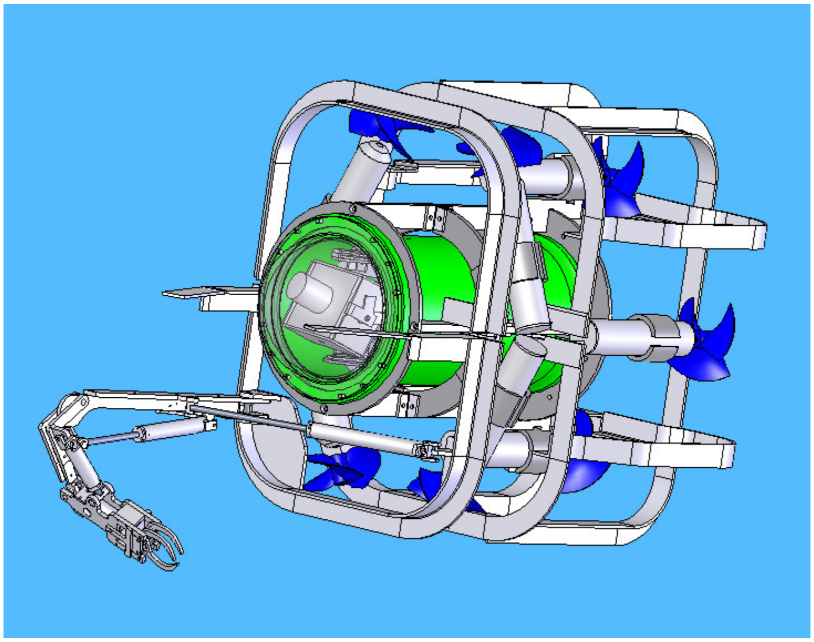
UNIVERSITY OF WATERLOO
UNDERWATER TECHNOLOGY TEAM

Development of a Highly Controllable and Highly Intuitive Remotely Operated Vehicle

June 2, 2006



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Abstract

Remotely operates submersibles have played a major roll as a tool in marine environments since they were first created. Significant advancements in ROV technology has occurred over the years, however, improvements in the intuitiveness and controllability of the vehicles have lagged behind advancements in power and telemetry systems. The University of Waterloo Underwater Technology Team has developed a vehicle for the MATE ROV competition that focuses on intuitiveness and controllability for the pilot. By implementing an intuitive, single-handed control system and eight independently controlled thrusters, the vehicle is highly controllable, capable of translating in any direction and rotating about any axis. A unique pan and tilt camera system has been incorporated allowing the camera position to be controlled by the position of the pilot's head through the use of a head mounted display and a head tracking system. This vision system immerses the pilot into the environment ensuring that both the control of the camera and an understanding of the images being returned are highly intuitive.

A majority of the components incorporated into the system have been custom designed specifically for this vehicle. Through the development process the involved students gained much experience in the design of submersible systems. Senior members of the group also gained significant team and project management skills.

1.0 Introduction

Remotely operated vehicles (ROVs) are an integral part of subsea research and operations. They are used in many applications, including inshore, offshore and pipeline inspections, maintenance and construction, maritime security, scientific research, and search and rescue. [1]

The University of Waterloo Underwater Technology Team [(UW)^{2}TT] has developed a highly intuitive and controllable ROV for the 2006 MATE ROV Competition, which will be held at the NASA Johnson Space Center's Neutral Buoyancy Lab (NLB) in Clear Lake, Texas. The competition focuses on the role of ROVs for construction and maintenance of the "next generation ocean observing systems" [2].

The team's ROV is designed to complete two tasks in the competition's EXPLORER class. For the first task, a cable-laying ship has deployed the central node's trawl-resistant frame and installed the submarine fiber optic cable from the frame to the shore station. The (UW)^{2}TT ROV must complete the node by transporting the electronics module to the frame, installing the electronics module in the frame, opening the frame door, and inserting the submarine power/communications cable connector into one of the open ports on the module. [2] The second task requires the ROV to lay a cable along a route that consists of four waypoints. The ROV will retrieve the instrument cable from an open box on the sea floor, lay the cable along the required route, and then insert the cable connector into the appropriately labeled open port on the electronics module. [2]

The following report outlines (UW)^{2}TT's design philosophy and strategy, as well as the complete ROV design and improvements for the future.

2.0 Design Philosophy

Modern commercially available submersible vehicles have significant technical advancements when compared to the technologies employed in their predecessors. ROVs have evolved from using topside analog circuitry with separate power lines for individual thrusters to vehicles that use digital telemetry by means of fiber optic networks. Despite these significant improvements in electrical and software architecture, vehicles continue to use joysticks, a rudimentary user interface, for their control. With this in mind the Waterloo team focused on creating a vehicle that was both highly controllable as well as highly intuitive.

User interfaces for the majority of vehicles on the market today use either one or two joysticks for vehicle control, depending on the thruster configuration for the vehicle. When camera pan and tilt functions are available the control consol often also uses a third manually operated input. When operators first sit down to pilot a vehicle it is not immediately understood what functions each of the inputs control. Even once the inputs are understood control is not intuitive until the operator has had significant practice time with the vehicle. The team surmised that the major issues with the current control systems are:

- Orientation of the joysticks does not match the orientation of the acceleration direction experienced by the vehicle. (i.e. moving the left stick back and forth may result in a forward and reverse thrust whereas moving the right stick back and forth may result in an up and down thrust)
- Multi-handed control requires coordination and the use of both hands. Hands are the most dexterous parts of the body and if freed may be used for control of other components of the vehicle.

The method in which information is returned to the pilot with commercially available vehicles was also identified as affecting the intuitiveness of the vehicle. When a fixed screen in front of the pilot displays the video from the pan and tilt camera, there are no indicators as to the direction the camera is pointed. This becomes particularly detrimental to the operation of the vehicle when the direction of travel is not in line with the direction the camera is pointed, as the operator must mentally orient frames of reference.

To overcome the issues with vehicle and camera control the Waterloo team focused on the design of the user interface. The Waterloo vehicle interface uses a 3dConnexion "Space Mouse" (force input device) to allow the pilot to control the vehicle. It also uses a head mounted display (HMD) for viewing the image returned from the camera, as well as a head tracker which allows the pilot to control the position of the camera through motion of their head. See Figure 1 below, for images of these systems.

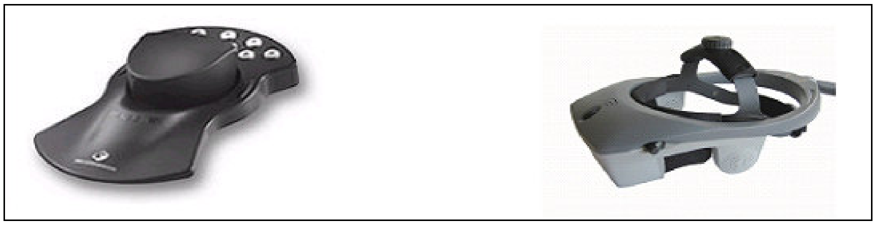


Figure 1: 3dConnexion Space Mouse [3] and NVISOR SX HMD [4]

The space mouse is a device that is operated with a single hand; it measures the forces and moments applied to it. Through software algorithms to determine what signals to send to the thrusters, the force and moment applied to the space mouse by the pilot is amplified and applied to the vehicle. This method of control overcomes both of the major issues identified with the control of modern commercially available vehicles. To overcome the challenges arising from modern pan and tilt cameras, a head mounted display with a head tracker is used. By using this system, the pilot will both have an understating of the position of the camera at all times as well as have the ability to maneuver the camera while still flying the vehicle. Figure 2 shows the information flow from the pilot to the various devices and from the devices back to the pilot. Components that are on the topside are shown in orange and components that are in or attached to the vehicle are shown in blue.

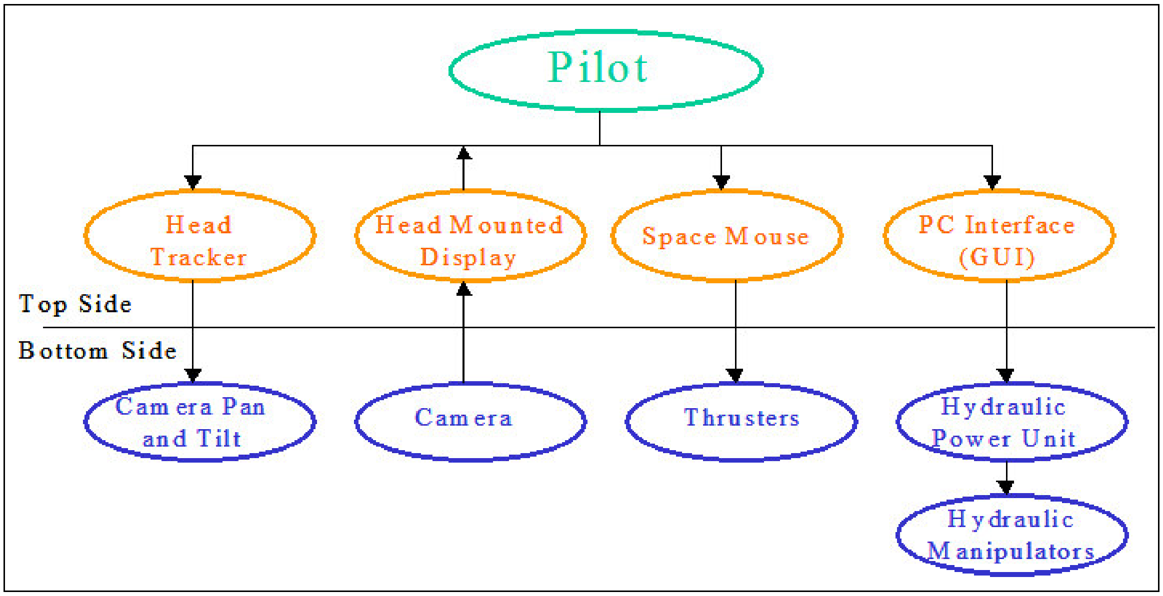


Figure 2: Information Flow

Each of the components related to the systems displayed in Figure 2 are outlined in the following sections.

2.1 Thruster Control System

When considering thrusters with respect to the controllability of a vehicle two key issues must be addressed. The first is the thruster configuration (how the thrusters are positioned on the vehicle) and the second is what methods of control and algorithms will be used.

2.1.1 Input Device Selection and Operation

When an object is in an unconstrained environment such as when it is free-floating and submerged in a body of water it has six degrees of freedom (DOF). Given this freedom and an appropriate thruster configuration it is possible to accelerate the vehicle in all three directions and about all three axes. In order to control a system with n degrees of freedom, n control inputs must be available. Therefore for a vehicle with the maximum controllability (six DOF) such as the Waterloo Vehicle, six control inputs are required. Using a series of small deflection sensors, the Space Mouse allows the pilot to intuitively input the desired 3-component vector force (Figure 3a and 3c) and three-component vector moment (Figure 3b, 3d) into the topside control computer via an RS-232 connection.

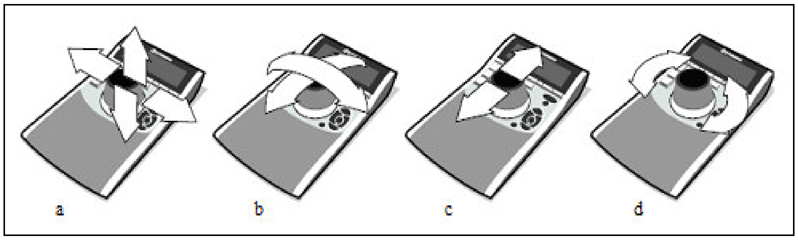


Figure 3: Space Mouse Degrees of Freedom [5]

The topside control computer monitors the force applied to this device, and through an algorithm the appropriate thrusters are run.

2.1.2 Thruster Configuration and Algorithm Design

For all ROVs the thruster configuration is the major factor determining the controllability of the vehicle. Since any vehicle has a maximum of six degrees of freedom, a minimum of six independently controlled thrusters must be on board in order to have full six degree of freedom controllability. Increasing the number of thrusters above six will not increase the controllability of the vehicle. However, to optimize vehicle efficiency and performance, eight independently controlled thrusters were used on the Waterloo vehicle. Most commercially available ROVs have the equivalent of four independently controlled thrusters resulting in less controllability. Figure 4 shows the thruster configuration on the Waterloo vehicle that allows for full six degree of freedom control.

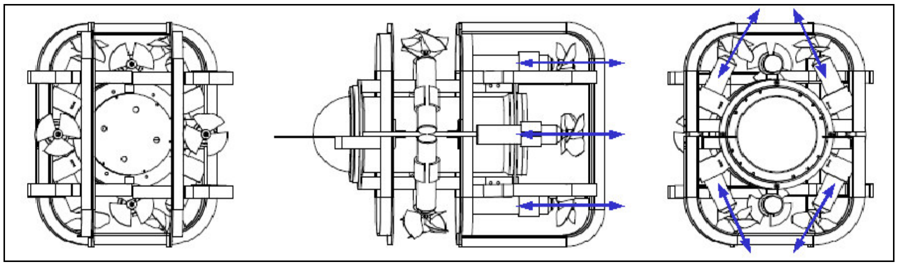


Figure 4: Thruster Configuration

The blue directional arrows represent the possible force vectors that each thruster can exert onto the vehicle. By varying the direction and force applied by each thruster, a force and moment can be applied to the vehicle in any direction allowing for maximum controllability.

Given the input vector force and moment from the Space Mouse an algorithm to determine the appropriate force from each thruster is required. For a derivation of the algorithm used see Appendix A. The state equations result in six equations (one for each force and each moment) and eight unknowns (force from each thruster). Because there are two extra unknowns, it is possible to set two of the thrusters to arbitrary values. The remaining thrusters are capable of obtaining a valid solution for any set of desired forces and moments applied to the vehicle. The advantage of the extra thrusters is that by setting these appropriately the total power required to produce the desired force state is minimized.

2.1.3 Thruster Design

The performance of the vehicle is directly related to the available power and the efficiency of the thrusters. To optimize the efficiency of the thrusters they must be matched to the drag of the vehicle at the desired optimal running speed. An optimal vehicle speed of 1.5 knots was selected and thruster design was performed based on this selection. While traveling at 1.5 knots the vehicle drag was estimated to be 80 N meaning that at the desired operating speed each horizontal thruster is required to produce 20 N of thrust. To hydro-dynamically optimize the design for the operating condition of 20 N thrust while traveling at 1.5 knots, standard drag equations were used in conjunction with a MathCAD worksheet (See Appendix B) and an Excel Macro. The diameter, pitch and blade area of the propeller were systematically varied and the thrust and power calculated for each permutation. The combination of parameters that resulted in the minimum power consumption while still meeting the required thrust was selected. Figure 5 shows a graph of the power consumption required to produce 20 N thrust while traveling at 1.5 knots over a range of parameters.

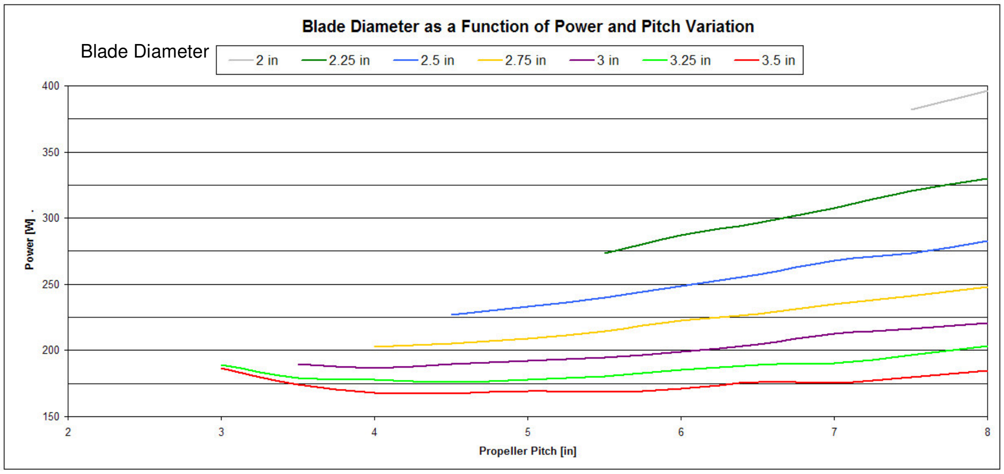


Figure 5: Effects of Blade Diameter and Pitch Variation

To calculate the blade performance the MathCAD sheet was set up to calculate the forces by decoupling the flow into normal and tangential components at all points along the blade. Using vector addition of the resulting forces, the thrust and torque were calculated. A propeller with an outer diameter of 3.5 in (89 mm) and a pitch of 4.25 in (108 mm) was selected since this is the design that provides the desired thrust with the minimum power consumption. Right handed and left handed propellers were then modeled using Solid Works and manufactured by Stratasys, Inc. using Fused Deposition Modeling (FDM), a rapid prototyping technique. See Figure 6 for images of a completed propeller.

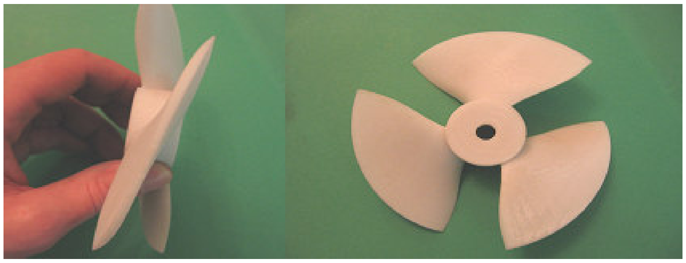


Figure 6: Completed propeller

By developing custom propellers that have been optimized specifically for this vehicle, the Waterloo team was able to increase the peak thrust, and thus the performance of the vehicle.

A commercially available motor capable of producing the required torque and RPM near the optimal operating point was selected and used for the design. The motor is mounted inside a custom housing that contains both ball and thrust bearings to react to the generated loads. An o-ring shaft seal is used given the shallow operating conditions. Minor modifications to the design are required to allow for a significantly improved depth rating. Figure 7 shows a schematic with the cross section of the custom thruster design.

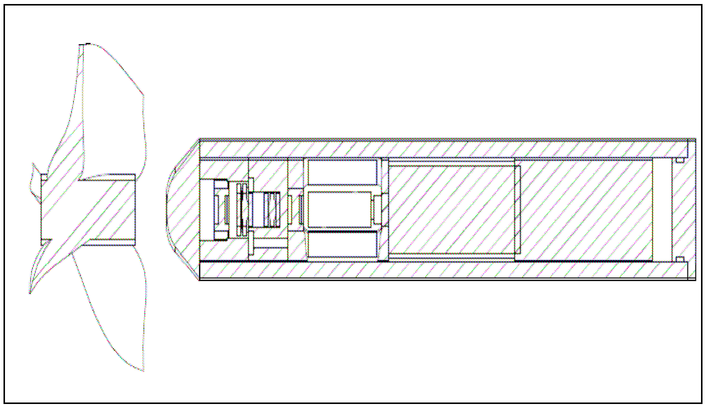


Figure 7: Thruster Assembly

2.1.4 Motor Control Board

The motor control electronics consist of a number of boards integrated with a number of conductive heat sinks, designed specifically for the circular cross section of the electronics housing. The board uses a PIC microcontroller connected to eight independently controlled H-bridge chips. By varying the signals to the H-bridge chips the microcontroller is capable of driving the thrusters at a variety of speeds and in both directions. See Appendix C for a schematic of the motor control board.

2.2 Pan and Tilt Camera System

The camera system of an ROV is the primary sensory input that a pilot's decisions are based on. Because of this, it is critical that control of the camera be highly intuitive. It is also critical that interpretation of the images being returned is highly intuitive. Creating an immersive experience for the pilot and making him or her feel as if they are a part of the ROV significantly improves both control of the camera as well as the ability to correctly interpret the visual information.

2.2.1 Head Mounted Display and Head Tracker

By convincingly immersing the pilot into the ROV the intuitive nature of the system will significantly improve. A high quality head mounted display (HMD) from NVIS Inc. was supplied to the team for use. This system provides a 60° viewing angle with 1280x1024 resolution. The HMD headset has mounting holes as part of the unit that can be used for integration with a head-tracking device. An integrated magnetometer and accelerometer device measures the orientation of the pilot's head and feeds this information into the topside control computer via an RS-232 connection.

2.2.2 Camera and Pan and Tilt Mechanism

By monitoring the position of the pilot's head and based on calibration values, the computer calculates where to position the camera. The pan and tilt mechanism uses two independently controlled micro servos to drive the mechanism. One servo controls the pan of the camera and the other controls the tilt. The mechanism is custom-designed specifically for the Iqinvision IQeye501 camera and constructed from aluminum sheet that has been water jet cut and then bent into shape. With a resolution of 1280x720, high quality, low light performance and a small package, this camera is ideal for use with submersible vehicles.

2.2.3 Pan and Tilt Control Board

To manipulate the angular position of the servos a pulse width modulated signal must be supplied. The custom designed pan and tilt control board communicates via an RS-232 connection. Command signals are sent from the topside software directing the board how to position the two drive servos. Figure 8 shows the completed and populated pan and tilt camera board.

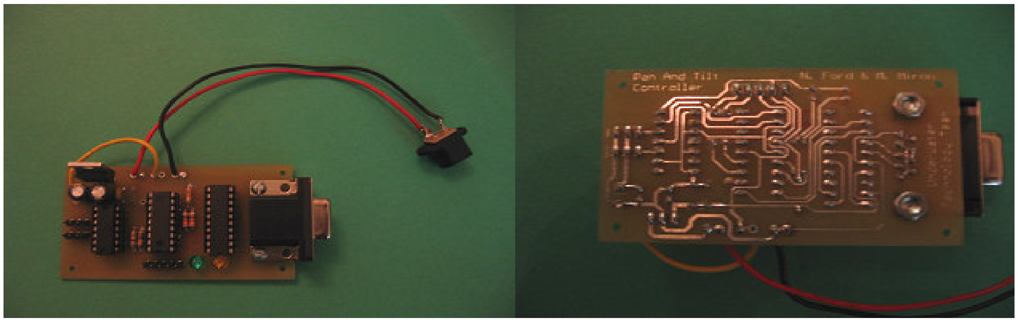


Figure 8: Pan and tilt camera board

2.3 Hydraulic Power Unit / Hydraulic Arm and Clamps

As vehicles become smaller the tendency is to remove components, thereby decreasing vehicle functionality. Most commercially available inspection class systems do not have a manipulator or have one that gives very limited functionality. By integrating an arm onto the Waterloo vehicle that is capable of multiple degrees of freedom, the pilot will have increased control of the vehicle when compared to currently available inspection class vehicles. Strategies to minimize the size and weight of the arm were required to allow a highly controllable arm to be feasible on a small vehicle.

2.3.1 Hydraulic Concept and Hydraulic Power Unit (HPU)

Two major concepts are unique about the hydraulic system design for the Waterloo vehicle.

1) The system uses water as the working fluid.
2) The hydraulic actuators do not involve a spring and only require a single fluid port where the water is both forced into as well as sucked out of the cylinder.

Water is an ideal fluid for submersible hydraulic systems when low flow rates are used. By using surrounding fluid as the reservoir it eliminates the need for added components. It also ensures that damage is not caused to the environment by releasing used oil when seals leak or fail. Another strategy to decrease size and weight is reducing the size of the hydraulic cylinders.

Typical single acting cylinders use a spring inside the cylinder to force the fluid from the cylinder into a reservoir. This strategy requires space within the cylinder for the spring. It also decreases the total force a cylinder can exert given a specified working pressure, as the spring opposes the force applied by the fluid pressure. Double acting cylinders do not involve a spring but rather a port on both sides of the diaphragm to allow for high-pressure fluid to be forced into both sides of the cylinder. A double acting cylinder requires more seals in the cylinder as well as more complicated hydraulic circuitry.

To overcome both of these issues, cylinders where the fluid is both forced into the chamber as well as sucked out were designed and the HPU was designed to accommodate this unique cylinder style. Appendix D shows the schematic for the HPU. A single pump is used in the HPU to force water into a high-pressure chamber and suck water out of a low-pressure chamber. When these chambers are connected by means of opening solenoid valves to the various hydraulic cylinders, the water is either forced in or sucked out. By using this strategy the size of the hydraulic components is reduced allowing for hydraulics to be used on small vehicles, thereby increasing their functionality and the degree to which they can be controlled.

2.3.2 Arm Mechanism and Cylinders

The arm is designed specifically for the competition tasks. It is capable of easily reaching down below the level of the vehicle to grab objects located on the pool bottom. There are three degrees of freedom within the arm, plus an extra for the claw. By having the ability to manipulate the arm with three degrees of freedom the operator can position the claw in any orientation within the range of the cylinders. This design allows for a highly controllable system, increasing the capabilities of the Waterloo vehicle. Control of the arm is facilitated by the topside user interface. Through software controls the pilot is able to select if the arm should be opening, closing or in a no flow state. Figure 9 shows a cross sectional drawing of a cylinder. Figure 10 shows an image of a completed cylinder.

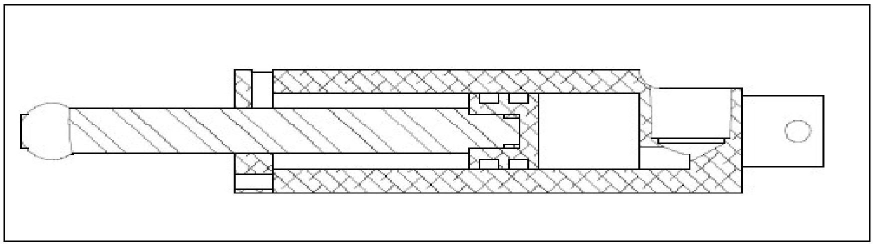


Figure 9: Cross Sectional Cylinder Drawing

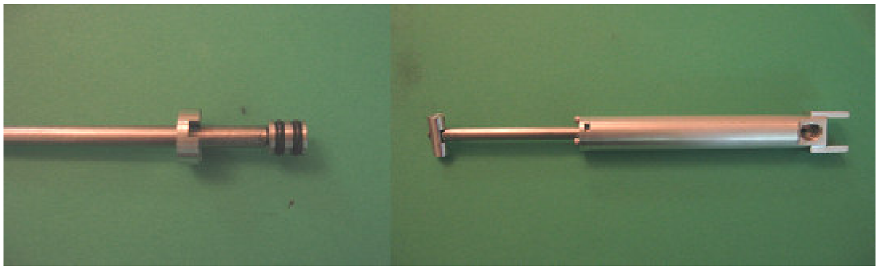


Figure 10: Completed cylinder

3.0 Support Systems

To allow the highly intuitive and highly controllable systems to operate, support systems are required. The Power, Telemetry (Data Transmission) and Structural components of the vehicle are discussed below.

3.1 Power

Given the ambitious vehicle controllability and thrust requirements and the competition-imposed limits on voltage and current, the power system design is critical to the controllability of the vehicle. The motor power was isolated from the electronics power on the topside to eliminate any issues with noise in the electronics generated from the motor back EMF. An electronics power budget was calculated based on the system components being used, the selected power converters, and their efficiencies.

Based on the power budget for the electronics and the power budget for the motors the two pairs of power conductors in the umbilical were specified. To minimize power losses in the line, the peak feasible voltage is used. The competition specifies a voltage limit of 51 VDC. A custom bottom side power module is used to drop the voltage from the main power line to the various power busses required on the vehicle. See Appendix E for a schematic of the vehicle power system. This power module incorporates conductive heat sinks to dissipate heat from the converters to the canister and then into the surrounding water.

3.2 Telemetry

Telemetry or data communication is an important aspect of all ROVs. The telemetry system on Waterloo's vehicle is both reliable and highly flexible. Many systems incorporate a large number of conductors in the umbilical, each to control or communicate with a unique device. The Waterloo vehicle is developed around an Ethernet network. Within the umbilical are two individually shielded twisted-pair wires carrying the data packets between the vehicle and the surface. An on board switch manages communication with the two Ethernet devices contained within the vehicle. One of these devices is the Ethernet camera and the other is a four port serial server. The serial server is a device that creates virtual RS-232 ports on any computer connected to the network. This device allows the topside GUI to communicate with the various custom boards as if they were plugged into a port on the computer directly. See Appendix F for a schematic of the vehicle communication structure. By using an Ethernet network on board the vehicle, the vehicle may be easily expanded to support a wide range of additional devices, allowing the standard vehicle to perform a large variety of tasks.

3.3 Umbilical

A vehicle's umbilical is its lifeline. Ensuring that the vehicle is able to receive power and instructions over a well designed and highly reliable cable will have significant benefits in harsh environments and when the system absolutely cannot fail. The umbilical for Waterloo's vehicle was custom designed by Leoni Elocab based on the specified power and telemetry requirements. Umbilicals can often pose issues regarding the controllability of a vehicle, particularly in environments that have high flow. Due to the drag on the umbilical while it moves through the water the vehicle often experiences a pitching force. This drastically impedes the controllability of the vehicle. The ability of Waterloo's vehicle to apply a moment in any direction will allow it to compensate for any pull on the vehicle as a result of the umbilical. To reduce the pull caused by the umbilical it has been designed to be neutrally buoyant and have as small a cross sectional diameter as possible in order to reduce drag.

3.4 Body / Frame

To hold the electronics a pressure vessel was designed, capable of safely being submerged to 61 m (200 ft). A hemispherical acrylic dome is used on the front of the housing to accommodate the pan and tilt camera. A bulkhead at the back of the housing incorporates four threaded holes for wet mate-able connectors to interface with various external systems (thrusters, HPU, topside power and topside telemetry). The housing was designed using analytical calculations in MathCAD and further analysis was performed using ANSYS finite element (FEA) software.
The housing body consists of three parts welded together. The tube was rolled from aluminum sheet and the end flanges were machined to allow for fastening holes and precise fitting of the o-ring seals. Figure 11 shows the complete housing.

Figure 11: Complete housing

4.0 Description of a Challenge

The University of Waterloo is well known for the quality of its engineering program. A major component of this program is the cooperative education system. Students alternate between four months of work term and four months of school term. This provides students with excellent work experience, significantly enhancing their education. However, it poses major problems for school teams. (UW)^{2}TT was established toward the end of the Fall 2005 term. During the Winter 2006 term the team leader was away on work term but was capable of returning to Waterloo for weekend meetings and design reviews. Other major members of the team were out of town, out of province and even out of the country during this period. The ability to communicate ideas effectively and discuss issues when team members were time zones apart resulted in significantly less progress than was originally estimated and ultimately required in order to construct a fully operational vehicle with the significant technological improvements that were desired. Despite the many technical challenges that the team faced through the design and construction of the vehicle, it is the communication challenge that was at the root of many problems. A variety of over-internet communication systems were used to assist the team with long distance communication.

5.0 Trouble Shooting Techniques

As a result of the ambitious and highly innovative design, the Waterloo team faced many technical problems and used a systematic approach to the solution of each. A flowchart representation of the troubleshooting process used is shown in Figure 12**.**

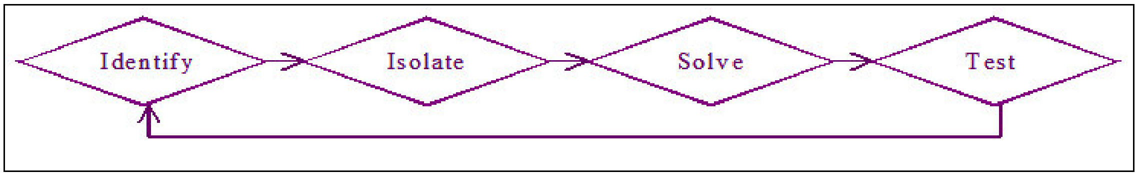


Figure 12: Troubleshooting process flow

This format was followed with much success throughout the design and construction of the vehicle systems. An example of its use can be seen in the design of the hydraulic system. The Waterloo team identified that the pressure required to actuate single acting cylinders with the desired capabilities was too great given the 1.03 MPa (150 psi) competition limit. After isolating the spring as the problem, an innovative solution was created. The solution involves a custom designed cylinder, where the fluid is both forced into the chamber as well as sucked out through a single port, eliminating the need for a spring. Through modeling, it was then shown that the new cylinder design is ideal for the specified problem.

6.0 Lesson Learned / Skill Gained

Throughout the project all members gained a combination of both technical and personal skills. As the mission statement for the team says, the purpose of the team is not only the development of technology to advance the industry but also to educate and develop the student members so that they may develop as highly skilled members of society, capable of influencing the marine or other industries.

The team is entirely student run, relying on its members to raise funds and manage all aspects of the design and build phase of the vehicle. Through this team structure, senior members gained significant team management and project management skills. All members of the team also gained design experience, as they were required to justify their design decisions and make modifications to their designs based on comments and suggestions from fellow students. A majority of the skills required to complete the vehicle were within the combined skill-set of the team and through discussions and design reviews the team was able to develop all aspects of the vehicle. A major skill added to the skill-set of the team is the ability to create mechanical designs and drawings that are both easy to build from as well as cost effective.

7.0 Future Improvements

Throughout the design of the vehicle many ideas were considered but were not implemented due to a lack of time and a lack of available funding. The design focused on the controllability and intuitiveness of the vehicle. The team was successful in developing a vehicle that met the design focus, however many improvements to the existing system as well as implementation of new systems will allow for even further controllability of the vehicle. A number of these improvements are discussed below.

- Sleeve for Arm Control

The vehicle itself has a highly intuitive method for control. However, the hydraulic arm must currently be operated one cylinder at a time through the graphical user interface. By providing the pilot with a sleeve system that monitors the position of their arm and hand, intuitive control of the robotic arm will be possible. This control strategy will allow the pilot to become further immersed into the system and the idea that they are the vehicle.

- Rotary Joints for the Arm

Using the hydraulic cylinders provides significant force to control the arm; however, there is a limited range of motion. Significant consideration is required to ensure that interferences do not occur during folding and stowing of the arm. By using rotary joints rather than cylinders greater controllability of the arm will be possible.

- Rate Controlled Vehicle

Currently the vehicle is force controlled. The pilot inputs a force into the Space Mouse and this force is then amplified and applied to the vehicle. By incorporating position and attitude sensors on the vehicle the velocities in all six degrees of motion may be determined. With this information a controller may be designed to interpret Space Mouse inputs as the desired rate of travel of the vehicle rather than the desired forces. Using this strategy will allow the vehicle to autonomously compensate for any disturbances rather than having the pilot compensate.

- Stereoscopic Vision

The HMD being supplied by NVIS Inc. allows for individual video feeds to each eye. This feature allows for stereoscopic vision, a technology based on the fact that depth perception is largely based on the slightly different points of view an individual obtains from each eye. Two cameras in the vehicle, slightly separated, will provide two unique images of the vehicle environment to the pilot and he/she will intuitively be able to obtain depth information about that environment.

Other design concepts to improve vehicle performance have been identified but the items presented are the ones most capable of further improving the intuitiveness and controllability of the system.

8.0 Applications of Technology

8.1 OceanWorks International Inc

OceanWorks International Inc (OWC) is an independent company specializing in manned and unmanned subsea work systems for key international marine industries. The company's services include design, manufacturing, test and integration, project management, training and technical support for both the commercial industry and military clients worldwide. [6]

OWC offers support for various engineering disciplines including:

- Mechanical Design
- Structural Design
- Hydraulic Design
- Control System Design
- Power System Design

Industry standard design tools such as Pro Engineer, AutoCAD, ANSYS, Tango and Algor are used to provide efficient and accurate designs. [6]

In August 2005, OWC announced the signing of a contract to design and manufacture a subsea cabled observatory, called VENUS, in Saanich Inlet for the University of Victoria. OceanWorks scope of work included the design and manufacture of the shore station equipment, the cabled observatory node, and the science instrument interface modules. [6]

8.2 The VENUS Project

VENUS is “a marine station on the seafloor, a public attraction in the ocean, a classroom of the sea” [7]. The VENUS Facility (Victoria Experimental Network Under the Sea) is a real-time information center that delivers observations from the seafloor and water column via the Internet to researchers across the country and the world. [7] Scientists will be able to respond to oceanic events, schedule additional observations, and observe rare and important phenomena, all in real-time. The VENUS cables will also deliver power to instruments, lights, and ROVs. [7]

Three arrays were planned: one in the Strait of Georgia, one in Saanich Inlet, and one in the Juan de Fuca Strait. Saanich Inlet was launched in January 2006. The VENUS array in Saanich Inlet serves a variety of project goals, including research, instrument testing, and evaluation of cabled observatory performance. Extending from the shore facilities of the Institute of Ocean Sciences, the VENUS array in the Inlet includes a shore station, the cable, a fully functioning VENUS Node, and a variety of oceanographic instruments that measure temperature, salinity, dissolved oxygen concentration, turbidity, currents, ambient sound, and the vertical distribution of zooplankton and fish. [7]

Figures 13, 14, and 15, below, are images from the VENUS array in Saanich Inlet.

Figure 13: VENUS node [7]

Figure 14: VENUS Instrument Platform [7]

Figure 15: The quillback rockfish [7]

VENUS is designed to support a broad range of scientific observing systems expected to evolve in response to advances in understanding and technology. A fundamental goal of VENUS is to develop and support a pan-Canadian Oceans Community through the observing platforms and the collaboration forum built into the data management system. [7]

9.0 Acknowledgements

(UW)^{2}TT would like to thank the following parties for their contribution to our team's efforts.

3Dconnexion A Logitech Company	(http://www.3dconnexion.com/index.php)	-Space mouse
ANSYS	(http://www.ansys.com/)	-FEA/CFD Software
ASI Group	(http://www.asi-group.com/)	-Funding, engineering support and testing facility
GPSI Global Plastic Services International	(http://www.globalplastics.ca/)	-Dome
IQinvision	(http://www.iqeye.com/)	-Camera
The Quality Connection LEONI Wire · Cable · Wiring Systems	(http://www.leoni-tmcs.com/)	-Umbilical
MH	(http://www.morrisonhershfield.com/)	-Funding
NVIS	(http://www.nvisinc.com/)	-Head mounted display
OceanWorks International	(http://www.oceanworks.cc)	-Funding and engineering support
PCBexpress	(http://www.pcbexpress.com/)	-Printed circuit boards
Profile Waterjet Cutting	(http://www.profilewaterjet.com/)	-Components
SDP/SI Stock Drive Products/Sterling Instrument	(http://www.sdp-si.com/)	-Bearings
SOTA	(www.sotawall.com)	-Funding
STRATASYS	(http://www.stratasys.com/)	-Propellers
University of Waterloo Engineering Machine Shop	(http://www.eng.uwaterloo.ca/%7Eengshop/index.html)	-Components

10.0 Budget

	DESCRIPTION	EXPENSE (CAD)	DEPOSIT (CAD)
1	Monetary Donations - *ASI Group, Morrison Hershfield, OceanWorks*		$2,000.00
2	Space Mouse - *3dConnexion*	$0.00	
3	FEA software - *ANSYS*	$0.00	
4	dome - *Global Plastics*	$0.00	
5	camera - *Iqinvision*	$0.00	
6	umbilical - *Leoni Elocab*	$0.00	
7	head mounted display - *NVIS*	$0.00	
8	printed circuit boards - *PCB Express*	$0.00	
9	component manufacture - *Profile Waterjet*	$0.00	
10	bearings - *SDP SI*	$0.00	
11	rapid prototyping service for propellers - *Stratasys Inc*	$0.00	
12	internal chassis - *UW & Profile Waterjet*	$0.00	
13	AC/DC converter - *University of Waterloo(UW)*	$0.00	
14	Body/Frame Material Costs	-$400.00	
15	Serial Port Server, RS-232	-$121.26	
16	Board components & misc. electronics	-$150.00	
17	*connector and cables	-$350.00	
18	servos for pan and tilt camera	-$31.05	
19	LB packing tape	-$3.29	
20	two DC gear motors (temporary)	-$43.05	
21	two DC gear motors (temporary)	-$43.05	
22	manufacturing of components - *UW Machine Shop*	-$640.00	
23	*head tracker	-$530.00	
24	*motors	-$1,600.00	
25	*motor housings	-$1,000.00	
26	Travel Stipend		$1,000.00
27	*Travel Costs (flight + taxi) - for 3 people	-$1,500.00	
28	*Hotel Costs	-$350.00	
29	*Shipping	-$600.00	
	TOTAL (CAD)	**-$7,361.70**	**$3,000.00**
	TOTAL (USD) using exchange rate of Jun2/06	**-$6,691.84**	**$2,727.02**

*estimated costs

11.0 References

[1] www.seabotix.com

[2] “Competition Scenarios and Mission Tasks: EXPLORER AND RANGER” www.marinetech.org/rov_competition/2006/2006_Scenario_Missions_FINAL.pdf

[3] http://www.3dconnexion.com/products/3a3.php

[4] http://www.nvisinc.com/literature/nvisor-sx_brochure.pdf

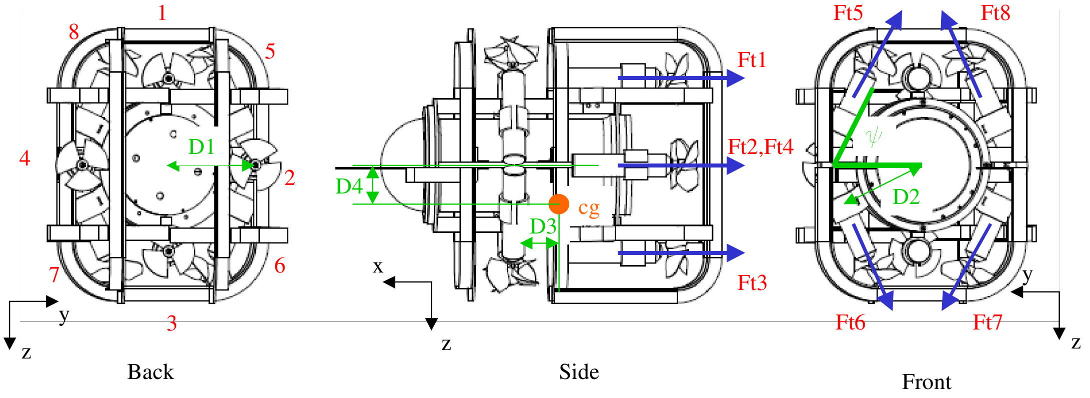
[5] http://www.3dconnexion.com

[6] www.oceanworks.cc

[7] www.venus.uvic.ca

Appendix A: Thruster Algorithm

A desired vector force and vector moment must be applied to the vehicle by appropriately setting the thrust from each of the eight thrusters.



Back

Side

Front

Thrusters have been numbered 1 through 8 and the positive force directions assigned based on the thruster direction. Values for the various dimensions are listed below.

$\psi := 63\text{deg}$

$D1 := 0.132$

$D2 := 0.15$

$D3 := 0.065$

$D4 := 0.081$

(All dimensions in units of meters)

Based on the dimensions of the vehicle, a system of six equations with eight unknowns may be determined. These equations are represented by the first six rows of the M matrix shown below.

$$M := \begin{array}{ccccccccl} \text{Ft1} & \text{Ft2} & \text{Ft3} & \text{Ft4} & \text{Ft5} & \text{Ft6} & \text{Ft7} & \text{Ft8} & \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & =\text{Fx} \\ 0 & 0 & 0 & 0 & -\cos(\psi) & -\cos(\psi) & \cos(\psi) & \cos(\psi) & =\text{Fy} \\ 0 & 0 & 0 & 0 & -\sin(\psi) & \sin(\psi) & \sin(\psi) & -\sin(\psi) & =\text{Fz} \\ 0 & 0 & 0 & 0 & -D2 & D2 & -D2 & D2 & =\text{Mx} \\ (D1+D4) & D4 & -(D1-D4) & D4 & D3\cdot\sin(\psi) & -D3\cdot\sin(\psi) & -D3\cdot\sin(\psi) & D3\cdot\sin(\psi) & =\text{My} \\ 0 & -D1 & 0 & D1 & -D3\cdot\cos(\psi) & -D3\cdot\cos(\psi) & D3\cdot\cos(\psi) & D3\cdot\cos(\psi) & =\text{Mz} \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & =\text{a} \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & =\text{b} \end{array}$$

Since the free body diagram results in only six equations two of the thrusters must be set arbitrarily in order for a solution to be found. In matrix M thruster 4 is set to a value of a and thruster 5 is set to a value of b. These variables will be adjusted in a later stage to determine the optimal vaues for each thruster.

By setting the desired forces and moments in matrix v (below) the system of equations may be solved t determine the required thruster forces 1 through 8 as a function of the arbitrary thruster values a and b.

$$v(a,b) \equiv \begin{array}{cl} \begin{pmatrix} 10 \\ -1 \\ 5 \\ 0 \\ 0 \\ 3 \\ a \\ b \end{pmatrix} & \begin{array}{l} \text{Fx} \\ \text{Fy} \\ \text{Fz} \\ \text{Mx} \\ \text{My} \\ \text{Mz} \\ \\ \\ \end{array} \end{array}$$

This v matrix defines the desired force state as 10 N forward, 1 N to the left and 5 N down. It also calls for 3 Nm of torque be applied to the vehicle such that it twists about the vertical axis.

$$\text{soln}(a,b) := \text{lsolve}(M, v(a,b))$$

Given any number of thrust values for a and b a valid solution may be obtained.

With thruster 4 assigned to 1 N and thruster 5 to 0 N, the desired thrust from each thruster may be calculated. Thruster values given different arbitrary selections for thrusters 4 and 5 are also shown below.

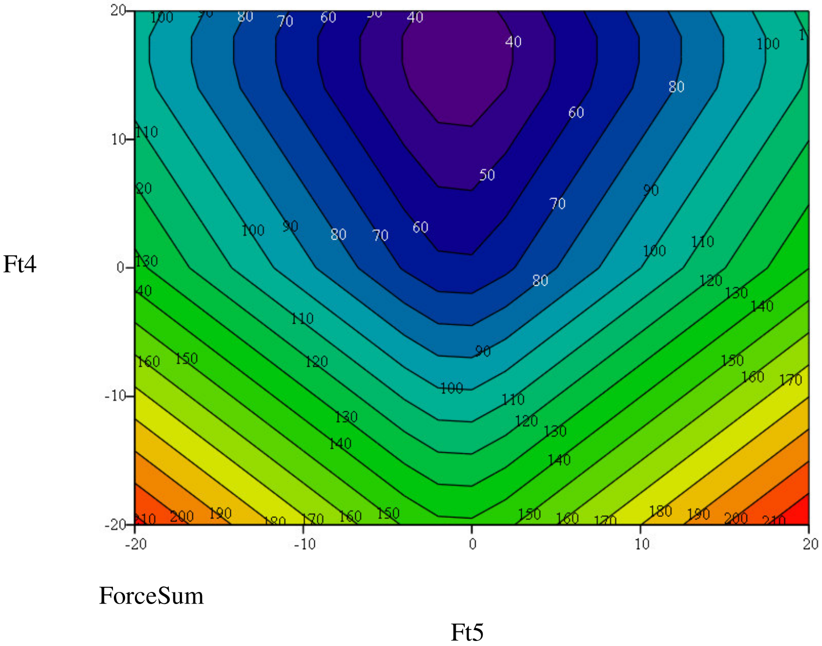
$$\text{soln}(0,1) = \begin{pmatrix} 13.773 \\ -22.22 \\ 17.447 \\ 1 \\ 0 \\ 2.806 \\ 1.704 \\ -1.101 \end{pmatrix} \qquad \text{soln}(5,1) = \begin{pmatrix} 13.773 \\ -22.22 \\ 17.447 \\ 1 \\ 5 \\ 7.806 \\ 6.704 \\ 3.899 \end{pmatrix} \qquad \text{soln}(0,20) = \begin{pmatrix} -5.227 \\ -3.22 \\ -1.553 \\ 20 \\ 0 \\ 2.806 \\ 1.704 \\ -1.101 \end{pmatrix}$$

$$\text{ForceSum}(a,b) := \sum_{i=0}^{7} \left|\text{soln}(a,b)_i\right|$$

By varying the arbitrary values, a pair of values can be determined that result in the desired force state with the minimum total thrust required by all eight thrusters.

$$\text{ForceSum}(0,1) = 60.051 \qquad \text{ForceSum}(5,1) = 77.848 \qquad \text{ForceSum}(0,20) = 35.612$$

The distribution in total force as a function of the thrust from 4 and 5 can be seen in the contour plot



By using a minimization routine the optimal values for the arbitrary thrusters may be determined.

$a := 0$

$b := 0$

initial "guess"

Given

$$-20 \le a \le 20$$

$$-20 \le b \le 20$$

$$\text{minVals} := \text{Minimize}(\text{ForceSum}, a, b) \qquad \text{minVals} = \begin{pmatrix} -1.434 \\ 16.452 \end{pmatrix}$$

$$\text{min\_a} := \text{minVals}_0 \qquad \text{min\_a} = -1.434$$

$$\text{min\_b} := \text{minVals}_1 \qquad \text{min\_b} = 16.452$$

When using the optimum values for the arbitrary thrusters the desired thrust from each thruster may be calculated.

$$\text{soln}(\text{min\_a}, \text{min\_b}) = \begin{pmatrix} -1.68 \\ -6.767 \\ 1.995 \\ 16.452 \\ -1.434 \\ 1.372 \\ 0.271 \\ -2.535 \end{pmatrix}$$

Appendix B - Analytical Hydrodynamic Prop Calculations

Conversion Formulas

$\mathrm{PropRadPM}(\omega) := 2\cdot\pi\cdot\omega\cdot\frac{\mathrm{rad}}{\mathrm{min}}$

allows the input of rotations per min and converts it to rad per min

Water Properties

at 10deg C

$\rho := 1000\frac{\mathrm{kg}}{\mathrm{m}^3}$

$\nu h2o := 1.307\cdot 10^{-6}\cdot\frac{\mathrm{m}^2}{\mathrm{s}}$

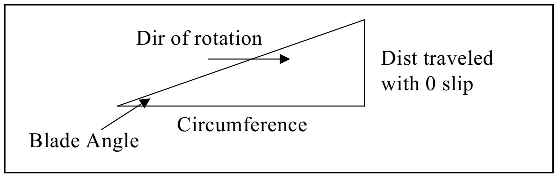
Geometry

$\mathrm{BladePitch} \equiv 4.25\mathrm{in}\quad \mathrm{BladePitch} = 4.25\,\mathrm{in}$

$\mathrm{hubDia} \equiv 0.75\mathrm{in}$

$\mathrm{numBlades} \equiv 3$

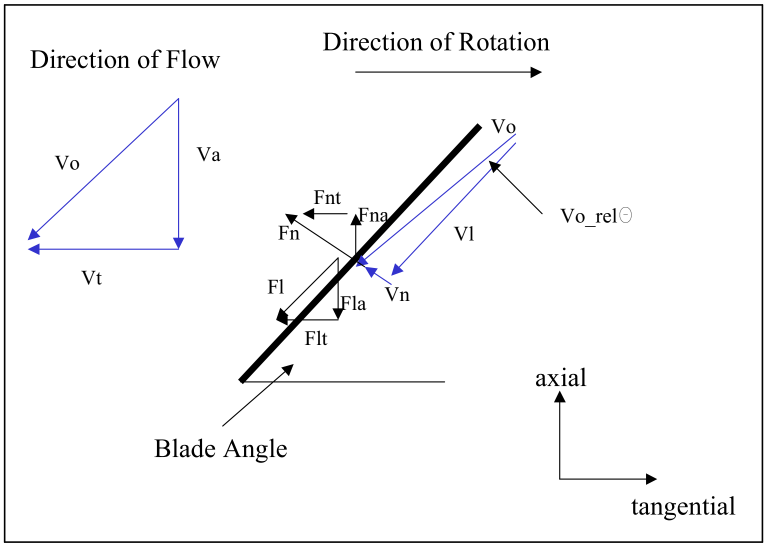
$\mathrm{outerDia} \equiv 3.5\mathrm{in}\qquad \mathrm{outerDia} = 3.5\,\mathrm{in}$



$\mathrm{BladeAngle}(r,P) := \mathrm{atan}\left(\frac{P}{\pi\cdot 2\cdot r}\right)$

$$\mathrm{BladeWidth}(r,P) := \Phi\left(r - \frac{\mathrm{hubDia}}{2}\right)\cdot\frac{\frac{1}{\mathrm{numBlades}}\cdot(2\cdot\pi\cdot r)}{\cos(\mathrm{BladeAngle}(r,P))}$$

Velocity Calculations



$\text{VehicleVelocity} \equiv 1.5\text{knot}$

$\text{Va} := \text{VehicleVelocity}$

$\text{Vt}(r,\omega) := r\cdot\omega$

$n \equiv 1500$ Prop RPM

$n = 1.5 \times 10^3$

Observed Velocity

$$\text{Vo}(r,\omega) := \sqrt{\text{Va}^2 + \text{Vt}(r,\omega)^2}$$

$$\text{Vo\_rel}\theta(r,\omega,P) := \text{BladeAngle}(r,P) - \text{atan}\left(\frac{\text{Va}}{\text{Vt}(r,\omega)}\right)$$

$$\text{Vn}(r,\omega,P) := \text{Vo}(r,\omega)\cdot\sin(\text{Vo\_rel}\theta(r,\omega,P))$$

$$\text{Vl}(r,\omega,P) := \text{Vo}(r,\omega)\cdot\cos(\text{Vo\_rel}\theta(r,\omega,P))$$

Force Calculations

$\text{Cd} := 1.15$ based on a flat plate

Determine the force on each radial element of the blade

$$\text{dFn}(r,\omega,P) := \frac{1}{2}\cdot\rho\cdot\text{Cd}\cdot\text{Vn}(r,\omega,P)^2\cdot\text{BladeWidth}(r,P)$$

determine the drag on the blade along the length

$$\text{ReL}(r,\omega,l,P) := \frac{\text{Vl}(r,\omega,P)\cdot l}{\nu\text{h2o}}$$

form of drag equation varies based on the renolds number

$$\mathrm{CD\_L}(r,\omega,l,P) := \left| \begin{array}{ll} \dfrac{1.328}{\mathrm{ReL}(r,\omega,l,P)^{\frac{1}{2}}} & \text{if } \mathrm{ReL}(r,\omega,l,P) < 5\cdot 10^{5} \\ \dfrac{0.031}{\mathrm{ReL}(r,\omega,l,P)^{\frac{1}{7}}} & \text{otherwise} \end{array} \right.$$

$$\mathrm{dFl}(r,\omega,P) := 2\left(\int_{0}^{\mathrm{BladeWidth}(r,P)} \frac{1}{2}\cdot\rho\cdot\mathrm{CD\_L}(r,\omega,l,P)\cdot\mathrm{Vl}(r,\omega,P)^{2}\,dl\right)$$

$$\mathrm{dFnt}(r,\omega,P) := \mathrm{dFn}(r,\omega,P)\cdot\sin(\mathrm{BladeAngle}(r,P))$$

$$\mathrm{dFna}(r,\omega,P) := \mathrm{dFn}(r,\omega,P)\cdot\cos(\mathrm{BladeAngle}(r,P))$$

$$\mathrm{dFlt}(r,\omega,P) := \mathrm{dFl}(r,\omega,P)\cdot\cos(\mathrm{BladeAngle}(r,P))$$

$$\mathrm{dFla}(r,\omega,P) := \mathrm{dFl}(r,\omega,P)\cdot\sin(\mathrm{BladeAngle}(r,P))$$

Integrate elemental forces to determine torque and thrust

$$\mathrm{PropTorque}(\omega,P) := \mathrm{numBlades}\cdot\int_{\frac{\mathrm{hubDia}}{2}}^{\frac{\mathrm{outerDia}}{2}} \left(\mathrm{dFnt}(r,\omega,P) + \mathrm{dFlt}(r,\omega,P)\right)\cdot r\,dr$$

$$\mathrm{PropThrust}(\omega,P) := \mathrm{numBlades}\cdot\int_{\frac{\mathrm{hubDia}}{2}}^{\frac{\mathrm{outerDia}}{2}} \left(\mathrm{dFna}(r,\omega,P) - \mathrm{dFla}(r,\omega,P)\right)\,dr$$

$$\mathrm{PowerReq}(\omega,P) := \mathrm{PropTorque}(\mathrm{PropRadPM}(\omega),P)\cdot\mathrm{PropRadPM}(\omega)$$

Results

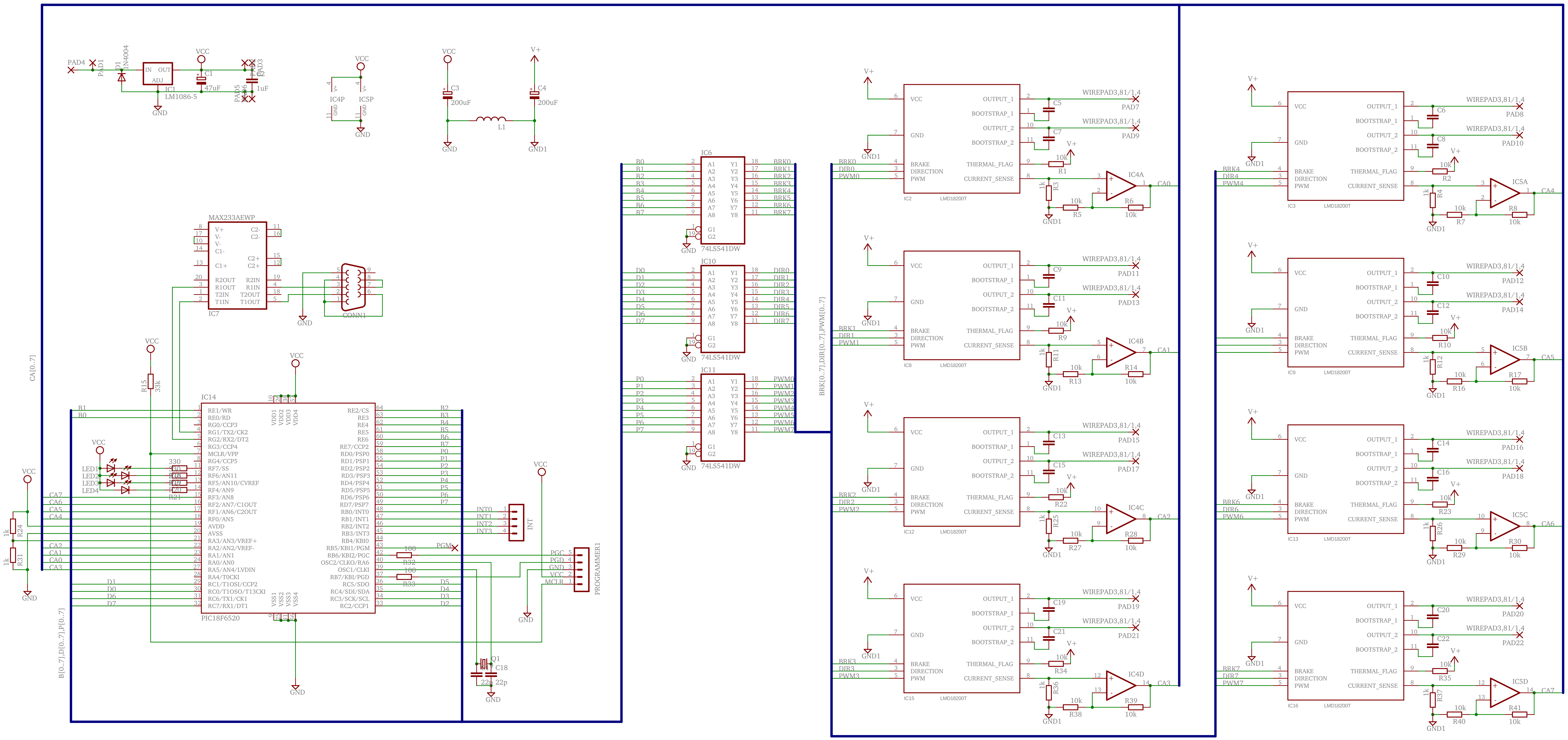
$\mathrm{PowerReq}(n, \mathrm{BladePitch}) \cdot 2 = 56.342\,\mathrm{W}$

A factor of 2 is applied to account for errors and motor losses.

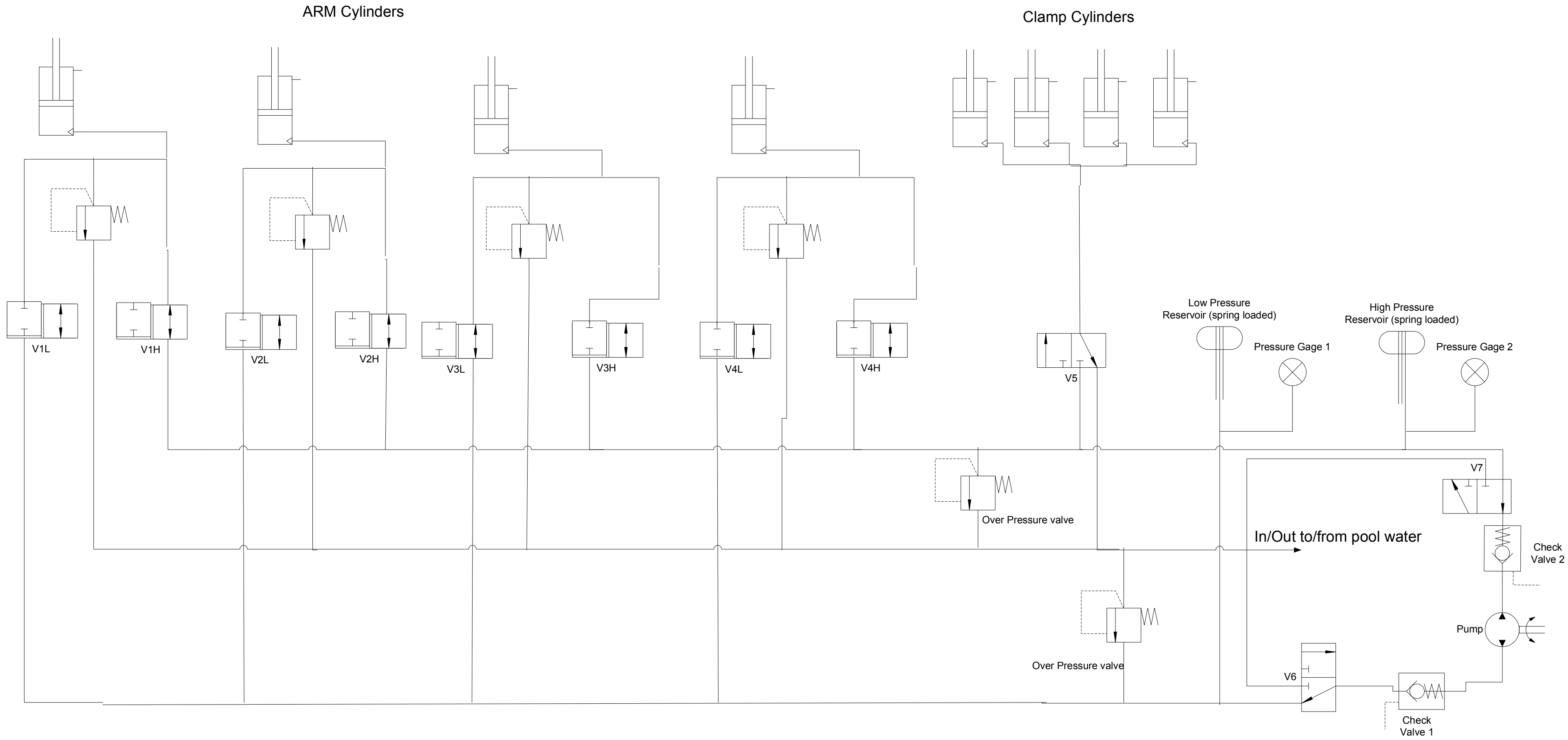
$\mathrm{PropThrust}(\mathrm{PropRadPM}(n), \mathrm{BladePitch}) = 8.78\ \mathrm{N}$

$\mathrm{PropTorque}(\mathrm{PropRadPM}(n), \mathrm{BladePitch}) = 0.179\,\mathrm{N} \cdot \mathrm{m}$

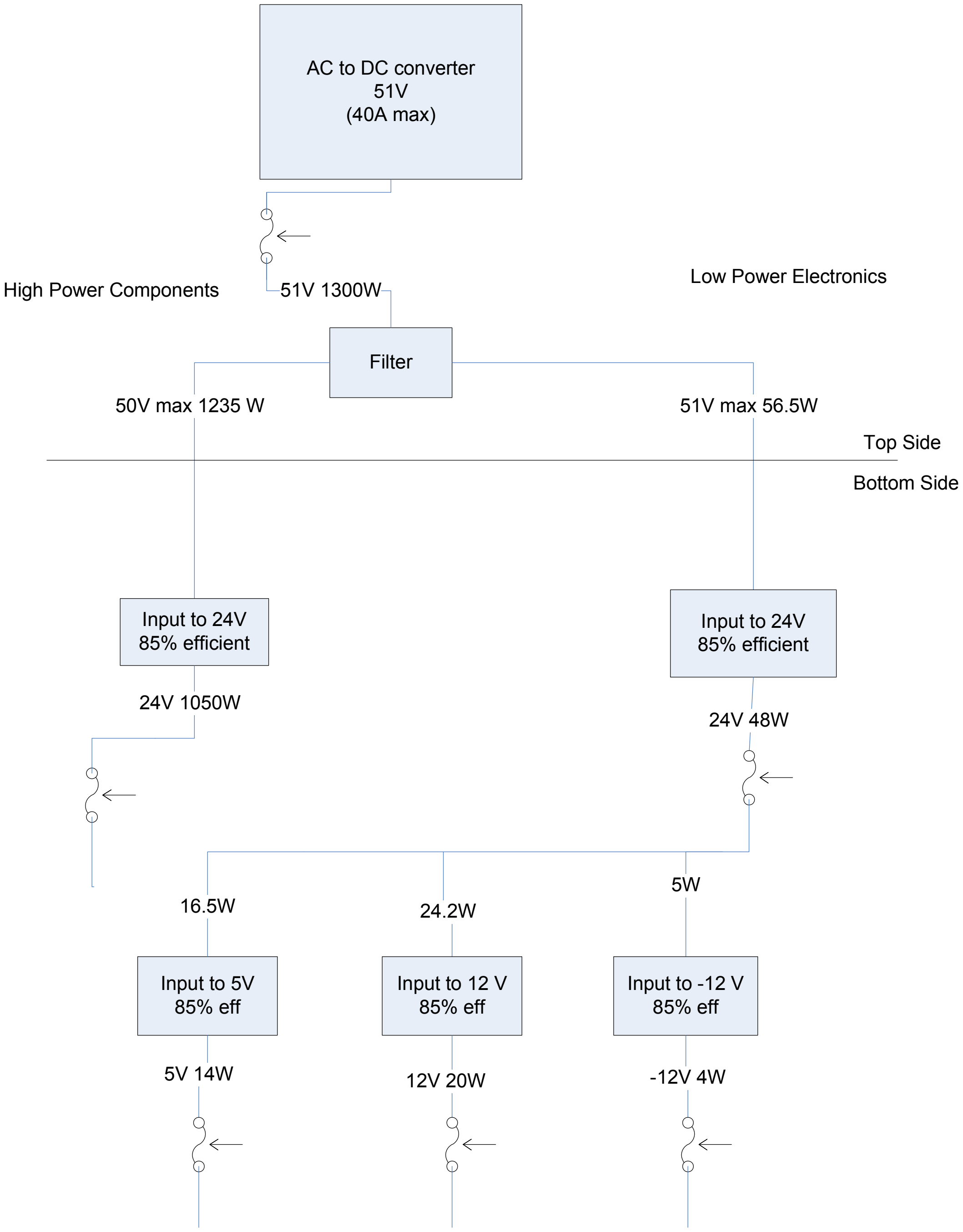
Appendix C – Motor Control Board Schematic


PAD4
PAD1
D1 1N4004
IN OUT ADJ
IC1 LM1086-5
VCC
C1 47uF
PAD3
PAD5
PAD6
C2 1uF
GND
IC4P
IC5P
C3 200uF
L1
V+
C4 200uF
GND1
MAX233AEWP
IC7
CONN1
IC6 74LS541DW
IC10 74LS541DW
IC11 74LS541DW
B0 B1 B2 B3 B4 B5 B6 B7
BRK0 BRK1 BRK2 BRK3 BRK4 BRK5 BRK6 BRK7
D0 D1 D2 D3 D4 D5 D6 D7
DIR0 DIR1 DIR2 DIR3 DIR4 DIR5 DIR6 DIR7
P0 P1 P2 P3 P4 P5 P6 P7
PWM0 PWM1 PWM2 PWM3 PWM4 PWM5 PWM6 PWM7
BRK[0..7],DIR[0..7],PWM[0..7]
CA[0..7]
B[0..7],D[0..7],P[0..7]
IC14 PIC18F6520
R15 33k
LED1 LED2 LED3 LED4
330
R18 R19 R20 R21
R24 1k
R31 1k
CA0 CA1 CA2 CA3 CA4 CA5 CA6 CA7
INT0 INT1 INT2 INT3
INT
PGM
R32 100
R33 100
PGC PGD GND VCC MCLR
PROGRAMMER1
Q1
C17 22p
C18 22p
IC2 LMD18200T
IC8 LMD18200T
IC12 LMD18200T
IC15 LMD18200T
IC3 LMD18200T
IC9 LMD18200T
IC13 LMD18200T
IC16 LMD18200T
VCC GND BRAKE DIRECTION PWM
OUTPUT_1 BOOTSTRAP_1 OUTPUT_2 BOOTSTRAP_2 THERMAL_FLAG CURRENT_SENSE
WIREPAD3,81/1,4
PAD7 PAD8 PAD9 PAD10 PAD11 PAD12 PAD13 PAD14 PAD15 PAD16 PAD17 PAD18 PAD19 PAD20 PAD21 PAD22
C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 C16 C19 C20 C21 C22
IC4A IC4B IC4C IC4D IC5A IC5B IC5C IC5D
R1 R2 R3 R4 R5 R6 R7 R8 R9 R10 R11 R12 R13 R14 R16 R17
R22 R23 R25 R26 R27 R28 R29 R30 R34 R35 R36 R37 R38 R39 R40 R41
10k
1k

Appendix D – Hydraulic Power Unit Schematic



Appendix E – Vehicle Power System



Appendix F – Vehicle Communications System