Development of an Intuitive and Partially Autonomous ROV

University of Waterloo
Underwater Technology Team

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Abstract

Remotely operated submersibles have played a major role as a tool in marine environments since they were first created. Significant advancements in ROV technology have 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. In addition, autonomous stabilization is capable of assisting the pilot during operation ultimately improving vehicle capabilities.

The majority of the components incorporated into the system have been custom designed for this vehicle. Through the development process the students involved 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 sub sea research and operations, particularly in the remote and harsh environment of the poles. Over the past two years, the University of Waterloo Underwater Technology Team [(UW)^{2}TT] has designed and built a highly intuitive and controllable ROV for the 2007 MATE ROV Competition, held at Memorial University in St Johns, Newfoundland. The competition focuses on the role of ROVs in an extreme polar environment. The team's ROV will complete three missions that simulate real-world environmental conditions in the competition's EXPLORER class.

- The first mission takes place in a large flume tank where the vehicle must run a messenger line through the eyelet of a simulated buoy anchor and return the line to the surface in preparation for recovering it.
- The second mission takes place in an ice tank where the ROV must collect simulated algae and jellyfish as well as deploy an acoustic device.
- The third mission takes place in a tow tank where the vehicle must be capable of working with a variety of simulated offshore oil and gas equipment with waves overhead.

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

2.0 Design Philosophy

Modern commercially available submersible vehicles have made significant technical advancements over 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 and 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 console 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)

- Traditional control methods require coordination 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 pilot does not receive physical cues related to the motion of the vehicle and must rely only on visual information for feedback pertaining to the motion and orientation 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, developing three unique features.

1) The Waterloo vehicle interface uses a Space Control ISD to allow the pilot to control the vehicle motion.
2) 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.
3) An “automatic stabilization processor” which autonomously stabilizes the vehicle in rough waters including flow and waves.

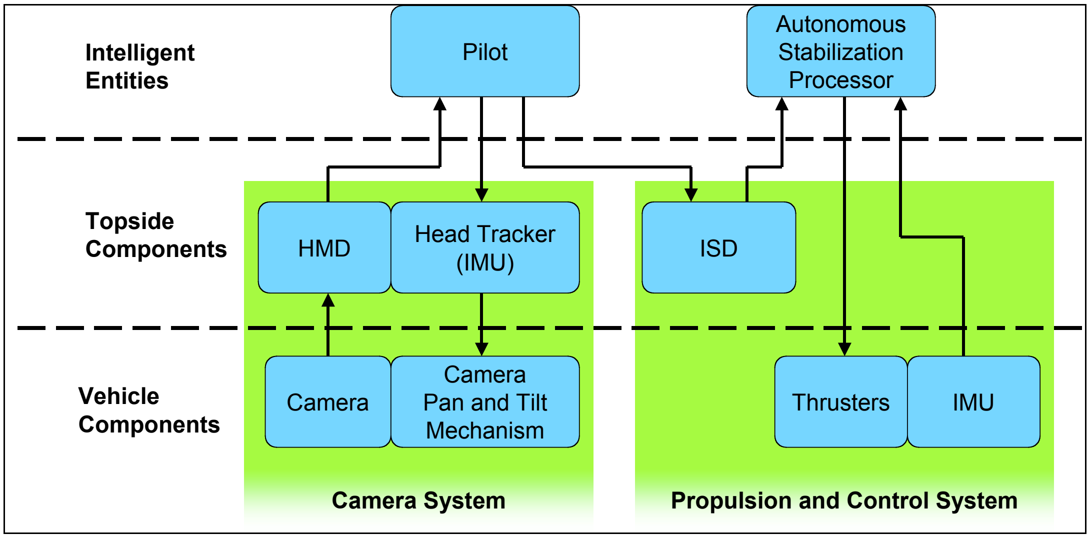

Figure 1: ROV Information Flow Diagram

2.1 Camera System

The camera is the primary feedback for the pilot. It is the only means for obstacle avoidance and target identification and thus it is critical that this system be highly intuitive. The system on the Waterloo vehicle is designed to be immersive allowing the pilot to feel as though he or she is in the one in the water, rather than the vehicle.

2.1.1 Head Tracker

The display helmet worn by the pilot contains a MicroStrain inertial measurement unit (IMU). This device communicates over RS-232 with the control computer, monitoring the pan and tilt angles of the pilot's head.

2.1.2 Pan & Tilt Mechanism

The head orientation data is transmitted from the surface to the dedicated pan and tilt controller circuit in the vehicle. This custom designed and built board receives the desired pan and tilt angles and controls a pair of servomotors that drive the mechanism. The mechanism is an intricate bent sheet metal design ensuring that the center of the camera remains at the center of the acrylic dome preventing changes in camera angle from causing image distortions.

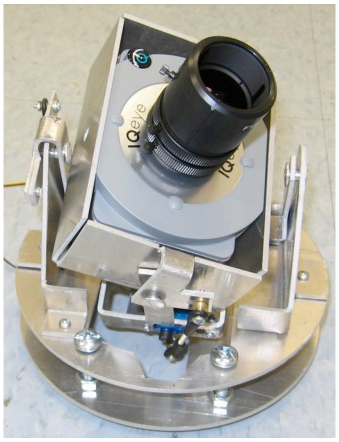

Figure 2: Pan and Tilt Camera

2.1.3 Camera

Mounted to the pan and tilt mechanism is the IQeye 501 Ethernet camera. The camera transmits the captured images to the control computer where they are overlaid with further sensor information for the pilot, increasing the intuitive nature of the vehicle. This camera was selected due to its resolution and quality of image in low light conditions.

2.1.4 HMD

The images from the camera are displayed in the pilots head mounted display (HMD). An I-O Display Systems HMD was selected for its relatively low cost. As the pilot moves their head the image they see changes accordingly. This immerses them into the system and ultimately results in a system that is far more intuitive than traditional ROV pan and tilt cameras.

The standard HMD has been mounted into a hardhat to improve ruggedness of the component and improve pilot comfort.

Figure 3: Pilot Display Helmet

2.1.5 Remote Monitoring

ROV inspections and work often take place in remote locations. Despite this, many people often have an interest in knowing the progress of the work. On site monitoring becomes particularly difficult when the work is being performed at or near the poles, as is being simulated at this year’s competition. The images captured with our camera are uploaded to a server for real time monitoring. Using a BlackBerry smartphone, these images may be monitored even when the third party observer is not at their desk.

2.2 Propulsion System and Vehicle Control

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.

2.2.1 ISD

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 independently 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 ISD allows the pilot to intuitively input the desired 3-component vector force (Figure 4a and 4c) and three-component vector moment (Figure 4b and 4d) into the topside control computer via an RS-232 connection.

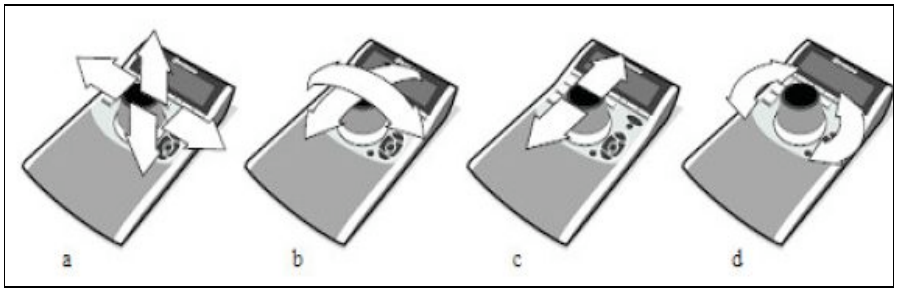

Figure 4: Industrial Steering Device - Degrees of Control

The topside control computer monitors the force applied to this device, and feeds these inputs to the autonomous stabilization processor where an algorithm is used to determine the appropriate power delivered to each thruster.

2.2.2 Thruster Configuration

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 are used on the Waterloo vehicle. The two additional thrusters also provide redundancy. If one of the thrusters fouls or becomes inoperable for any reason, the remaining 7 are able to compensate. Most commercially available ROVs have the equivalent of four independently controlled thrusters resulting in less controllability. Figure 5 shows the thruster configuration on the Waterloo vehicle that allows for full six degree of freedom control.

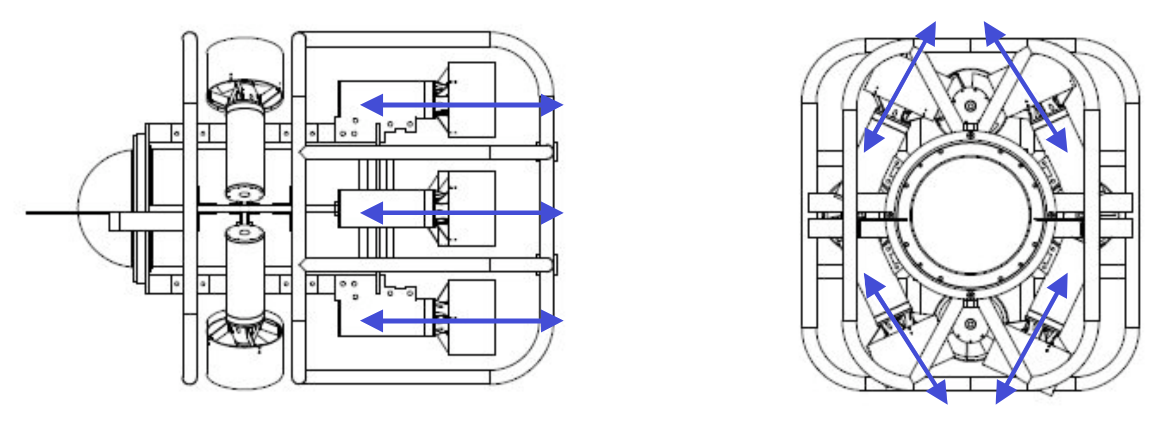

Figure 5: Vehicle Thrust Vectors

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.

2.2.3 Thruster Design

Significant analysis was performed for the development of the custom thrusters. In order for the vehicle to be highly controllable in both the wave and the flume tanks, the thrusters must be capable of overcoming the drag on the vehicle. Based on calculated drag values for the vehicle and umbilical with a desired relative forward speed of 1.5 knots, optimal propellers were designed, capable of providing 8.75N of thrust.

Two analysis methods were used for propeller design. Through blade element analysis in initial optimization occurred. This method considers small sections of the blade in two dimensions and integrates the thrust and torque that results from each element to obtain the complete result. Further optimization took place through CFD and FEA analysis.

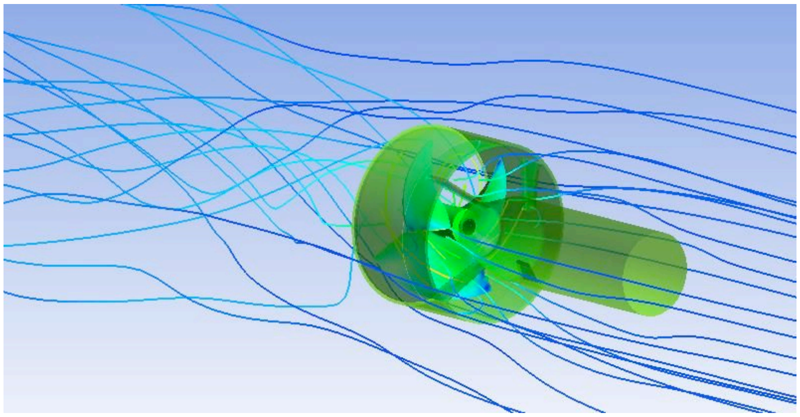

Figure 6: Thruster CFD

The strength of the blade geometry was verified through the ANSYS Fluid-Solid Interface (FSI), where the stress in the propeller blade was accurately determined based on the simulated pressure.

Once the propeller was designed the motor was selected based on the power, speed and price requirements. The Maxon 24V A-Max 32 motor with a 6:1 planetary gear speed reduction was selected. Custom housings were designed and built for the thruster assembly. Aside from the motor, the housings contain both thrust and radial bearings to support the stainless steel shaft. All static seals are standard o-rings while the dynamic shaft seal is a Parker shaft seal. The propeller is shrouded for operator protection and to provide increased thrust at low speeds. Finite element analysis of the load bearing components was performed to verify structural integrity from both external water pressure and from reaction forces due to propeller thrust.

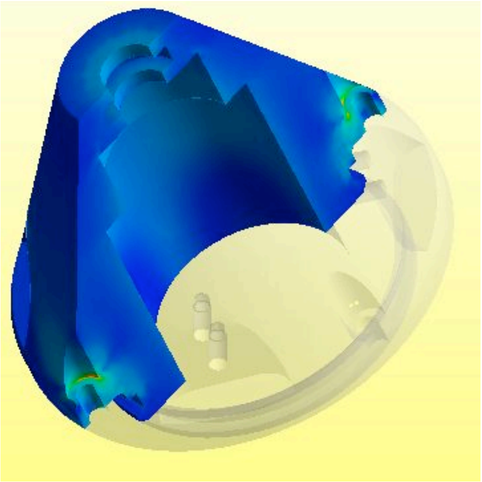

Figure 7: Thruster Nose Cone FEA

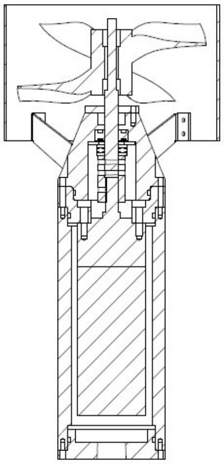

Figure 8: Thruster Assembly Cross Section

2.2.4 Attitude Sensor

To obtain an understanding of the orientation of the vehicle an IMU was incorporated. The MicroStrain 3DM-GX1 was selected for its high accuracy and simple RS-232 interfacing. This device contains MEMS (Micro Electro Mechanical System) accelerometers, gyroscopes and magnetometers. Through advanced sensor fusion combining information from all available sensors, the device is capable of accurately providing the orientation of the vehicle as well as the vehicle accelerations in all directions. This data may be monitored by the pilot to assist with operation of the vehicle as well as by the Autonomous Stabilization Processor to assist the pilot in controlling the vehicle.

2.2.5 ASP

Reducing the complexity of stabilizing and positioning the vehicle allows the pilot to focus on the specific task they are attempting to complete. The ASP has two tasks, attitude stabilization and position stabilization.

Since the thrusters are configured in a way to allow a moment to be applied to the vehicle about any axis, the vehicle may be stabilized into any orientation. In order for this to be possible the method of stabilizing the vehicle through buoyancy is counter productive. If the thrusters attempt to pitch the vehicle such that it is sloped on a 45^o angle and the vehicle has a traditional high flotation buoyancy design, then the thruster will need to be continually fighting the righting effects of the buoyancy. On vehicles that do not have the controllability of the Waterloo system, high flotation buoyancy is required to keep the vehicle stable; however it is constrained to working in the horizontal plane. The buoyancy of the waterloo vehicle has been positioned such that the vehicle is neutrally buoyant in the water but free to rotate to any with a minimal righting moment.

A standard PID controller was implemented, decoupled along each Cartesian axis. There are multiple ways for the pilot to control the orientation of the vehicle. Through the GUI a desired roll, pitch and yaw angle is entered or the pilot can manipulate the vehicle into the desired orientation and allow the computer to then take control. The control system compares the difference between the actual angle of the vehicle and the desired angle of the vehicle and applies an appropriate moment about each axis to correct for this error.

Position stabilization is useful when the vehicle is experiencing sudden or cyclic external forces due to waves. A controller will attempt to match the phase and frequency of the oscillations with cyclic inputs to the thrusters such that the motion is damped, and ultimately we hope to completely cancel out the wave motion. The controller will be tuned through MatLab simulations prior to the competition, however we will not know if it will work until we are at the competition, as we do not have access to a safe and reliable wave tank.

The forces in each direction for stabilization are added to the forces from the ISD and the appropriate power and direction for each thruster is calculated using the algorithm outlined in Appendix A. These thruster values are sent over the network to the custom motor control board containing 8 H-bridge chips capable of providing the required motor current.

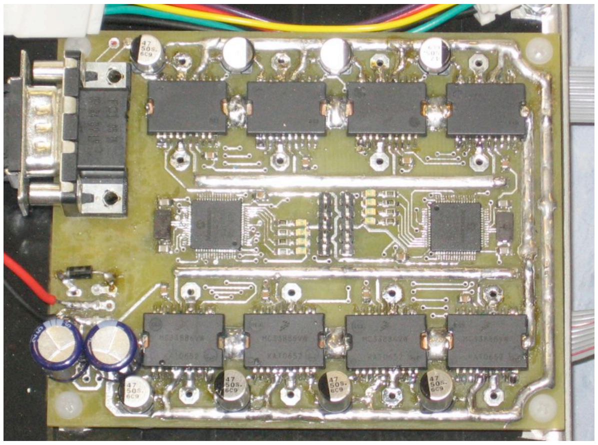

Figure 9: Motor Control Board

2.2.6 User Interface

To monitor and control the system a user interface was developed capable of modifying and reading all parameters for any of the 6 nodes in the system as well as the on board camera. The user interface was written in Visual C# with each node controlled by a separate tab. This interface provides the user with complete control over the vehicle not only during operation but also during testing and debugging, allowing for independent systems to be isolated and easily adjusted.

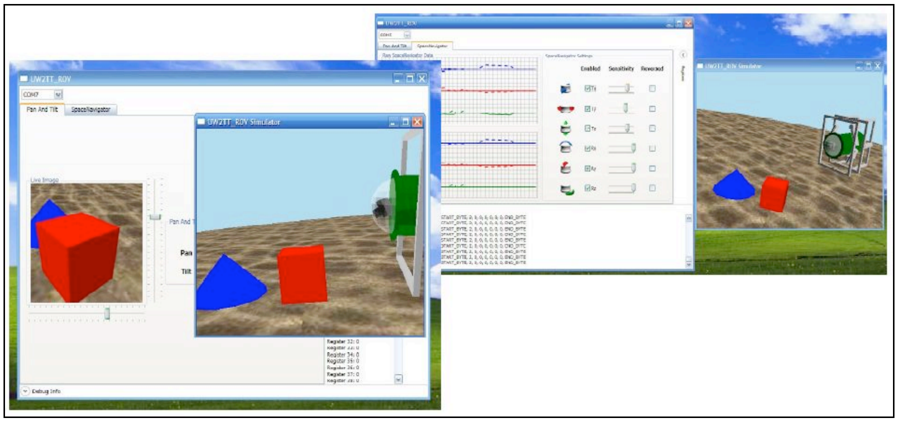

Figure 10: GUI Screenshots

As seen in Figure 10 a simulator has also been developed allowing pilot training to take place in a risk free manner. Complete software flow charts for the custom boards as well as a representative flow chart for the GUI may be found in Appendix B.

2.3 Power and Telemetry

2.3.1 Power

Sufficient power must be provided to the vehicle for the thrusters to be capable of providing the required level of controllability. To conserve space in the vehicle housing the motor power is isolated from the electronics power at the surface to eliminate any problems with motor-generated line noise. To minimize power losses in the lines, a supply voltage of 48V is used. This voltage is within the competition limits while allowing for a safety factor of 3V. At full load (8 thrusters operating at 2A each), the voltage at the vehicle is 35V on the primary power line, due to the voltage drop over the umbilical. A high power DC-to-DC converter in the vehicle drops the input voltage to a constant 24V for the motors.

For secondary power (electronics) a power budget was calculated based on the system components being used, the selected power converters, and their efficiencies. Based on this power budget, a custom board capable of providing all required voltages was designed. See Appendix C for a vehicle and topside wiring schematics. To eliminate the chance of an incorrect voltage being applied to a specific board, each power connector from the board has all available voltages, while the matching connector on each electronics board only has pins in the appropriate places. This system is analogous to the power supply of a personal computer.

2.3.2 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. 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. If desired, the copper umbilical could easily be switched for a fiber optic solution in the future. An onboard server manages communication between the Ethernet camera and the RS-232 boards. 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 directly into a port on the computer. By using an Ethernet network on board the vehicle, the vehicle may be easily expanded to support a wide range of additional devices.

In addition to umbilical communications, each board is capable of being programmed without the need to break the main housing seals. Inside the housing, a multiplexing board is connected to the programming pins on each of the boards containing processors. When the vehicle is on the surface a customized programmer may be connected to this board through a bulkhead connector and the specified board can be programmed. This eliminates the need to open the housing of the vehicle when making program modifications. This minimizes the need to open the housing to access the electronics, and allows us make and test vehicle modifications quickly.

2.4 Body / Frame

To hold the electronics, a pressure vessel capable of safely being submerged to 61m (200 ft) was built. 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 holes for custom penetrator style and bulkhead connectors. The housing was designed using analytical calculations in MathCAD and further analysis was performed using ANSYS finite element analysis (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.

2.5 Waterproofing and Connectors

To provide sufficient current carrying capacity and reduce costs, penetrator style connectors were custom designed and fabricated. These were machined from brass hex stock and incorporate both a face seal and a seal in piston action. A custom mold fabricated from plastic was fabricated and the connectors were potted using potting compound.

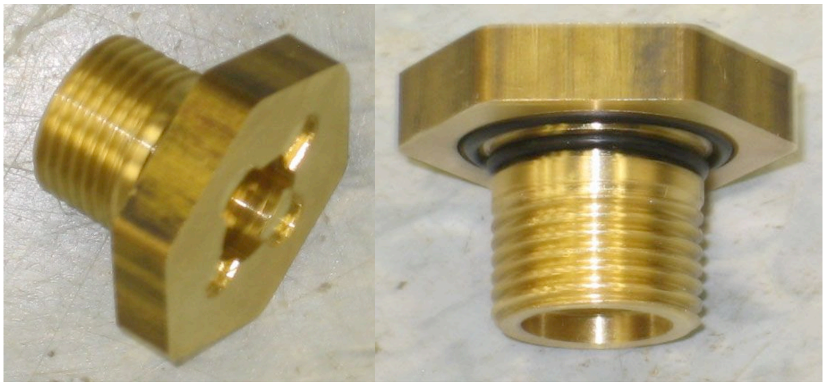

Figure 11: Custom Penetrator Fittings

2.6 Manipulator

A hydraulic 4 degree of freedom arm has been built. However, the hydraulic power unit to control the arm has not been completed. Significant analysis was performed for the arm prior to fabrication. Through ANSYS FEA analysis it was verified that the members of the arm would not fail under the anticipated worst case loading.

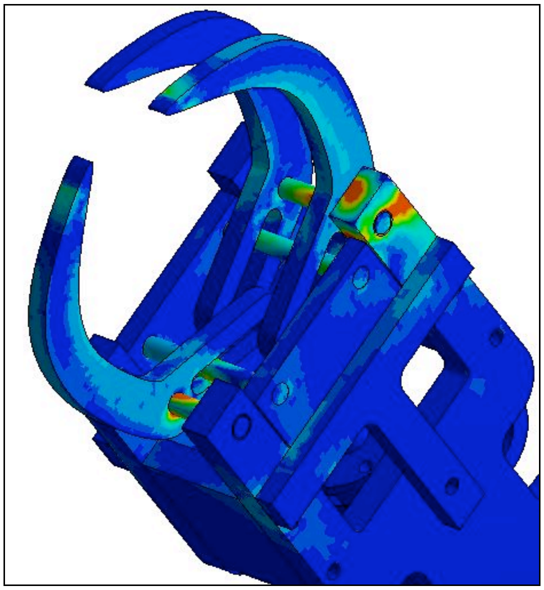

Figure 12: Hydraulic Claw FEA

Since the HPU has not been completed, at the competition a number of hooks and hockey sticks will be used to manipulate the various objects. Due to the maneuverability of the vehicle simple manipulators will be sufficient to accomplish the various tasks.

3.0 Challenges

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 student teams since one stream of students is leaving town for coop work placements while the other stream is returning to classes. The Underwater Technology Team has over 15 student members between both A and B streams. This situation requires significant coordination of the various projects. Despite the team Business Manager and the Electrical Lead both being involved with the team since its inception, the 2007 competition is St. John’s will be the first time these two have met face to face. During the past two years we have managed to run the team across international borders and time zones. Through regular team communication and a well-structured team hierarchy this challenge was overcome.

All meetings were well documented with meeting minutes, which were then sent out to the whole team. These meetings generally occurred on a bi-weekly basis documenting recent progress, problems that had arisen and goals for completion of the next steps. People who were out of town would submit an update as to their progress prior to each meeting.

To manage the many aspects of the project 4 senior management positions were established.

The Team Lead:	Ensured that overall system integration was feasible and coordinated subsystem design and fabrication.
The Business Manager:	Managed team finances and ensured that external appointments and deadlines were met.
Electrical/Software Lead:	Managed the design and fabrication of all electrical and software systems.
Mechanical Lead:	Managed the fabrication of all mechanical components.

By overcoming our communication and logistical problems the team was capable of effectively overcoming our technical problems and ultimately developing an advanced ROV system capable of being successful at the MATE competition.

4.0 Troubleshooting Techniques

To avoid problems significant work went into ensuring that the systems on the vehicle were reliable. The team had procedures in place where designs had to be checked by multiple other members prior to fabrication. A significant number of design fixes and improvements were implemented as a result of this practice. However, we were unable to eliminate all potential problems during the design phase.

When troubleshooting the vehicle systems during fabrication and assembly an incremental approach were employed, for each of the mechanical, electrical and software systems. This involved isolating a single component of the system and verifying its functionality prior to assembling the next component. The frame for the vehicle was welded and assembled in stages with a series of welding and aligning steps taking place. This ensured that holes and members fit with the overall vehicle despite slight disparities with the dimensions of the bent members as well as warping of the parts due to the welding.

Fabrication of each of our custom boards also followed this approach. The board providing electronics power to the vehicle supplies four different voltages. During fabrication of the board each power bus was brought online separately. Through this process a problem was discovered with the 24V supply. After verifying that the second chip using the 12V line as a reference was not the problem, we could quickly identify that the problem was the compatibility between the two 12V regulators. Since the problem had been well identified we were able to contact the manufacturer and ultimately developed a solution.

Due to our extensive designing and testing of each subsystem prior to complete integration we have not had to troubleshoot any major problems with the vehicle. However, when problems do arise with the overall vehicle we will first ensure that the system is powered and then ensure that data is being sent back to the surface. To perform these checks a combination of digital millimeters and oscilloscopes will be used along with simple diagnostic software to verify that communication into and out of each device is working. Ultimately, by bounding the location of a problem we will be able to gradually narrow down the potential sources of the fault and ultimately rectify any problems.

5.0 Future Improvements

One of the biggest lessons from the past year of development is that the vehicle will never be truly finished. We are always thinking up new ideas and have numerous projects lined up to improve the existing systems. The project that is at the top of the list is not glamorous or difficult but it will both increase the reliability and safety of the vehicle. Robust electrical current monitoring and control will be implemented onto a new motor control board. This board will be capable of providing feedback regarding the current draw from each motor independently. Currently a 2A slow blow fuse is in line with each thruster. These fuses will prevent damage from occurring however, no feedback is given to the pilot and nothing is done to prevent the failure. With the new system, feedback will be provided and the power sent to each motor will be regulated, such that the motors do not exceed an acceptable current draw. The current draw data can also be used to gauge the ware of the thruster shaft seals. A significant decrease in current draw from the thruster when operating in air is an indication that the shaft seals are wearing out. We determined that ensuring safe and reliable operation of the vehicle should be our primary concern and implementing current feedback is the ideal next step due to the number of benefits with this modification.

6.0 Lessons Learned

Our team consists of individuals with a wide range of skill levels and experience. Some members are first year students who started with minimal to no hands on experience while others had both design and field work experience in the marine robotics industry. Since inception, the team has grown and over 25 students contributed to the design and fabrication of the vehicle. Through this process each member learnt a variety of skills. Senior members acted as mentors and administrators, learning how to motivate, teach and manage less experienced teammates while junior members were exposed to and learnt everything from machining using mills and lathes to PCB design and fabrication to networking and device interfacing. To complete this process everybody on the team had to and was encouraged to push their boundaries sometimes resulting in mistakes and failures. The team dynamic is such that failures are not punished or even discouraged and when they do occur the team supports one another to learn from these errors and proceed with the system development.

7.0 Polar Research

In order to further understand the climate, environment and human society in Canada's harshest climates, researchers have deemed 2007-2008 the International Polar Year.

Despite the cold, the wind, and the dryness, there are still groups of people living in the North and South Poles of the world. In Antarctica, there are no permanent residents - only tourists and researchers visit. About five thousand members of expeditions visit every year, and only one fifth of those stay through the winter. On the other side of the world, there are colonies of Inuit living at and near to the North Pole.

Life is very different in the North Pole compared to the South Pole. At the North Pole, survival is often dependent on hunting, fishing, and wearing furs for warmth. Transportation is made possible by the use of dog sleds or snowmobiles. Most indigenous inhabitants live close to the water for access to food. Some of their nourishments include fish, seals, whales, caribous, plants and berries. Traditionally, these people either establish camps or migrate, depending on the season.

Figure 13: Research Vessel Navigating Through an Ice-Flow

Due to the lack of permanent residents at the South Pole, people reside in Antarctic research stations. Staying in tents is made possible from recent advances in nutrition and clothing. Also, modern technology, which includes over-snow vehicles, ski-equipped and fixed-wheel aircrafts, and ice-strengthened ships, has made travel to and around the continent easier. Time is spent playing football, skiing, and playing other winter sports. However, most of the day is usually spent doing research.

Recent technological advances and discoveries may change the future of life for inhabitants of the Poles. In the Arctic, the discovery of oil, diamonds and minerals may increase work and bring more people. Also, advances in transportation, communication, and water systems may bring more humans to both regions. Further understanding of these areas can aid in the further development of human life in these harsh areas. ROVs and other marine technology is critical for this effort as these systems are capable of operating in the harsh environments.

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8.0 Reflections

By Jason Gillham – Team Lead and Founder

Involvement with this project has been the most rewarding experience of my undergrad career here at Waterloo! From a young age I have always been interested in oceanography and marine biology but selected Waterloo engineering for my equally passionate interest in system design. This project has given me an opportunity to combine my academic endeavors with my passion for the marine environment and share the experience with others. As the team has grown over the past year and a half I have had the opportunity to work with a great group of people and some equally interesting characters. I truly feel that I have learnt as much or more from younger members as they have learnt from me.

Personally, the most challenging aspect of the team was learning how to best motivate people (a difficult task when they are not being paid). I found that the best way to keep people interested is to keep giving them things to do, challenging them to accomplish their tasks, and publicly recognizing these accomplishments. My exposure and enjoyment with project management and system development through this project is a significant factor in my deciding to pursue graduate school and ultimately establish a company within the industry. Over the past six months I have been gradually passing responsibilities to other members so that I can step aside and allow others to develop the leadership skills that I have. Seeing the project move from a vehicle concept and just a few people to a large team and a functional system has been a truly rewarding experience and I fully expect that I will feel a further sense of satisfaction as the team continues to return in future years.

9.0 2006-2007 (UW)2TT Financial Summary

* estimated cost

		Industry Cost	Cost to the Team
Vehicle Costs			
	Serial Servers	$276.26	$121.26
	IQeye camera	$966.67	$0.00
	Laptop Computer	$319.19	$319.19
	Ethernet Switch	$38.19	$38.19
	ISD*	$250.00	$0.00
	HMD	$962.02	$913.92
	TS power supply	$484.50	$0.00
	Connectors and Wiering	$90.50	$20.50
	Fasteners	$90.96	$90.96
	Seals	$54.06	$54.06
	3DM-GX1 (qty: 2)	$2,890.00	$1,477.17
	helmet	$15.96	$0.00
	material costs	$378.79	$378.79
	machining costs	$13,650.00	$3,150.00
	propellers	$1,306.40	$0.00
	motors	$2,944.00	$1,288.00
	servos	$35.56	$35.56
	BlackBerry Handheld	$599.00	$0.00
	umbilical and cabling	$2,846.12	$0.00
	dome	$34.20	$0.00
	board manufacturing	$483.00	$207.00
	board components	$200.00	$163.71
	potting compound	$36.80	$0.00
	8pin bulkhead and mating connectors *	$200.00	$200.00
	hundreds of student design and fabrication hours	priceless	$0.00
	Vehicle Sub-Total	**$29,152.17**	**$8,458.30**
Prototyping and Spares			
	Motor	$368.00	$368.00
	propellers	$342.70	$0.00
	Seals	$108.11	$108.11
	Fasteners	$22.74	$22.74
	ISD*	$250.00	$0.00
	board components	$111.72	$22.80
	Prototyping Sub-Total	**$1,091.55**	**$498.85**
2006 Competition Costs			
	travel	$1,256.49	$1,256.49
	housing	$424.58	$424.58
	apparel	$59.66	$59.66
2007 Competition Costs			
	travel (flights)	$3,014.96	$3,014.96
	travel (other) *	$100.00	$100.00
	housing	$568.00	$568.00
	meals	$204.61	$204.61
	shipping *	$400.00	$400.00
	apparel *	$400.00	$400.00
	Competition Costs Sub-Total	**$6,428.30**	**$6,428.30**
	Total Expenses	**$36,672.02**	**$15,385.45**
2006-2007 Funds Raised			
	Waterloo Eng. Endowment Fund		[redacted]
	ASI Group		[redacted]
	MATE		[redacted]
	OceanWorks		[redacted]
	Sota Glazing		[redacted]
	Research In Motion		[redacted]
	Morrison Hershfield		[redacted]
	Waterloo Eng. Society		[redacted]
	Total Funding		**$15,745.00**
	Balance		**$359.55**

10.0 Acknowledgements

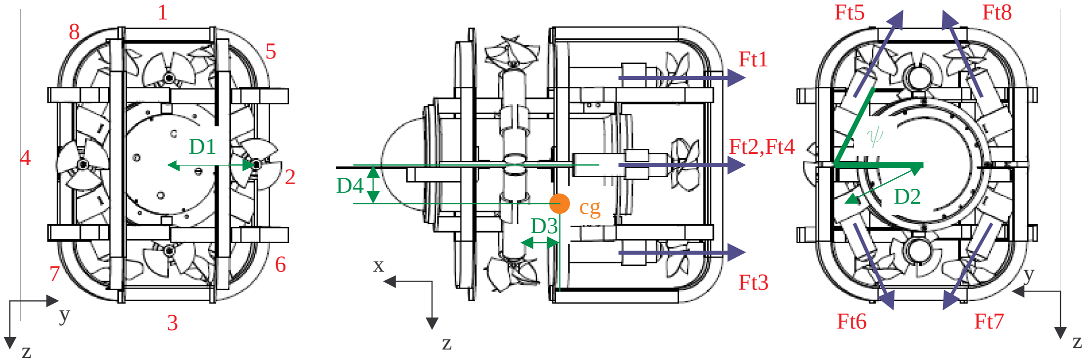
The University of Waterloo Underwater Technology Team would like to thank the many people and companies who have contributed their time and resources to this project.

Person or Organization	Contribution
ANSYS	Elemental Analysis Software Donation
ASI Group	Funding and Guidance
Electromate / Maxon	Discounted Motors
Global Plastics	Donated Acrylic Dome
IQinvision	Donated Camera
Jet Cut	Water Jet Cutting at no Cost
John and Kwai Student Shop Supervisors	Advice and Patience
Leoni	Donated Umbilical
MicroStrain	Discounted IMUs
Morrison Hershfield	Funding
OceanWorks	Funding
SDP/SI	Motor Bearings
SOTA Glazing	Funding
Space Control	Donated ISD
Stratasys	Fabricated Propellers
Sunstone Circuits	Custom Circuit Board Printing
Systech Corporation	Serial Server Donation
Mike H. UW Engineering Machine Shop	Fabricated Thrusters at Reduced Rate
WEEF	Funding

Appendix A – Thruster Algorithm

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.

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

$D1 := 0.132$

$D2 := 0.15$

$D3 := 0$

$D4 := 0$

(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.

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

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 b and thruster 5 is set to a value of a. 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.

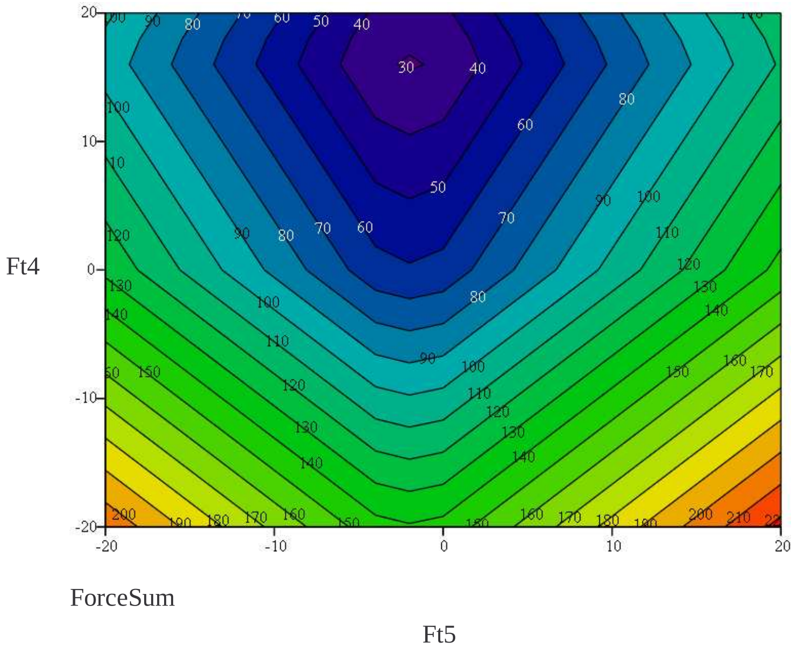
$$\text{soln}(0,1) = \begin{pmatrix} 15.364 \\ -21.727 \\ 15.364 \\ 1 \\ 0 \\ 2.806 \\ 3.907 \\ 1.101 \end{pmatrix} \qquad \text{soln}(5,1) = \begin{pmatrix} 15.364 \\ -21.727 \\ 15.364 \\ 1 \\ 5 \\ 7.806 \\ 8.907 \\ 6.101 \end{pmatrix} \qquad \text{soln}(0,20) = \begin{pmatrix} -3.636 \\ -2.727 \\ -3.636 \\ 20 \\ 0 \\ 2.806 \\ 3.907 \\ 1.101 \end{pmatrix}$$

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

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.

$$\text{ForceSum}(0,1) = 61.269 \qquad \text{ForceSum}(5,1) = 81.269 \qquad \text{ForceSum}(0,20) = 37.814$$

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

$-20 \le a \le 20$

$-20 \le b \le 20$

$\text{minVals} := \text{Minimize}(\text{ForceSum}, a, b)$

$$\text{minVals} = \begin{pmatrix} -1.12 \\ 16.364 \end{pmatrix}$$

$\text{min\_a} := \text{minVals}_0 \qquad \text{min\_a} = -1.12$

$\text{min\_b} := \text{minVals}_1 \qquad \text{min\_b} = 16.364$

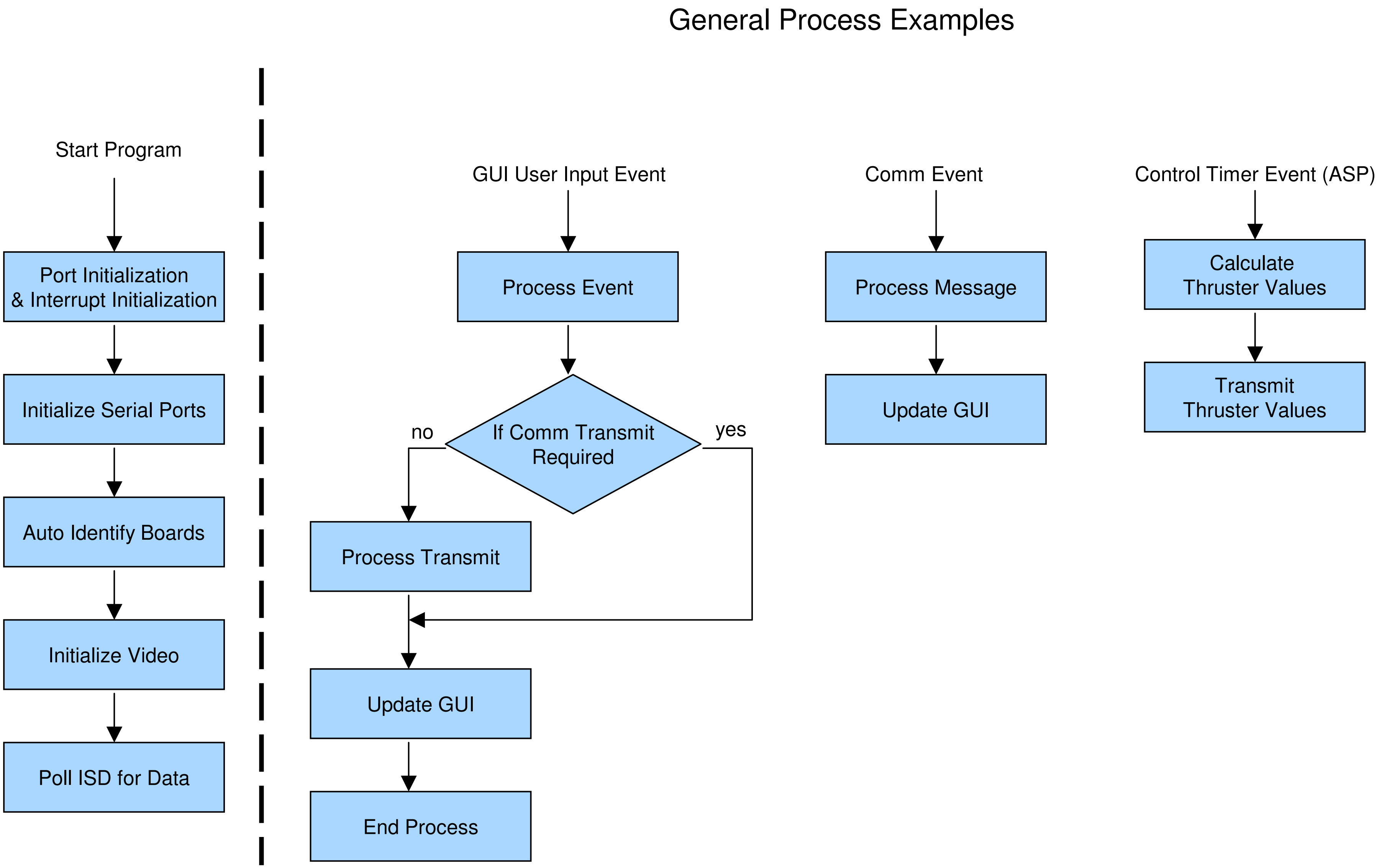
When using the optimum values for the arbitrary thrusters the desired thrust from each thruster may be calculated.

$$\text{soln}(\text{min\_a}, \text{min\_b}) = \begin{pmatrix} -8.48 \times 10^{-8} \\ -6.364 \\ -8.48 \times 10^{-8} \\ 16.364 \\ -1.12 \\ 1.686 \\ 2.788 \\ -0.018 \end{pmatrix}$$

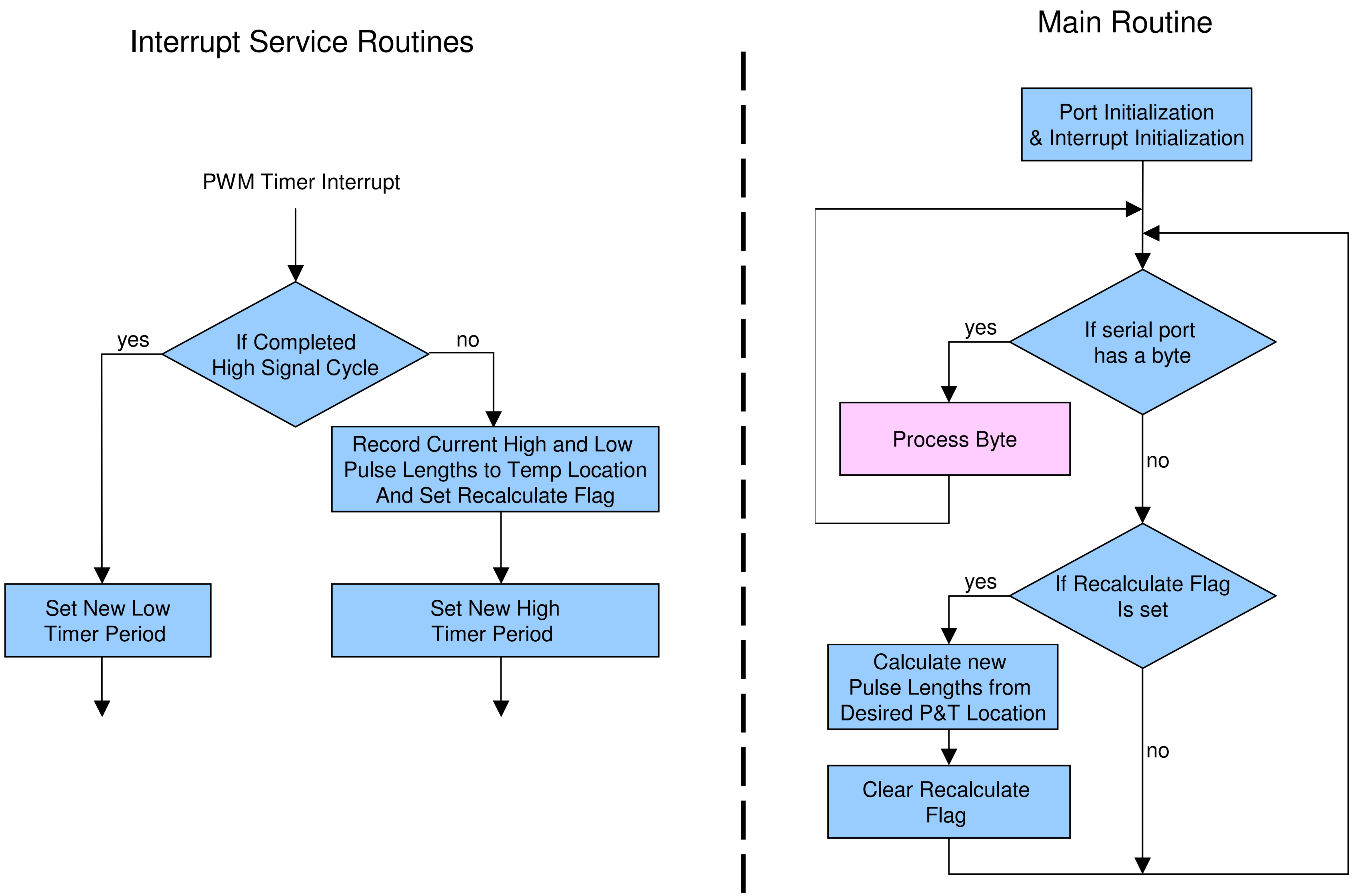
$\text{ForceSum}(\text{min\_a}, \text{min\_b}) = 28.339$

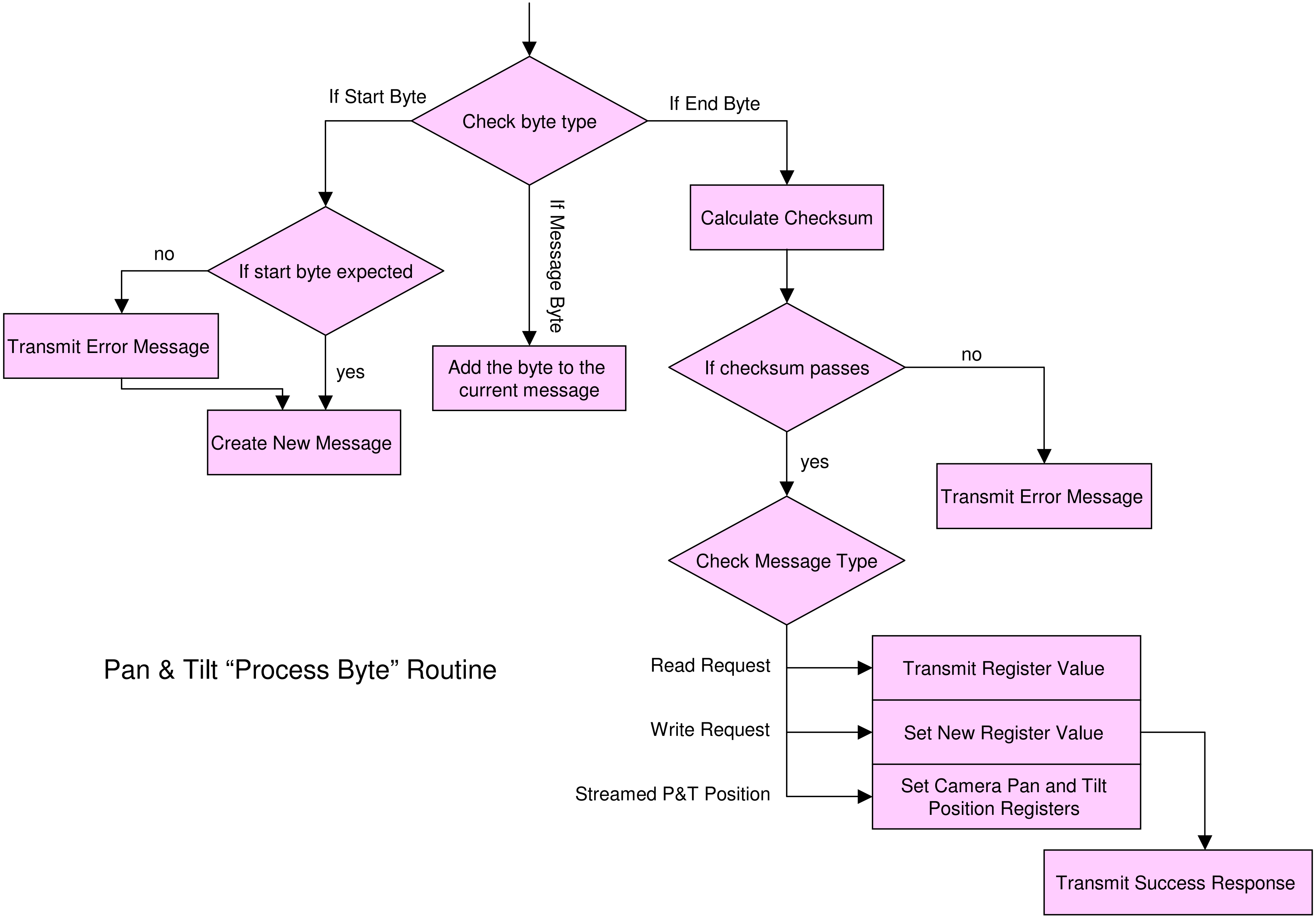
Appendix B – Software Flow Charts

GUI Overview



Pan and Tilt Control Board Software Flow

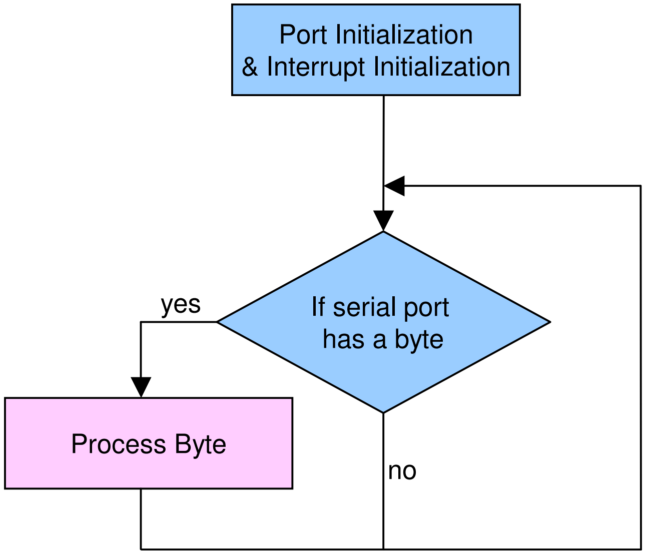




Pan & Tilt “Process Byte” Routine

Thruster Control Board Software Flow (Master Chip)

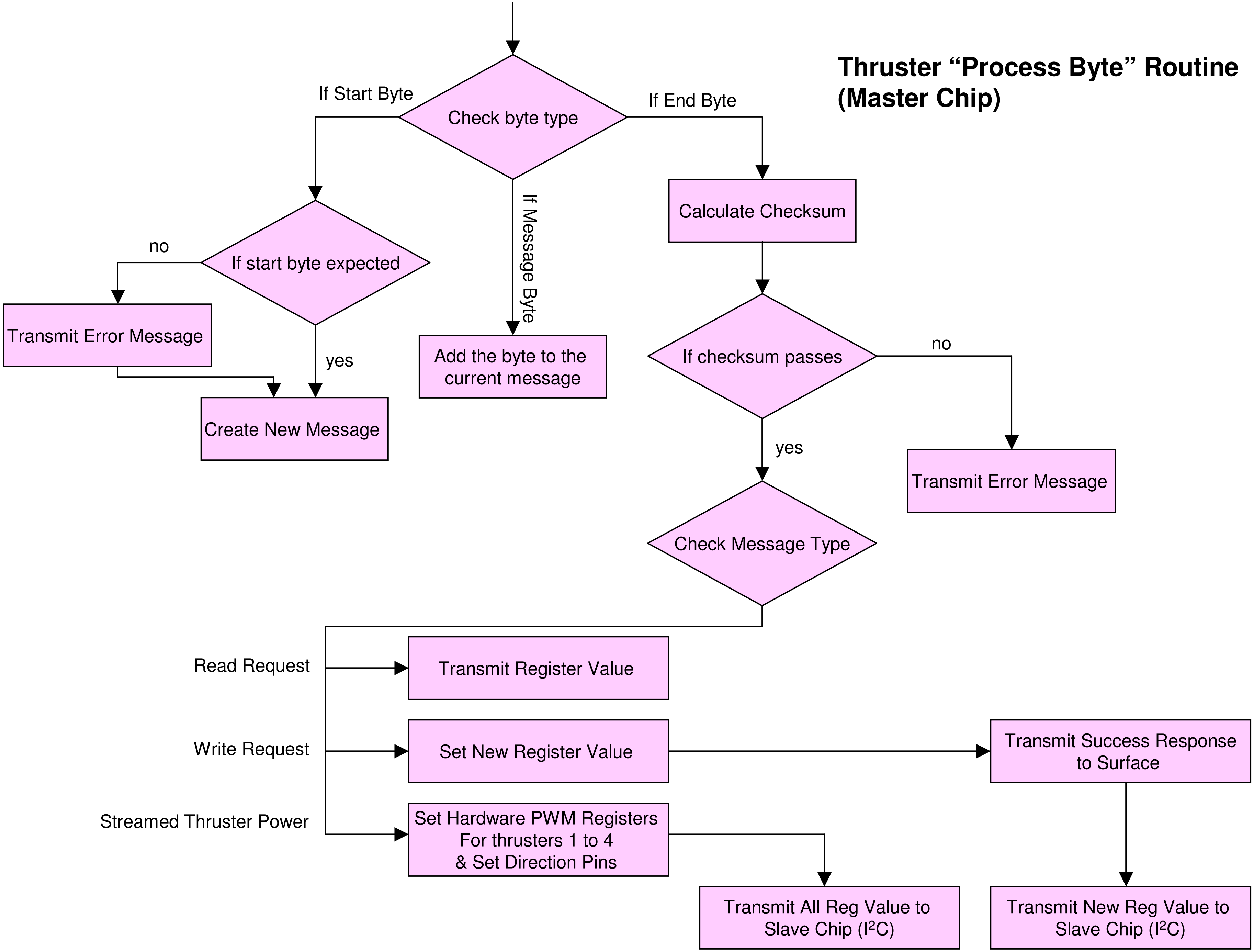
Main Routine



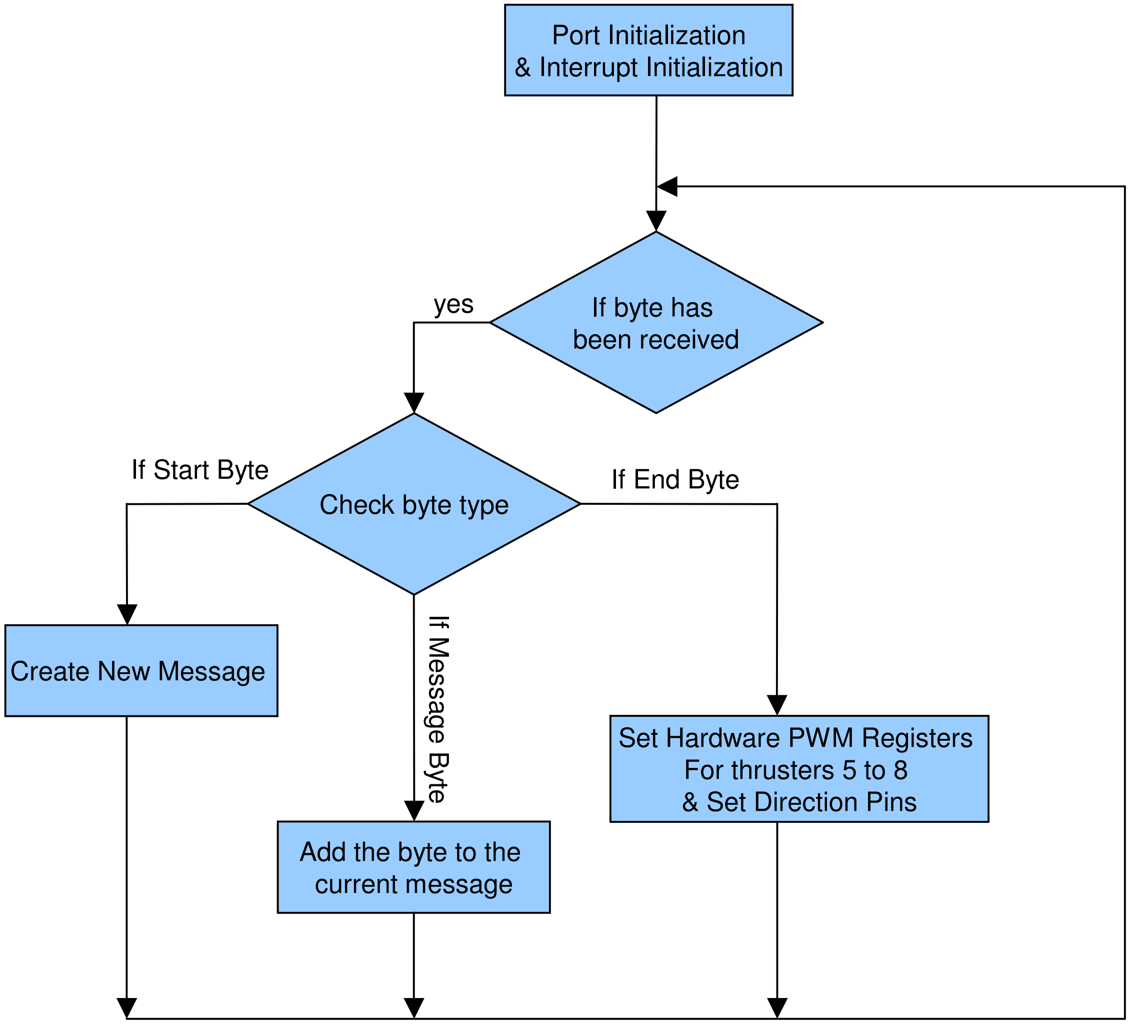
Note:

The PWM control signals for the motor driver are administered through hardware.

Thruster “Process Byte” Routine (Master Chip)



Thruster Control Board Software Flow (Slave Chip)

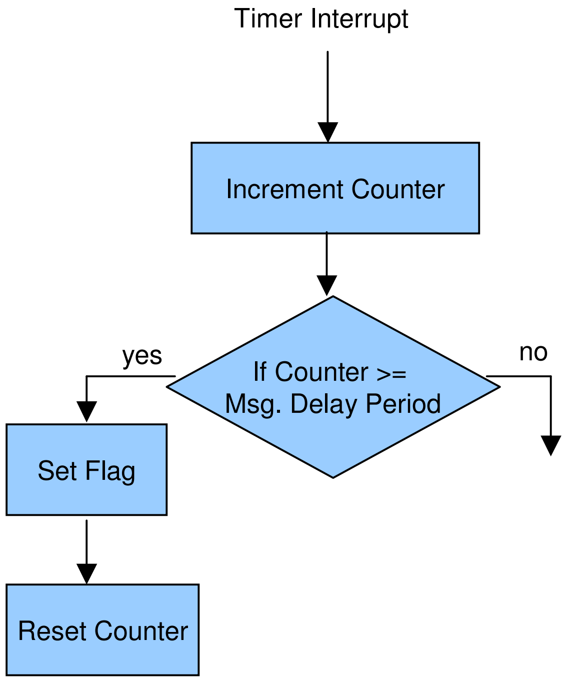


Note:

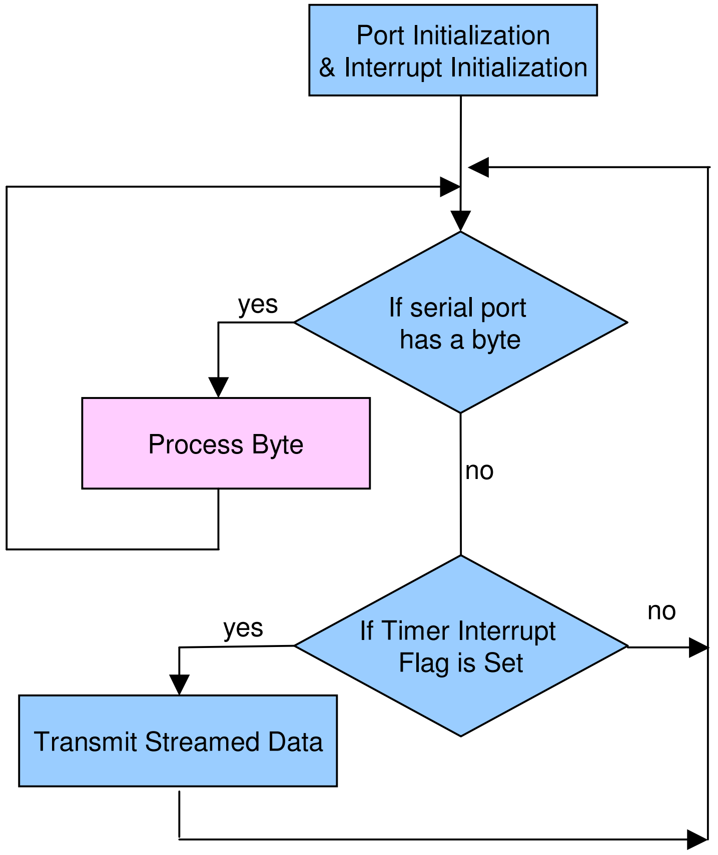
The PWM control signals for the motor driver are administered through hardware.

Sensor Control Board Software Flow

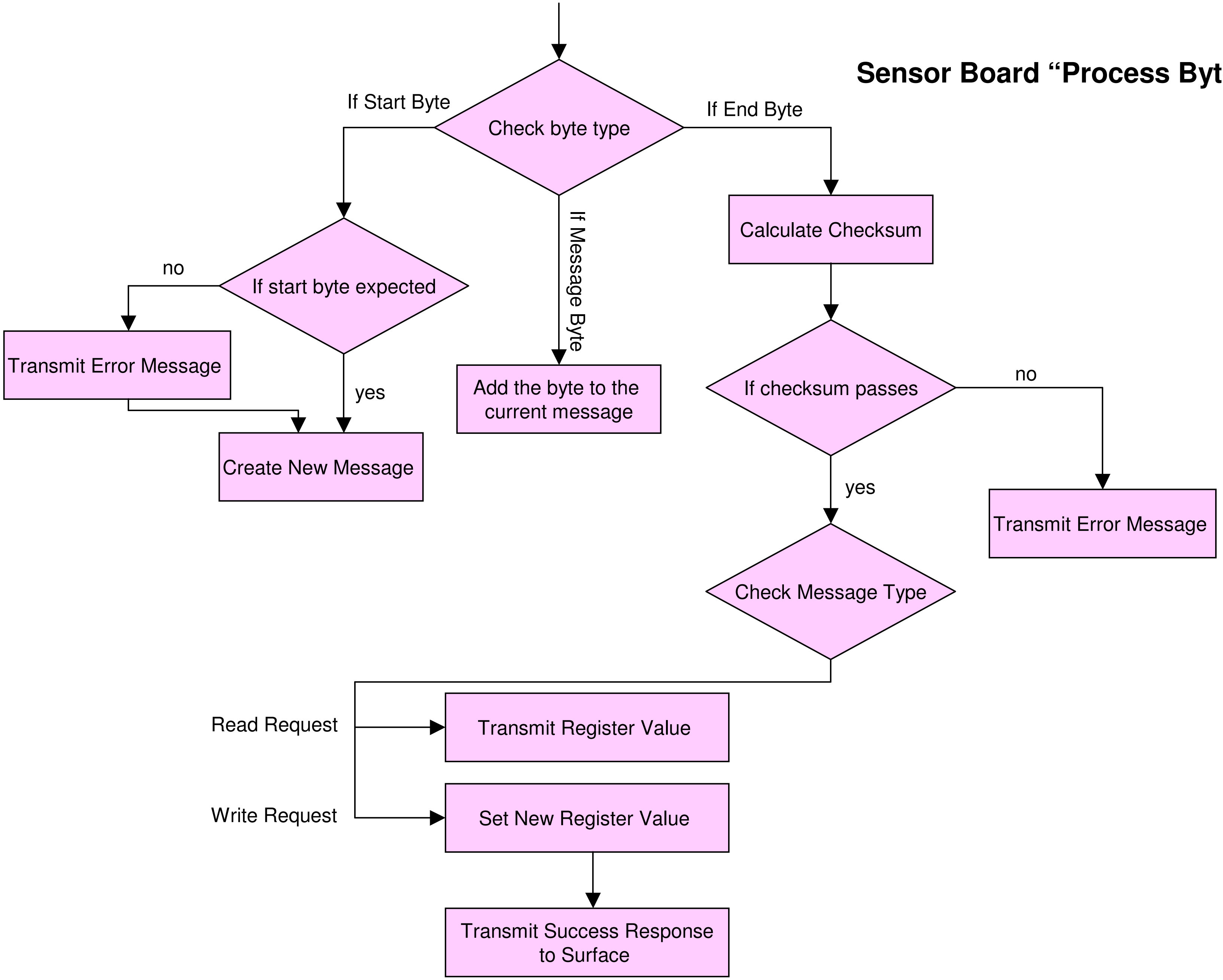
Interrupt Service Routine



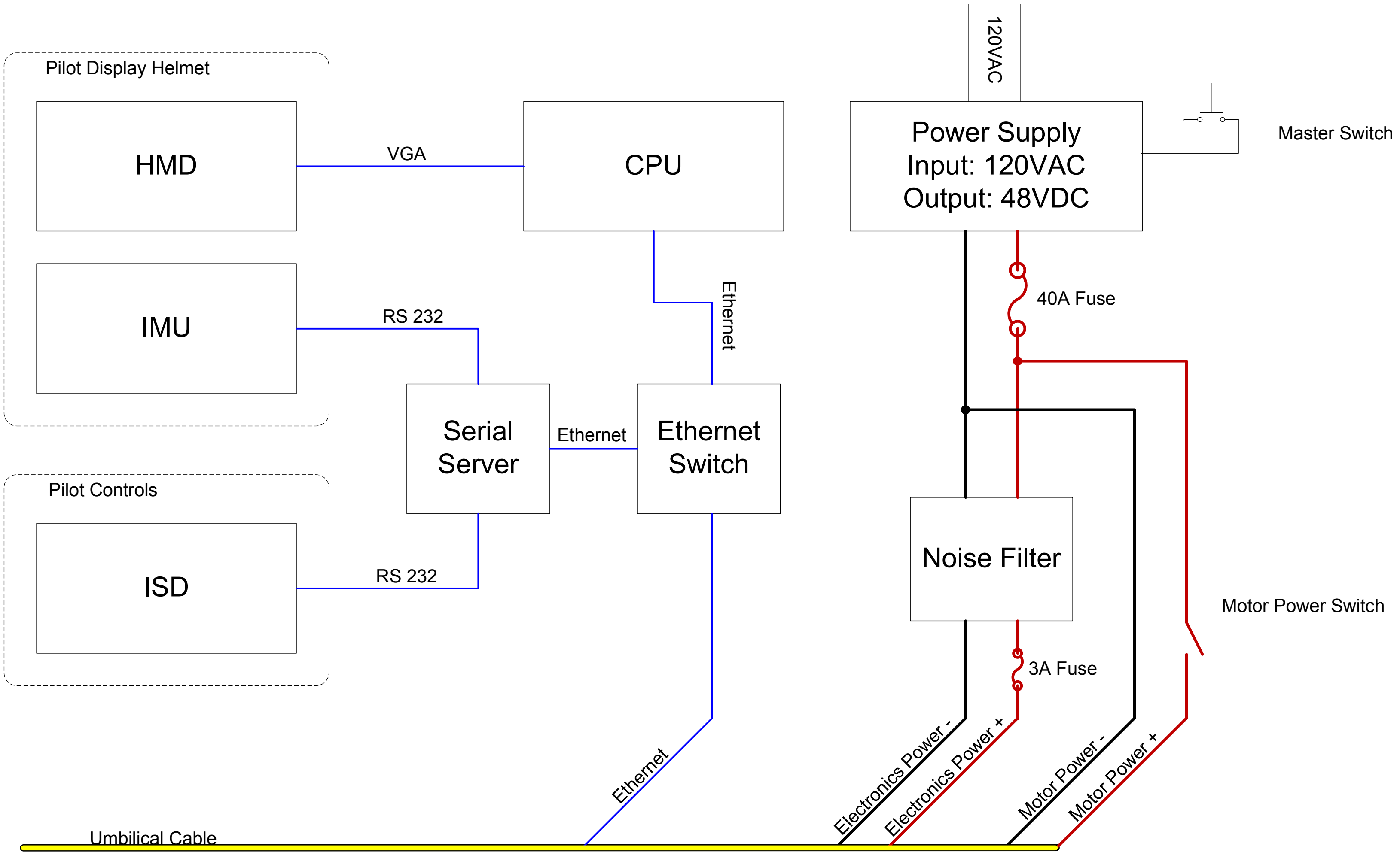
Main Routine



Sensor Board “Process Byte” Routine



Appendix C – Vehicle and Topside Wiring Schematic



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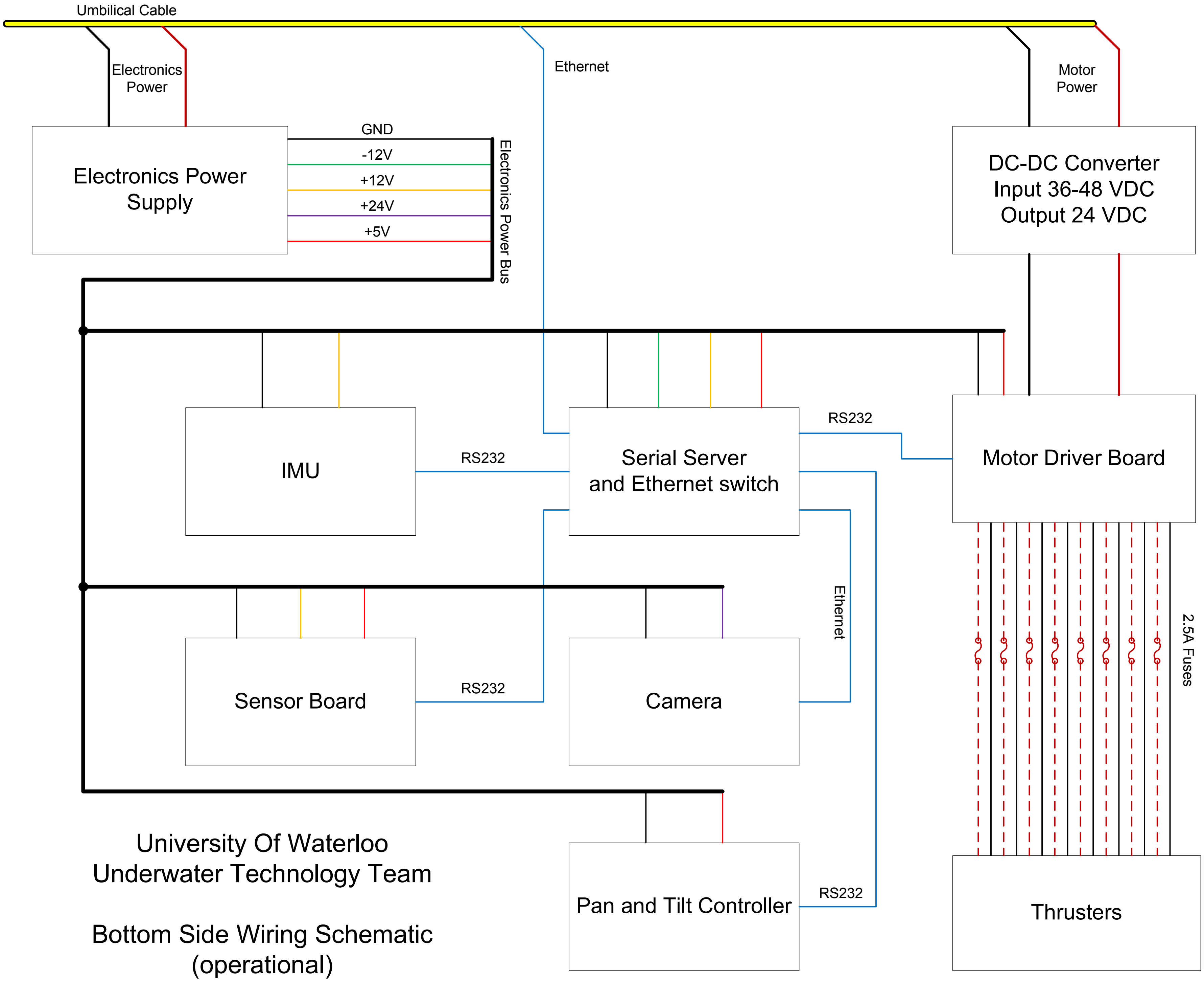
Top Side Wiring Schematic



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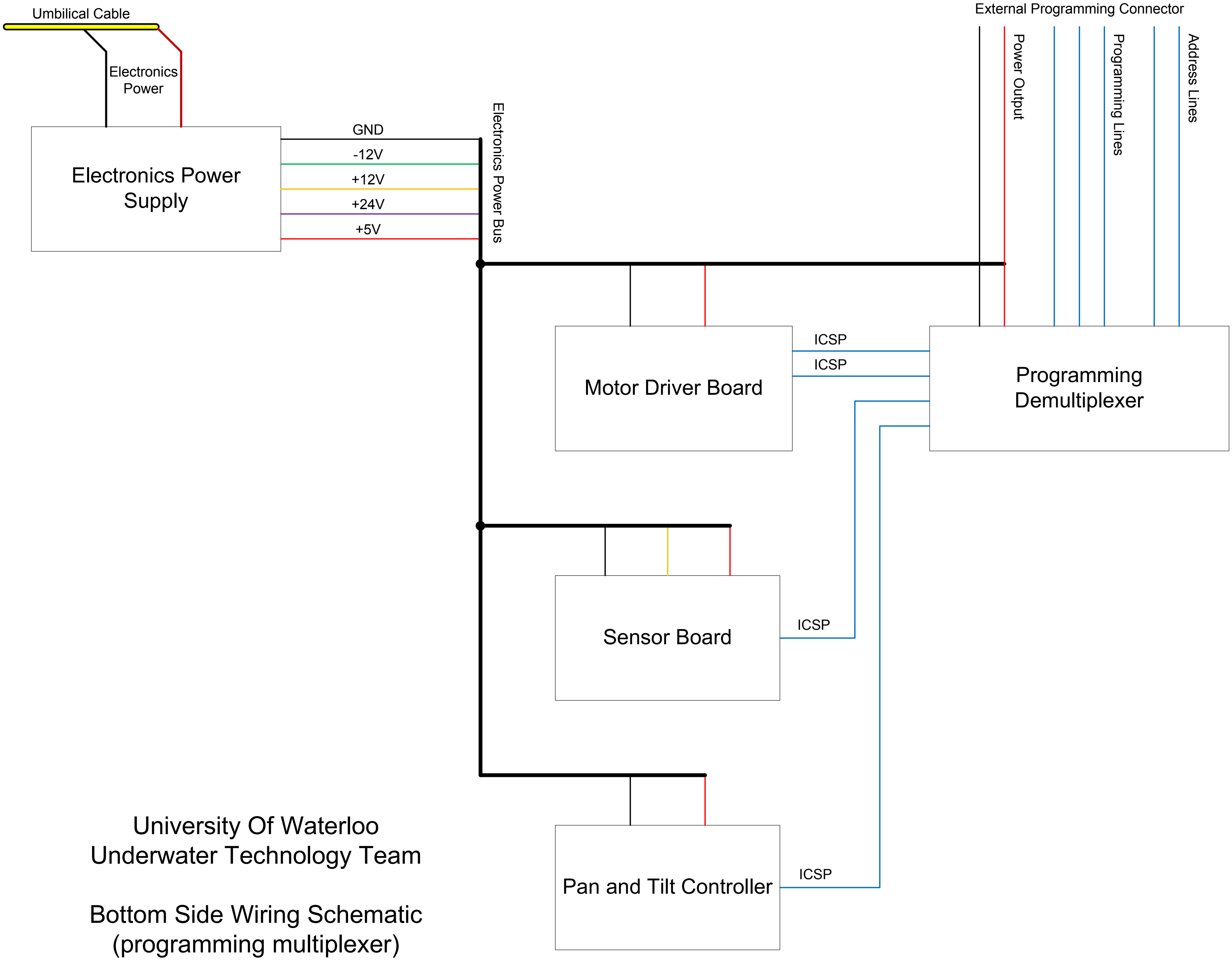
Bottom Side Wiring Schematic
(operational)



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Bottom Side Wiring Schematic
(programming multiplexer)