of Nylon tubing inserted in the three cable glands at the back of the junction box. The hoses are cable-clamped to the Nylon tubing.

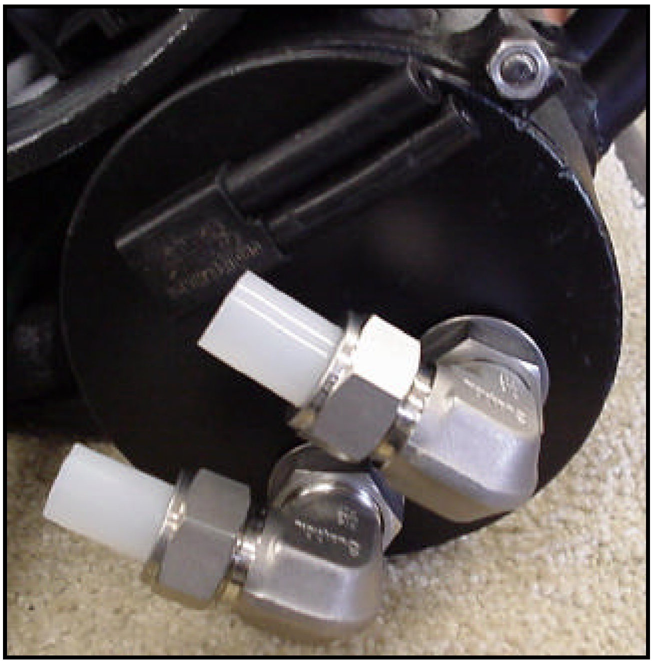


Figure 5.13 THE NEW SWAGE-LOC FITTINGS AND WHITE NYLON-TUBING.

The flexible hose containing the eight motor cables from the starboard hull is run along the starboard hull, and can be coiled in front of the vertical thruster or along the starboard hull. The end of the tube is cable clamped to a piece of Nylon tubing, which is mounted inside a small plastic box called the Motor Junction box. Inside this box, each of the four pairs of motor conductors from the Motor Driver card are connected to the respective thruster cables. The box is potted and attached to the starboard side of the ROV. The underwater connectors and cables from each thruster are salvaged from the original umbilical plug connections, allowing each thruster to be easily unplugged.

The flexible hoses are filled with oil via the fill and bleed plugs from the junction box. The pressure from the water when the ROV is submerged squeezes the tubes, maintaining the internal pressure at the level of the external water pressure. This protects the seals from leaking, as the same pressure is experienced inside the tubing and junction box as the outside. Each thruster motor has a bladder which also seals the internal bearings against the water by similar oil filled flexible hosing.

5.5 THE UMBILICAL

To control and/or monitor the ROV, an umbilical connection must be established. This allows the ROV to operate at a distance remote from the workstation, and supplies power to the motors, electronics and onboard computer.

The original umbilical was a specially made cable consisting of the following:

- 1 50? coaxial
- 1 #20AWG shielded twisted pair
- 1 #14AWG insulated conductor
- 9 #18 AWG insulated conductors
- Philistrand core

The new umbilical consists of four standard electrical cables and is made up of:

- 1 3-core 2.5mm flexible cable to conduct the centre-tapped supply from the Motor Transformer
- 1 3-core 0.5mm flexible cable to provide 230VAC to the ROV computer
- 1 3-core 0.5mm flexible cable to provide 230VAC to the Electronics Transformer
- 1 50 ? coaxial network connection cable

The cables were each cut to be 15m long. They were gathered at one end and inserted into a 25mm plastic syringe shell, which was weakened along two sides by filing. A potting compound was mixed and poured into the syringe.

After the compound was set, the syringe case was removed. Potting the umbilical provides a way to create a sealed entry point into the junction box, as the 32mm cable gland can compress onto the epoxy rubber. It also provides strength against flexing of the umbilical at the junction box while the ROV is underwater. The umbilical is attached into the ROV and cable ties secure the umbilical to the ROV silver lifting frame.

5.6 ENSURING ELECTRICAL SAFETY

The underwater aspect of the thesis project requires careful attention to the electrical characteristics of the system. The ROV is isolated from any surface power to ensure handling of the active ROV is safe. Isolation also protects the chassis from corrosion.

The Motor Transformer, Motor Power Rectification board (refer Figure 2.25) and a small isolating transformer are enclosed inside a plastic box called the Power box (refer Figure 5.14). The isolating transformer supplies the ROV computer, Electronics Transformer, and the surface computer if needed. Due to the 60kg weight of the Motor Transformer, the Power box is reinforced at the bottom by a wooden base.

230VAC mains power is connected to the Power box through a Residual Current Device (RCD). The ROV system is protected by a Main fuse which is mounted to the outside of the box for easy access (refer Figure 5.15). The fuse connects the mains power to a connector block mounted to the side of the Motor Transformer. The Power box has three switches on the front of the box to control the mains power to the ROV computer, Electronics Transformer and the Motor Transformer. The umbilical is connected to the Power box centre-tapped supply, mains, and the coaxial cable from the surface computer. The umbilical cable can be removed to travel separately from the Power box, making the system easier to transport.

The umbilical, mains supply and coaxial connection are inserted into the Power box with cable glands providing protection and strain relief to each conductor.

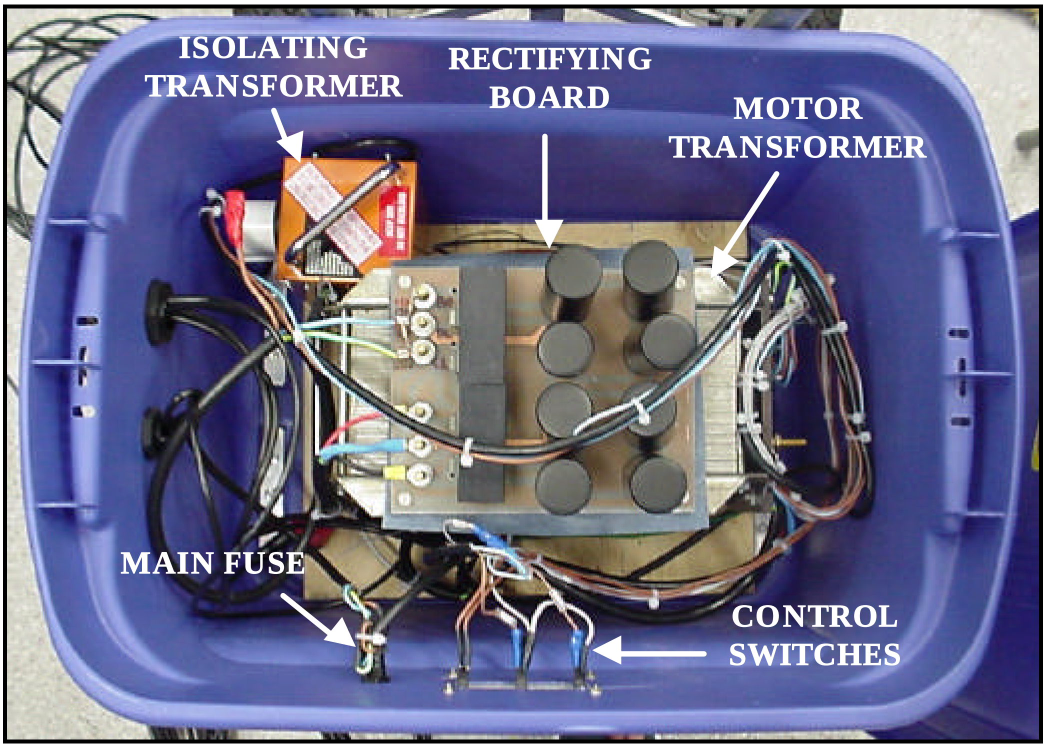


Figure 5.14 THE INTERNALS OF THE POWER BOX.

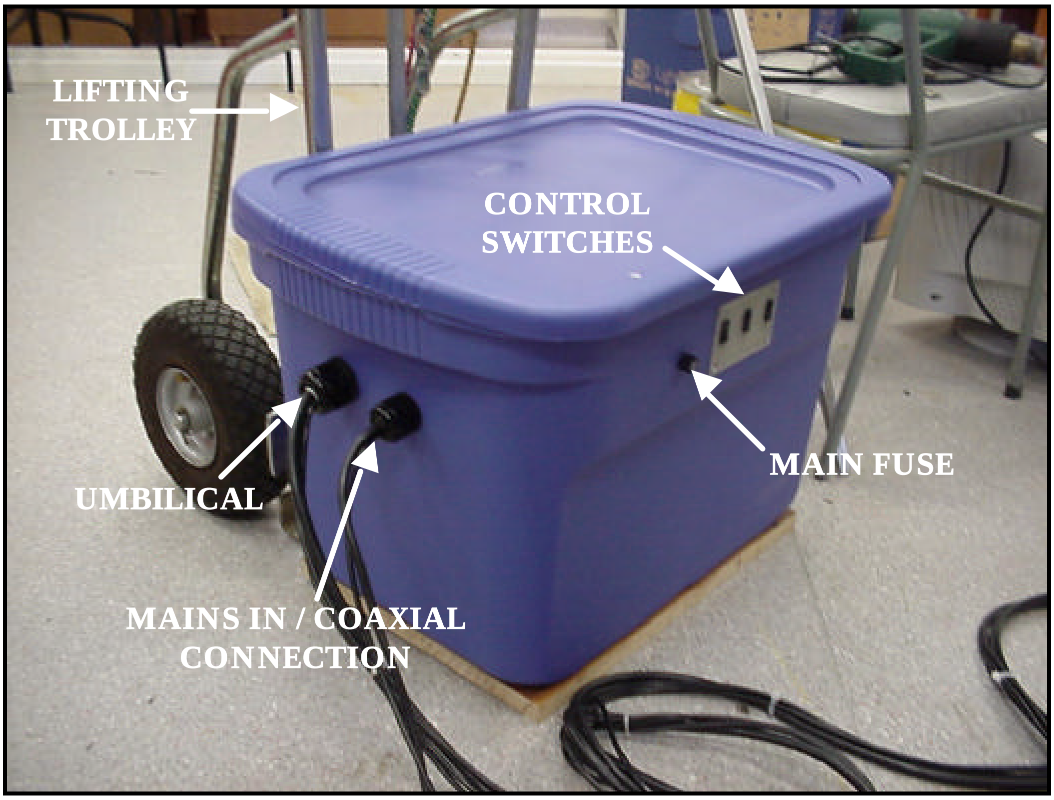


Figure 5.15 THE POWER BOX.

5.7 THE DELPHINUS SYSTEM

An overview of the major components of the new system is given below in Figure 5.16.

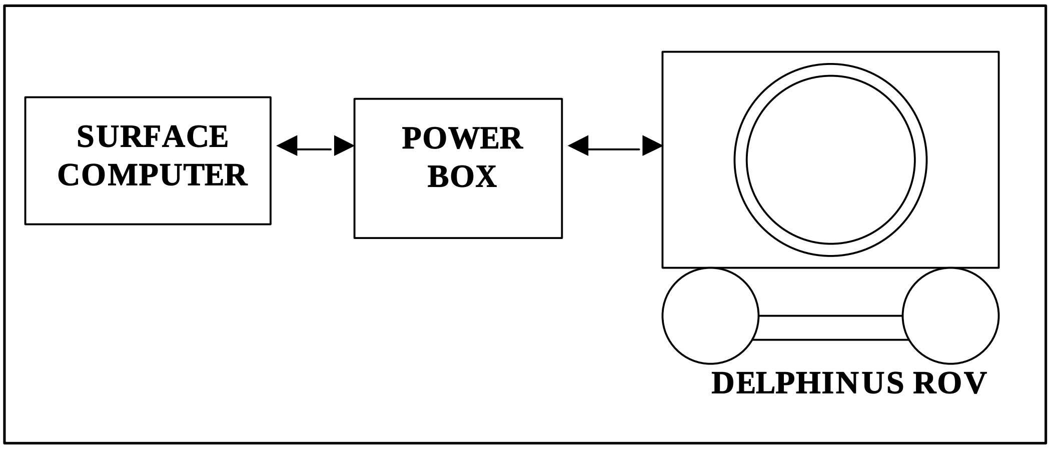


Figure 5.16 THE DELPHINUS ROV SYSTEM.

5.8 PREPARING FOR WATER TESTS

To perform the first underwater tests, the DELPHINUS ROV must be completely sealed against water leaks and assembled one hull at a time.

5.8.1 Inserting the Canisters

All the ROV o-rings to seal the main, starboard and port hulls were cleaned in hot soapy water and felt for defects that could cause the ROV to leak. Every sealing surface was prepared by cleaning with isopropyl alcohol (a clean surface is imperative as grit and impurities can allow water to enter), and a thin layer of grease applied to every sealing edge and o-ring.

The Motor Driver card and Power supply card of the starboard hull were covered with Mylar film to insulate the high side FETs from the chassis. The starboard canister was carefully inserted into the starboard hull on an angle of approximately 60?, allowing the wiring from the Motor Driver card to run freely up through the side pipes and into the main hull. The port canister was inserted, and both canisters were tightened and sealed with two L-shaped bolt clamps (refer Figure 5.17).

The main hull front cap was carefully inserted so each edge was exactly flush, preventing damage to the sealing edges. The insertion of the cap was achieved by holding it against the main hull so it was just touching around the complete circumference, making sure all wiring was clear. The cap was pulled into the hull by three g-clamps, positioned at the three bolt frame mounts and tightened by the same amount incrementally until the cap was fully assimilated. The clamps were then removed, and three bolts were placed through the frame mounts with two nuts in between the cap and the main hull, and one nut on the end. The two nuts allow the hull cap to be removed, as when they are tightened against the main hull, the cap is pulled out.

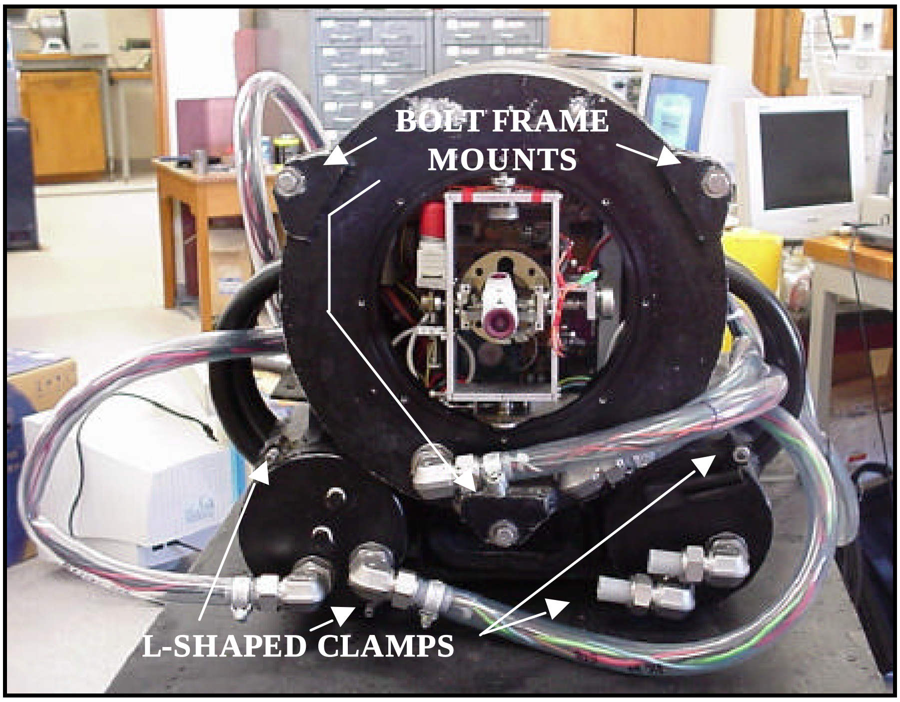


Figure 5.17 THE PARTIALLY RECONSTRUCTED ROV.

The clear acrylic dome was attached to the main hull by eight screws positioned evenly around the edge.

5.8.2 Oil Filling

Before the ROV can be completely reconstructed, the flexible tubing and junction box must be filled with oil to equalise the external water pressure when submerged.

To fill the tubing and junction box with oil, the air inside them must be allowed to escape. Raising the junction box higher than the tubing permits the air to rise upwards while the oil is flowing downwards. The fill and bleed plugs are removed, and oil is poured in through a funnel. Each tube is squeezed to ‘burp’ them of air, and the junction box is continually filled until all air is removed. Once full, the box is left to rest to allow any oil leaks to be found.

A fault in the design of the junction box meant that it did not seal against the lip of the lid, and oil escaped via the screws attaching the lid to the box. A new lid was constructed from a thick piece of Perspex, and a hole was drilled into the Perspex to allow the water to compress the diaphragm as before. To attach the new lid to the box, two clamps were made from aluminium strips and 4mm threaded rods.

The front bumper bar was bolted to the chassis to prevent damage from a collision, along with the lifting frame and yellow buoyancy block (refer Figure 5.18).

5.8.3 Weighting the ROV

The ROV must sit level and balanced in the water for stable flight. Weights were cable tied to the frame before the ROV was put into the water, so they could simply be clipped off to balance the frame.

To the bottom of the chassis near the starboard and port motors, 3.5kg was added. To counterweight the Electronics Transformer in the starboard hull, 2.2kg was added to the port side of the chassis, and 4.7kg remained from the original DART configuration, located under the main hull by the vertical thruster.

The added weight to the frame was the final consideration, and the ROV is now ready to be submerged for operational tests.

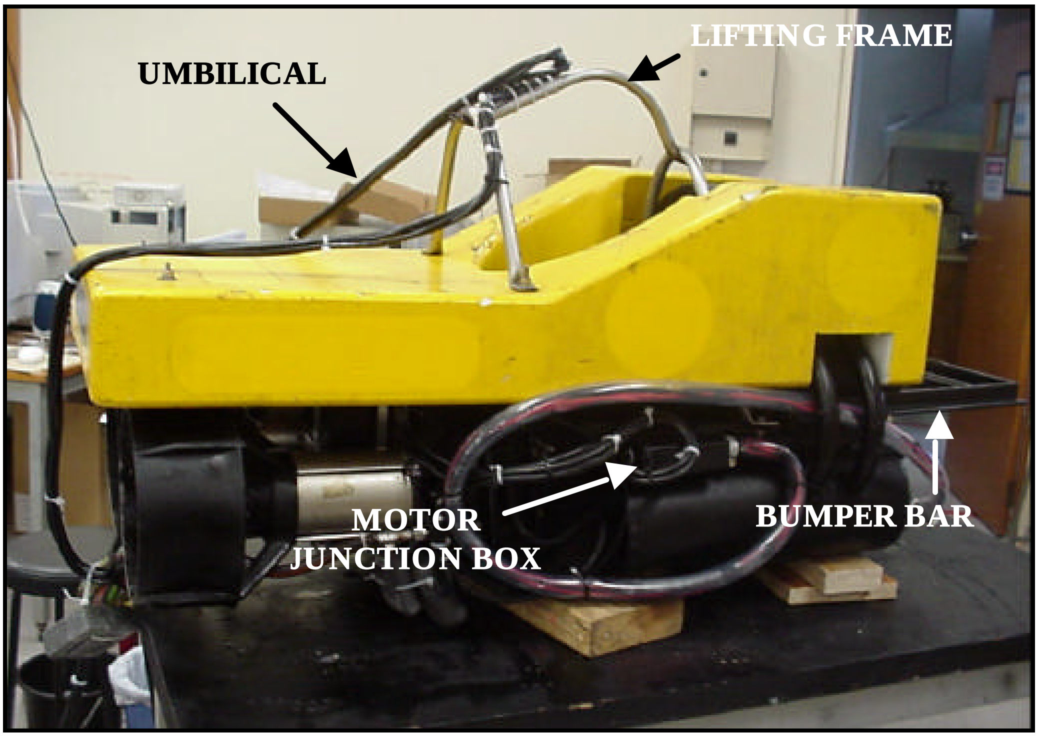


Figure 5.18 THE RECONSTRUCTED ROV.

6. RESULTS

To test the operation of the ROV underwater, the DELPHINUS was taken to the University of Waikato campus pool. The enclosed CD contains excerpts of video footage recorded during the water trials.

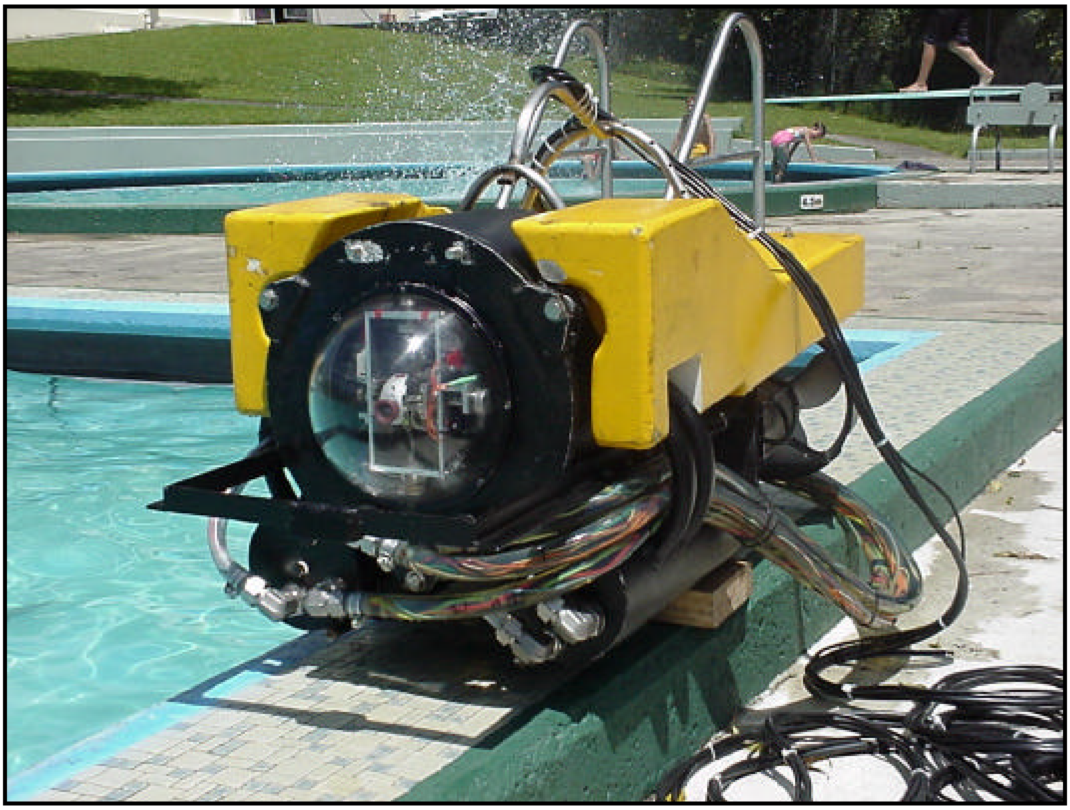


Figure 6.1 THE DELPHINUS ROV AT POOLSIDE.

Once power was applied and the ROV computer had sufficient time to boot up, a Virtual Network connection was established with the laptop. This connection accesses the hard drive of the ROV computer and creates a virtual screen which is displayed by the surface computer.

The LabVIEW VI was run, and the DELPHINUS front panel loaded. To retrieve the video image from the ROV camera, Windows NetMeeting was activated and placed onto the space provided in the front panel. A preliminary test of motor and sensor operation was undertaken at poolside before the ROV was put into the water (refer Figure 6.1), to ensure that any last-minute problems could be identified without the added complication of a leak. The tests checked the direction of the Compass with respect to the ROV heading, the depth of the Pressure transducer, the Tilt sensor (roll and pitch) and the control of each of the four motors.

Once the ROV was released into the water, the stability of the vehicle was established by balancing the chassis. It was found to be too heavy at the front, and 4.7kg were removed from under the main hull. To further level the chassis, 2.2kg was added to the umbilical, ensuring that the ROV was weighted correctly with the body sitting flat just under the surface of the water.

6.1 THE LEAK

Soon after the first water test of the vertical motor in a diving operation, the surface computer lost the network connection to the ROV computer. Initial poolside investigations found a blown fuse in the isolating transformer, but replacement of the fuse did not revive the ROV, and the DELPHINUS was removed from the water for further scrutiny in the lab.

A complete dismantling of the ROV found a leak emanating from one of the Swage-Loc fittings on the main hull, and a pool of water had gathered underneath the computer power supply. The port and starboard hulls were found to be completely dry and intact, with no damage to any of the contained components.

The Swage-Loc fitting of the main hull was loose from handling and travel, and an uncompressed o-ring seal had allowed water to force its way in during the diving motion. Although the power supply was irreparably damaged, the high mounting positions of the remaining computer hardware gave them protection from the water and no harm was done to these devices. The main hull was thoroughly dried, and replacement of the power supply allowed the operational water tests to continue.

6.2 SUB-SURFACE SENSOR BEHAVIOUR

The Compass was observed to accurately output the current heading of the ROV, with a 2? fluctuation in the needle. This fluctuation is due to the fast scan rate of the analogue inputs, and can be easily improved by averaging the values read inside the COMPASS sub-VI. When the ROV turned over 360?, the Compass needle followed the motion. The Tilt sensor was observed to accurately portray the roll and pitch of the ROV chassis, however the Pressure sensor was not able to be tested over a significant depth, and therefore did not show a marked change in position.

6.3 CAMERA

There was a marked delay in the video, as the refresh rate of the camera image via the virtual network connection was too slow. To control the ROV in an underwater environment via the video image, a faster refresh rate is needed, otherwise the operator could risk running the ROV into a object that has not appeared on the video.

6.4 SUBSURFACE MOTOR CONTROL

The motor tests included forward and reverse cycles of the port and starboard motors, the turning motion of the ROV, the diving capability of the vertical thruster, and the left and right movement of the lateral thruster.

6.4.1 ROV in Forward Motion

To measure the velocity of the ROV in a forward motion, a tape measure was laid alongside the pool. The tape measure was marked at 2m intervals over a length of 8m, allowing a sufficient path length for accurate timing.

To record the time taken for the ROV to pass each mark, a person with a stopwatch was located at each 2m interval, and the ROV was placed at the starting position with power applied to the port and starboard motors. After allowing time for the motors to reach full speed, the ROV was released from the start point and all stopwatches began timing. Such a procedure eliminated the variable of operator set-up time (to arrange the respective motor controls). Each person stopped timing when the front of the ROV yellow buoyancy block crossed their mark, and the time measurements were recorded. The vertical and lateral thrusters were switched off to allow the forward velocity to be measured as accurately as possible.

The tests were completed at four different power levels to demonstrate the full range of motor response (20%, 50%, 80% and 100% power). Each run at the different power levels was undertaken at least twice before being averaged and plotted. The velocity profile for the different power levels is shown in Figure 6.2.

At 20% power the ROV took the longest time to reach the 8m mark, with an average of 22 seconds. At 50% power the ROV took an average of 17 seconds to complete the run. At 80% power, the average time was 13 seconds, and at 100%, it was 11.5 seconds.

Up to 80% power, it takes approximately 4 metres to reach a constant velocity, while at 100% power maximum velocity was reached at the 6m mark. At 20% power the maximum velocity is $0.4ms^{-1}$, 50% gives $0.6ms^{-1}$, 80% gives $0.7ms^{-1}$ and 100% power is approximately $0.8ms^{-1}$.

At 80% and 100% power, the ROV was moving considerably faster than previous runs. To compensate for the increased momentum, and to ensure the ROV would not crash into the wall of the pool, the ROV was turned off slightly earlier than at 20% and 50% power. This is the reason for the drop in velocity at the end of the two runs.

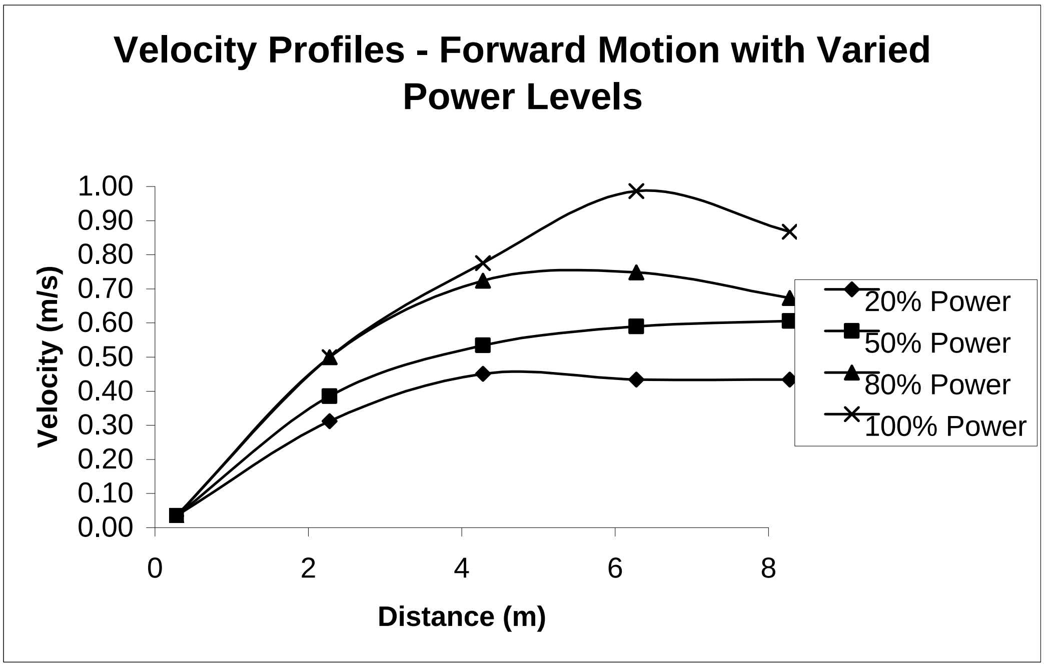


Figure 6.2 VELOCITY PROFILE OF THE ROV IN FORWARD MOTION.

6.4.2 ROV in Reverse Motion

To measure the reverse velocity of the ROV, the same method of measurement as for the forward direction is used, the only difference being that the ROV is turned backwards, and the port and starboard motors were powered in the opposite direction. Again, the vertical and lateral thrusters were off. The velocity profile of the ROV in reverse is shown in Figure 6.3.

At 20% power, the ROV took approximately twice as long to complete the 8 metre distance compared to the time taken when travelling in a forward direction at the same power setting. This was thought to be due to the fact that the ROV was primarily designed to be driven forward, with the flow of water through the thrusters being less constricted when powered in the forward direction. However, during testing out of water, the ROV thrusters were observed to work more efficiently in the forward direction than reverse for the same power setting, indicating that the velocity differences are also due to the usage of drill motors (refer Section 2.2), which have different operating characteristics in forward than reverse.

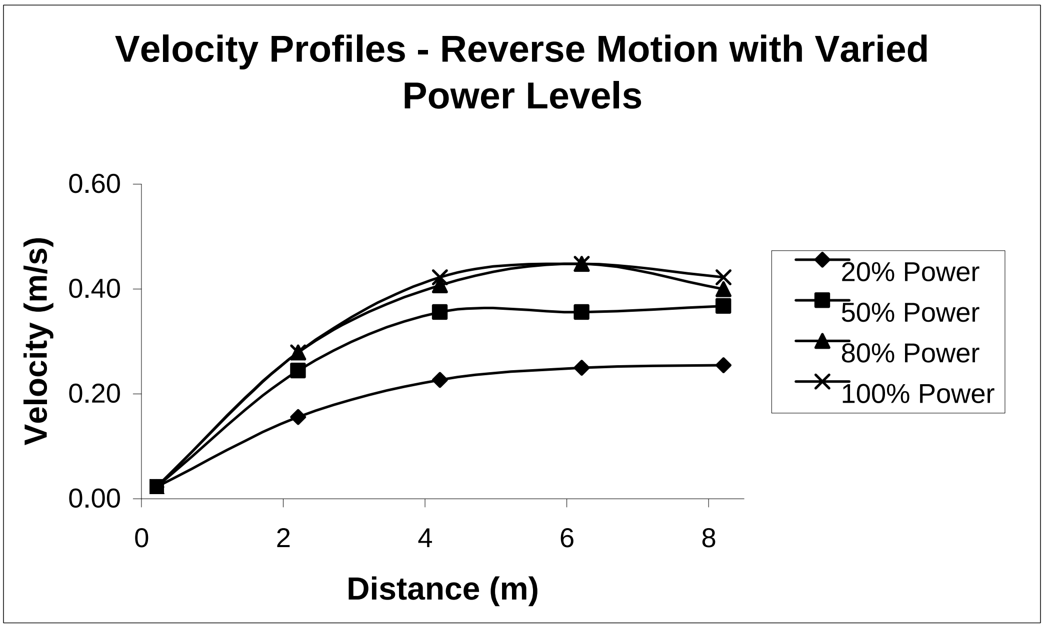


Figure 6.3 **VELOCITY PROFILE OF THE ROV IN REVERSE MOTION.**

The maximum velocity of the ROV is observed to be much slower than for forward motion, with the peak velocity for 100% power being approximately the same value as for 20% power in forward motion.

6.4.3 ROV in Turning Motion - Two Motors

To observe the ROV's smallest turning circle, the starboard and port motors were driven in the forward and reverse directions respectively. A power level of 25% was chosen so as to easily examine the ROV's performance. Five revolutions were completed to account for any timing errors, with the time for each rotation plotted in Figure 6.4. Averaging of the data reveals that the ROV took approximately 7.8 seconds per revolution with the power at 25%. In motion, the ROV was observed to generally rotate about its central axis, however over the period of five revolutions the ROV did drift laterally. This was due to the different velocities of the two motors when powered in opposite directions (as noted in Section 6.4.2).

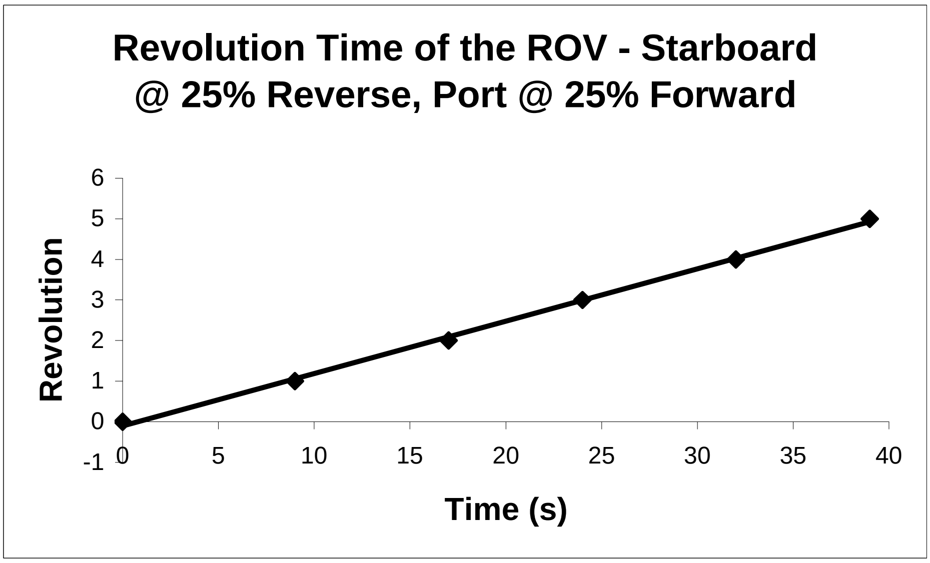


Figure 6.4 ROV REVOLUTION TIME WHEN TWO MOTORS ARE POWERED IN OPPOSITE DIRECTIONS.

6.4.4 ROV in Turning Motion - One Motor

To observe and record the turning motion of the ROV when only one of the rear motors is active, the starboard motor was powered at 100% in the forward direction. Five revolutions were completed and the time for each rotation is recorded in Figure 6.5.

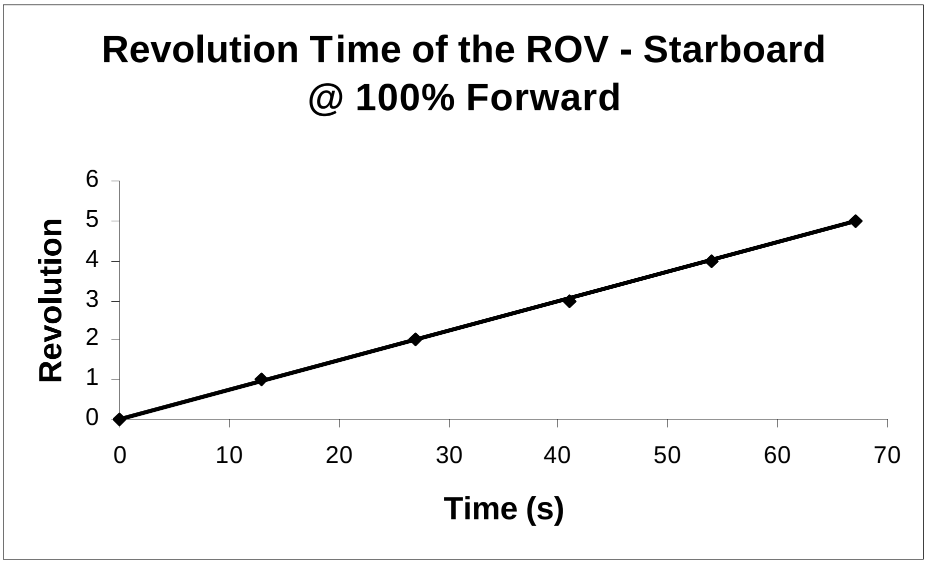


Figure 6.5 ROV REVOLUTION TIME WITH THE STARBOARD MOTOR AT FULL POWER.

Averaging of the data shows that the ROV takes approximately 13.8 seconds to complete a revolution with only the starboard motor at full power, with a turning circle of approximately 2m.

6.4.5 ROV Diving – Vertical Motor

To observe the ROV when diving, all motors were stopped, and the ROV was left floating in the pool. 50% power was applied to the vertical motor, and after approximately 3 seconds the ROV forced itself just under the surface of the water. After the ROV had sunk beneath the surface, the descent to the bottom was rapid, and the ROV covered the 1.3 metre depth in less than 1.5 seconds.

The ROV was then tested to observe the behaviour of forward movement while completely underwater. The port and starboard motors were powered to full speed, and the ROV was driven forward for 1m, before 50% power was applied to the vertical motor. An initial forward motion was observed, before the vertical motor submerged the ROV. The port and starboard motors remained powered moving the ROV forward while still submersed.

It was found that the power to the vertical motor could be removed, and the ROV would remain under the surface while the port and starboard motors were actively pushing the ROV forward. If all motors were stopped, the ROV floated up to the surface in approximately 4 seconds, and remained balanced throughout ascent.

The forward motion of the ROV while submerged was not directly measured, however it appeared to be similar to its surface velocity.

6.4.6 ROV – Lateral Motor

The lateral motor was powered in both directions to observe its effect on the ROV. When the motor was active in the forward direction, the ROV moved to the left in a slightly diagonal direction, in reverse, the ROV moved to the right in a similar diagonal motion. This apparent diagonal movement is most likely due to the off-axis position of the thrusters.

The ROV was observed to function well underwater. The motors were tested for operation in all directions to gather an impression of the behaviour and influence of each on the ROV motion.

7. CONCLUSIONS

7.1 ROV SYSTEM EVALUATION

The original DART ROV was a completely manually-controlled system incapable of autonomous functioning. Simple navigational capabilities and an outdated camera system permitted the ROV to perform only as a remote underwater “eyeball”. At the surface the motors were controlled by a pilot, who also manipulated the camera pointing direction. The heading and depth data was written in text across the black and white image of the video using a simple microcontroller, which also performed other limited duties. Due to the many surface components used to control the ROV (refer Figure 1.8), the system was bulky and complicated.

In comparison to the original system, the DELPHINUS now possesses the resources necessary for autonomous operation. An onboard computer provides a central control system for all the hardware located within the vehicle. The increased processing power of the computer can provide three-dimensional image mapping and analysis of an underwater environment, which can be included in autonomous control algorithms. The processor is able to complete extended periods of data-logging while simultaneously controlling the ROV, monitoring the sensors, and completing a specified task. The computer also permits a range of high-level software to be used by the ROV.

The main control software, LabVIEW, is extremely flexible and well suited for this application. Sensors and motor control elements have been integrated into a front control panel that is simple to interpret and use. A control loop consisting of many sub-VI’s controls the four thrusters, camera orientation, and the displayed video and sensor readings. The software has been developed in a modular manner to allow future additions to be easily incorporated.

The Data Acquisition card captures all the digital and analogue I/O data at a sufficiently fast rate to allow the software to always maintain control, even at the maximum velocity of the ROV. The analogue inputs read in the current heading, depth, roll and pitch, with an additional three inputs available for future applications. The display of the sensor data has been significantly improved with the use of a LabVIEW VI, that displays the sensor data pictorially instead of writing data across the screen as in the original system.

The camera system has been extensively reduced in size and weight, and now provides colour images directly through the network connection to the front panel. An increase in the speed of the network connection would greatly improve the refresh rate of the video to the surface computer. An alternative would be to transfer the video signal directly to the surface, although the USB cable of the camera cannot simply be extended as signal complications arise if it is more than 5m in length.

The motor control and sensing systems are completely contained within the vehicle, and controlled by the central onboard computer. The power electronics are located in a separate hull from the sensors and computer to ensure signal integrity. The limited space within the hulls has been well utilised to ensure room for the addition of future components, such as an underwater lighting control system.

The connections between the hulls and from the umbilical have been designed for easy replacement if different wiring is required. Mechanical alterations to the ROV now allow individual access to the port, starboard and main hulls, saving extensive time if a fault occurs or if alterations are needed. Fault diagnosis is simple, as every component can be removed easily for replacement or repair.

The motor power supply has been designed to allow flexibility in the length of the umbilical, with only a minor adjustment required to allow for the changing voltage drop along the cable. The main supply for the entire ROV has been totally enclosed within a portable container and completely isolated to ensure the electrical safety of the operators.

Although a high power-to-weight ratio was stated in the manuals (refer Section 1.4), the thrusters had less influence than was expected, indicating that the best environment for the ROV is in water with only limited currents (such as lakes or swimming pools). To facilitate longer testing runs, the umbilical should be extended to at least 30m.

7.2 FUTURE WORK

The ROV has been designed to eventually achieve autonomous operation, with the sensing systems and motor control completely contained within the vehicle. Auto-heading and auto-depth functions are well within the current capabilities of the ROV, but to incorporate fully autonomous behaviour (such as identifying a target location, following set paths and environment mapping), the ROV must be equipped with an accurate navigation system.

7.2.1 Autonomous Control

To enable autonomous control, the ROV must be able to constantly determine its **attitude** (heading, pitch and roll), **velocity** and **position** [19]. The attitude of the ROV is obtained via measurements from the Compass and Tilt sensor, but both the velocity and position are unknown.

7.2.1.1 Velocity

To obtain an accurate measure of vehicle speed, a Doppler Velocity Log could be used. This device transmits acoustic energy of a specific frequency and monitors the resulting received reflections. These received signals are Doppler-shifted in frequency from the transmitted signals, and the amount of shift is used to calculate the speed of the vessel. If the bottom is within the range of the transducer, true speed over ground can be found. Typically, a 3MHz system has a range of 5-8m; a 1.5MHz system, 15-25m; and a 500kHz system will reach 50-70m [20]. The choice of sensor is dependent on the maximum depth required of the ROV, and the available funding.

The Doppler Velocity method is preferred over determining the actual speed of each motor and using odometry-based speed calculations, as it would be difficult in an underwater environment to incorporate optical sensors or shaft encoders with the existing motors. Ascertaining vehicle speed from motor speed is also prone to large errors, as the characteristics of each motor must be individually taken into account, and the dynamics of the entire system completely understood. Problems could occur if the vehicle speed is based solely on the motor speed, since if the vehicle became lodged, the motors would still be operational and give a speed reading, but the vehicle would not be moving. Inaccurate readings can also obtained in varying current conditions.

Doppler Velocity Logs that operate from 15VDC are available, allowing operation from the onboard electronics power supply. The sensor can be chosen for a low cost and small size, although additional features such as depth, temperature and ocean current measuring are available (along with a commensurate increase in price).

7.2.1.2 Position

The position of a ROV is usually determined by one of two methods:

- Dead-Reckoning
- Gyroscope technology

Dead-Reckoning involves multiplying the heading of the ROV with vehicle speed, and integrating the obtained velocity vector. Although this is the simplest and cheapest option, the error in Dead-Reckoning accumulates over the distance covered because of the lateral position and speed errors.

Gyroscope technology incurs a higher cost, but has a marked improvement in accuracy. A gyroscope measures acceleration and angular velocity, which is integrated to retrieve the position and speed of the vehicle. A position error from the gyroscope is accumulated over time due to zero-error, which is the bias voltage (similar to the Tilt sensor) output by the gyroscope when it is experiencing no rotation. To account for this error and accurately pinpoint the exact position of the vehicle, a Kalman filter can be used [19]. This filter can be configured to adjust for the error in the measured velocity from the Doppler Velocity log, and also compensate for the position errors of the vehicle by including data from all onboard sensors in its calculations.

A Global Positioning System (GPS) could give an initial position while the ROV is at the surface, and also allow the ROV to reposition itself and correct for navigational errors during operation. An alternative to onboard GPS is to acoustically couple the ROV to a series of GPS buoys, allowing the ROV to determine its current position with respect to the buoy's fixed positions. The limitation to this, however, is the increased development cost and the total reliance on the buoys while the ROV is in operation. If the ROV should need to venture outside of the transmitting range, the buoys will have to be relocated.

The amalgamation of added components, sensors, and filters to create an inertial navigation system is possible due to the incorporation of an onboard computer and data acquisition system. Control loops to complete autonomous functions can be developed in LabVIEW.

The vision system can be used to enable three-dimensional environment mapping, and when used in conjunction with the inertial navigation system could further correct accumulated error in position.

7.2.2 Improving the System

A minor adjustment to the front panel and main program would achieve better control over the motors. By incorporating a virtual joystick to replace the four motor control sliders of the front panel, the flight of the ROV would be much improved when used in manual mode.

If the ROV is to operate out of sight of the operator, a faster video update-rate is needed. This would allow the ROV to explore deeper underwater regions, record autonomous flight, and be able to work in real time with a control algorithm. Two

50W underwater lights donated to the ROV project by Rob Carrillo of Carrillo Underwater Systems need to be incorporated (not included due to the lateness of their arrival), allowing operation of the ROV at night or in dark waters. A digital output on the DAQ card is available to control the lights.

Additional sensors can be incorporated into the main hull if the DAQ I/O card is replaced by a custom made I/O connection system which utilises less space. Manipulators could be added to the frame to perform underwater tasks, monitored by video and controlled either manually or autonomously.

Sonar sensors could map the surrounding environment and form part of an automatic obstacle avoidance system. Strain sensors could be incorporated to monitor the umbilical, with the ROV programmed to realise when it is tangled or under stress, and correct its position accordingly.

Communication through the water without the tether could be a further advancement. To date, the umbilical of the ROV is the main weakness, due to the increased weight at long lengths, and the difficulty to fly into and around underwater locations. If the ROV could be powered internally, it would then technically be totally autonomous. However, major modifications would have to be made to the frame and payload to do this.

7.3 SUMMARY

The developed DELPHINUS ROV has been shown to operate underwater with a maximum velocity of up to $0.8ms^{-1}$ in the forward direction, and $0.4ms^{-1}$ in reverse. A velocity plateau was reached in the reverse direction which meant any power increase above 50% did not affect the speed of the vehicle. If the port and starboard motors were powered in opposite directions, the ROV turned approximately about its axis with a small amount of drift, and if only one motor was powered, the ROV had a 2m turning circle. The ROV was able to dive successfully, and remained stable while moving under the surface.

The advanced processing capabilities of the onboard computer provide the main control system of the ROV and allow for autonomous functioning. The flexibility of an onboard computer permits the incorporation of numerous types of hardware and software. LabVIEW controls the ROV via a front panel which is designed so that an inexperienced operator can easily interpret the system. The software provides a straightforward base with which autonomous control algorithms can be incorporated. The Data Acquisition card provides reliable, fast and adaptable access to onboard sensors and controls, and is easily manipulated in LabVIEW. The heading, roll and pitch of the vehicle are displayed accurately on the front panel, although further testing of the depth sensor (by diving the ROV to a significant depth) is necessary to correctly calibrate the pressure transducer sub-VI.

The camera system has been significantly reduced in size and weight, with the captured images now being in full-colour. Although the network connection is too slow for this application, the video provides a robust foundation for future work.

Each hardware component is easily accessed due to the mechanical alterations, and can be quickly removed for fault diagnosis and repair. The sensors are located separately to reduce interference, and there is space available in each hull for future additions. Specialised underwater lights have been obtained to provide the ROV with the ability to dive in deep water or at night, and can be integrated into the system simply.

The motor power supply is adjustable to allow for variation in umbilical length, and is contained within a small portable enclosure with the remaining ROV power supply components. The ROV is completely isolated to ensure safety, and the connections between the surface and the ROV are easily replaceable. Pressure equalisation for depths of water up to 300m has been provided, and although no great depth has been tested, it has performed well in shallow water for extended periods of time.

The portability of the entire system has been greatly improved, due to the fact that the ROV now operates from a single surface computer, which controls and monitors all video, sensors and the entire motor control system. The network connection allows the software to be altered during operation, which is essential with a submersible mechatron of this size.

The transformation of a ROV shell into the fully functional DELPHINUS ROV has required the incorporation of sensing systems, motor control, and video capture capabilities. To enable the system to perform simple autonomous functions, only minor software enhancements are required, which can be easily made during operation of the vehicle. The straightforward integration of a Doppler Velocity Log, GPS and a Kalman filter will provide accurate speed and positioning of the ROV, allowing complex navigational tasks to be undertaken. The DELPHINUS presents an ideal platform for further underwater autonomous research by the Mechatronics Group.

APPENDIX A : REFERENCES

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APPENDIX B : CD CONTENTS

The attached CD contains the following:

- **Software**
  - LabVIEW main program
  - 87LPC768 c code

- **Schematics**
  - Motor Driver card
  - Motor Power Rectification board
  - Power Supply card
  - Level Shifter board
  - Compass Power Supply board
  - Compass Differential Input board
  - Camera Pan/Tilt board

- **Datasheets**
  - Data Acquisition card
  - 87LPC768 Microcontroller
  - Compass
  - Pressure Transducer
  - Tilt Sensor
  - USB camera

- **Water Trials Video Excerpts**

- **ROV Photo Gallery**