University of Toronto - Design and Implementation of SubZero Autonomous Underwater Vehicle

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Abstract. Aiming to push the bounds of Autonomous Underwater Vehicle (AUV) technology, MDA has developed the next iteration of its AUV design christened 'SubZero'. This design strongly focuses on robust system performance, efficient system integration, and cost efficiency compared to MDA's previous AUV: AquaTux. SubZero sports a new cylindrical hull to better withstand the aquatic environment and be modular enough to allow fast attachment and detachment of peripherals while being lightweight. MDA has re-purposed and improved AquaTux's electrical system to allow for an expansion of AUV capabilities to include sonar and fine thruster control. SubZero also has completely revamped its computer vision software and artificial intelligence for excellent autonomy.

I. INTRODUCTION

The University of Toronto's Mechatronics Design Association (MDA) is comprised of over 20 undergraduate students from the University of Toronto. Using 11 years of Autonomous Underwater Vehicle (AUV) development in conjunction with motivated members to challenge themselves, MDA has created a brand new AUV for its 9th entry into the 2015 RoboSub competition, where teams compete with specially developed AUVs to complete various underwater tasks.

To meet all the complex challenges entailed in a large engineering design project, MDA is subdivided into a mechanical, electrical, software, and executive team to adequately develop an effective, low-cost, agile AUV platform that meets all the RoboSub requirements. With each consecutive year, extensive hands-on projects are conceptually developed, prototyped and constructed within an 11 month AUV design cycle.

II. MECHANICAL SYSTEMS

The mechanical systems are tasked with providing a waterproof enclosure to house all of SubZero's advanced electronics needed for AUV operations. SubZero's infrastructure also allow for precise underwater movements and functionality. This is achieved through the use of a single cylindrical hull with internal and external frames. The mechanical system is designed to be easily machinable and assembled, while remaining as cost efficient as possible. Models of SubZero were designed and assembled using SolidWorks. Individual parts were designed for large dimensional tolerances and manually machined.

A. Hull. During the design stage of the hull, we strived to use familiar geometry to decrease manufacturing issues while increasing the structural integrity of the AUV. A cylinder was chosen for these reasons. Flanges are attached to both ends of the cylindrical hull to provide clearance for the exterior frame (Figure 1). Polycarbonate was chosen over other materials due to its light weight, availability, machinability, and transparency.

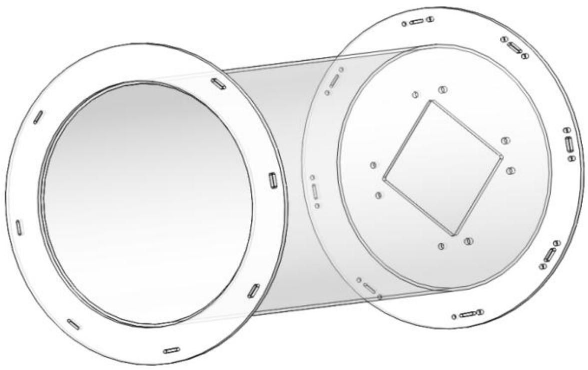

Figure 1. Model of hull with flanges.

Front Lid. The front of the AUV uses a cap mechanism to open and close the submarine, which allows users to access the interior. The lid is composed of two 1/2" polycarbonate plates—one spanning the inner diameter of the hull and the other, a superimposed hexagon covering the hole. The hexagon is superimposed to evenly spread the hydrostatic pressure on the hull and flange. The circular plate is fitted with a concentric O-ring for a plug seal. The hexagonal plate was chosen for ease of machining. Both plates are bolted together with 4 bolts each with a rubber washer attached for waterproofing (Figure 2).

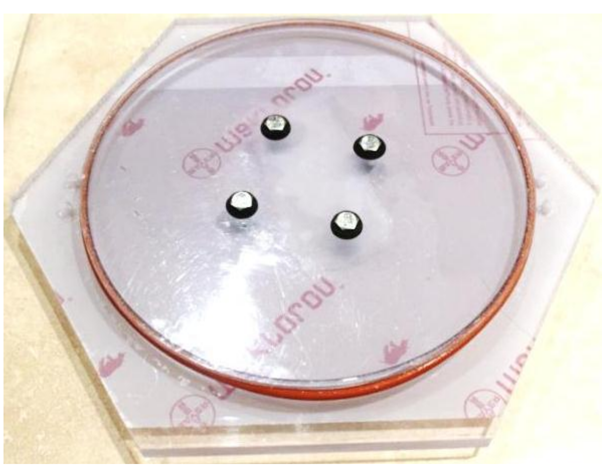

Figure 2. Set up of the front lid.

Back Connector Plate. The rear section of the hull is O-ring sealed using another polycarbonate plate and eight bolts. The O-ring is placed inside a groove machined into the plate to prevent water leaks. This plate also acts as the interface between the exterior electronics and the interior electronics, exhibiting seven 8-pin waterproof connectors and the pressure sensor. Each connector, pressure sensor, and bolts are paired with O-rings for waterproofing (Figure 3).

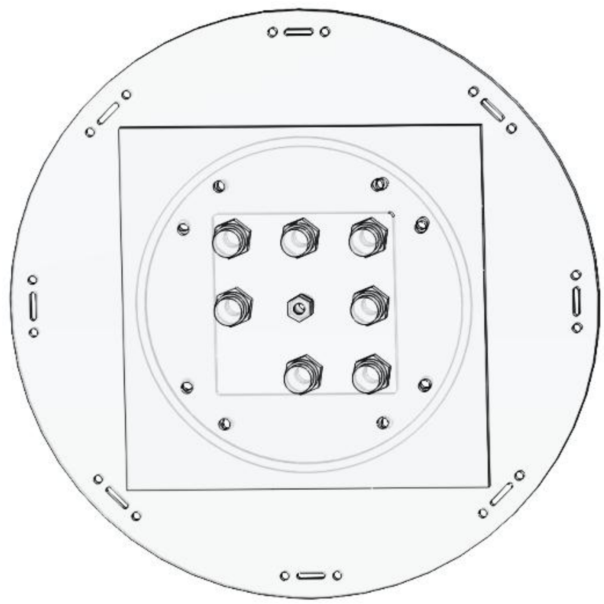

Figure 3. Model of back connector plate.

B. Interior Frame. The structure of the interior frame consists of a rectangular base with triangular bars at both ends. The base provides a flat and stable platform to secure the electronics components. The triangular bars secure the padding at both ends of the hull and acts as anchors for the inner connector pins and the front webcam. Wood with a waterproof coating is used as the material for the interior frame because it is cost-efficient, easy to acquire, and easy to machine (Figure 4).

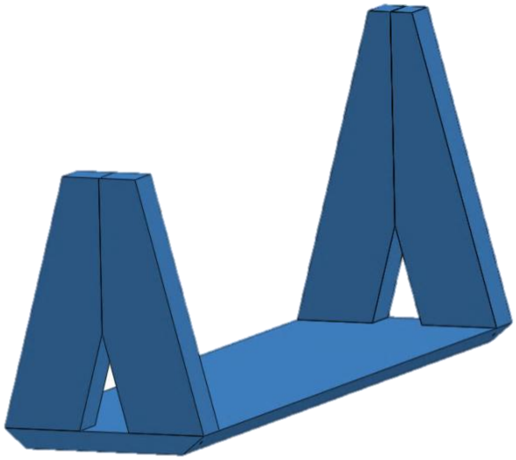

Figure 4. Model of interior frame.

C. Exterior Frame. In order to attach peripherals to SubZero, an exterior frame was created out of six epoxy-finished steel shelving tracks affixed parallel to the longitudinal axis of the hull. The tracks were chosen for their sturdiness, cost, and built in grooves, which allow for easy attachment of thrusters and peripherals to the exterior frame. In addition, the tracks hold the ballast system, while providing anchor points to hoist SubZero (Figure 5).

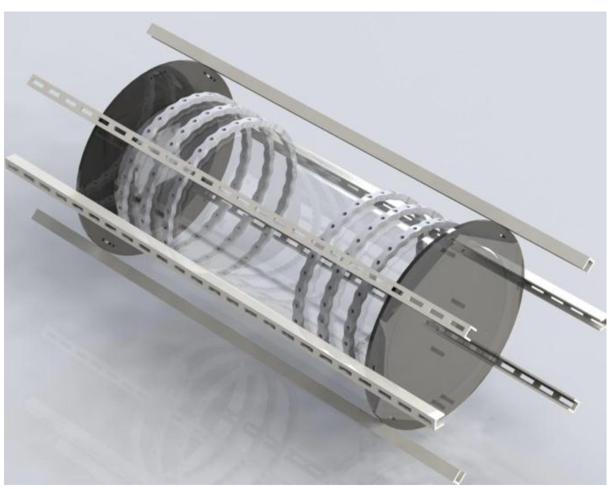

Figure 5. Model of exterior frame.

All tracks are secured in place by six belts of 3/4" width galvanized steel strapping for easy adjustability. The strappings are then bolted together in tension, keeping the tracks aligned to the flange (Figure 6).

Figure 6. Detail of strap bolting.

Ballast System. The ballast system contains weights required to keep the AUV slightly positively buoyant. It is used to help balance the vehicle and mitigate any offsets in pitch by keeping the centre of gravity and centre of buoyancy in line relative to gravity. Adjustable gym weights are used as ballast weights for versatility and are clamped onto a suspension frame on the bottom of the AUV. To prevent the tracks from bending to the ballasts, a suspension system is set up using galvanized aircraft cables and turn buckles (Figure 7).

Figure 7. Ballast system with suspension.

Thrusters. Three Seabotix BTD-150 thrusters are placed on the exterior frame to give SubZero the degrees of freedom it requires. Two thrusters are directly mounted on to the tracks. The third thruster is attached to the top of the AUV via a customized brace (Figure 8 and 9).

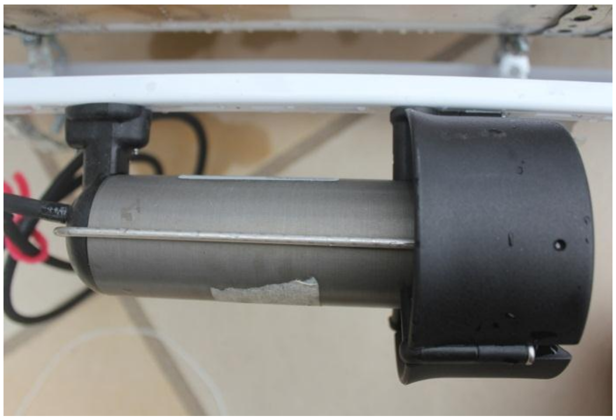

Figure 8. Side thruster placement.

Figure 9. Top thruster prototype.

The minimal configuration was taken to reduce weight and allow for sink, rise, forward, backward, left and right movements. These thrusters connect to the electronics through the back connector plate.

III. ELECTRONICS SYSTEMS

Our electronics serve to interface our high-level software commands to the actuators on SubZero (i.e. thrusters), as well as power all the circuitry. The circuitry is modularized into separate stacks and designed to handle all low-level tasks required to maneuver SubZero and acquire sensor data from our inertial measurement unit (IMU) and depth sensor. Each stack is composed of printed circuit boards (PCB) that were designed in-house. These stacks are managed by the embedded system, which centralizes the control and management of each electrical component.

SubZero's electronics are arranged into two stacks of PCBs—one dedicated to power distribution and management, and the "main stack", which interfaces the embedded system with the PCBs.

A. Power Source. Nickel metal hydride (NiMH) battery packs were custom designed by our team to provide a constant source of power for the electronics excluding the netbook, which contains its own portable battery. SubZero utilizes two battery packs; each pack consists of twenty SY136T Sanyo NiMH batteries. These batteries are connected in series to form a 24V nominal battery pack with a capacity of 4100mAh. Temperature sensors are also installed as a fail-safe in each pack to terminate SubZero in the case of overheating.

B. Power Management Stack. This stack is tasked with the management and distribution of power throughout SubZero. It is connected to the batteries through a relay switch. Removing the magnetic kill-switch will cut this connection, eliminating power from SubZero (Figure 10).

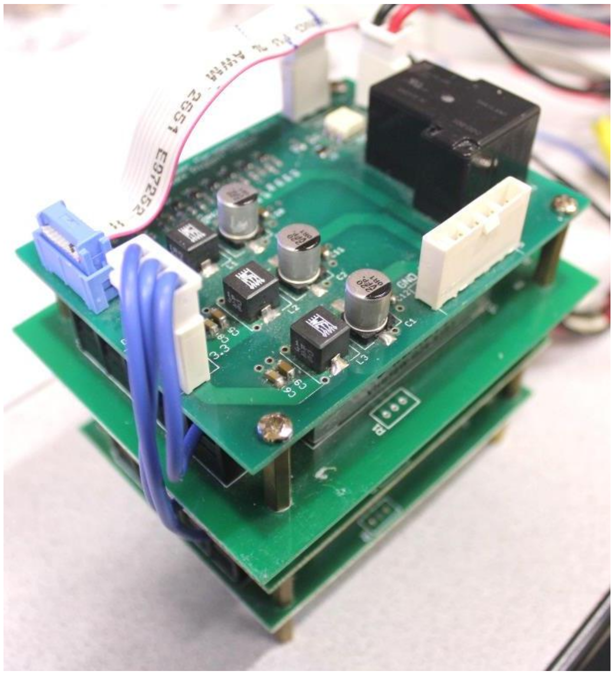

Figure 10. Power management stack.

Since several different components require different voltage levels, this stack splits and provides the necessary power to each component. Three DC/DC converters are used to attain the desired voltages of 3.3V, 5V and 12V. LC output filters then remove any switching harmonics before splitting the voltages through a series of copper bus-bars.

Four pairs of analog comparators are used to detect when any of the rails go over or under their nominal voltage by 5 percent. As a final precaution, breakers have been inserted between the batteries and relay, and between the stack and bus-bars.

C. Main Stack. The main stack houses the embedded system along with the interface PCB, motor driver PCBs and sonar PCB. These boards are connected via the main stack connector, a 120 pin board-to-board connector. These connectors form a wide bus between the embedded system and the mated boards (Figure 11).

Figure 11. The main stack connector with IMU.

The interface board on the top provides communication between all of SubZero's peripherals and sensors, and the embedded systems. These include the rugged VectorNav VN-100 IMU, pressure sensor, hydrophones, and thrusters. The IMU and pressure sensor are connected directly to the interface board. The hydrophones and thrusters pass through the sonar and motor driver boards respectively.

D. Peripheral Motor Driver Boards. The motor driver boards are used to control the thrusters used on SubZero and other internal actuators. They are controlled by digital pulse-width-modulation signals to determine the speed and direction of a given motor. Each motor driver board (Figure 12) consists of 8 NMOS high-side half H-bridges driven by LT1660 half H-bridge drivers.

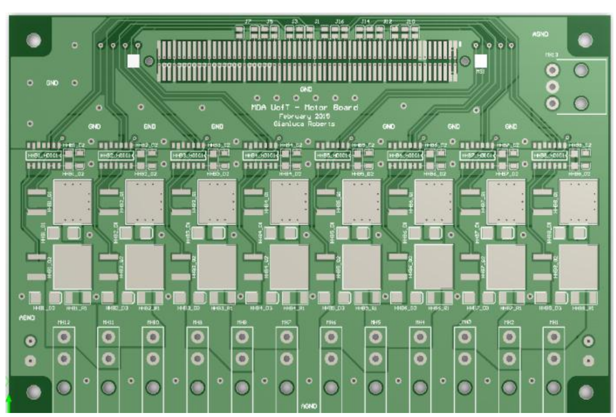

Figure 12. Motor driver board design.

Each half-H-bridge can be independent or used in combination with another half-H-bridge to form a full-H-bridge, providing extra flexibility and allowing the same boards to actuate other peripherals such as the marker dropper and torpedo launcher in the future.

E. Sonar Board. The newly designed sonar board is used to pre-amplify, filter, and digitize the analog signals from our four hydrophones. Placement and routing of the board are designed to be optimized using power and ground layers. This keeps high speed digital and analog signals far away from each other, while making trace impedance as small and consistent as possible to minimize noise and signal reflections (Figure 13).

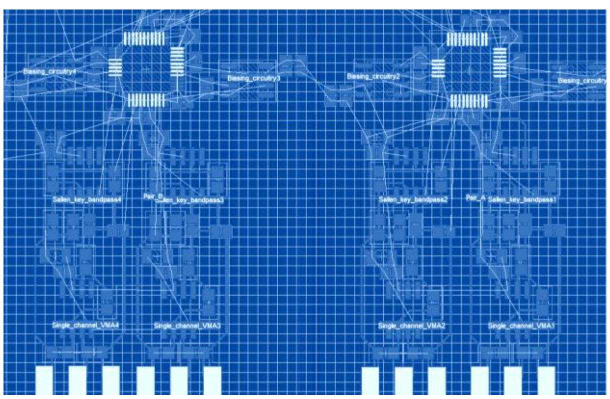

Figure 13. PCB layout of the sonar board with a channel for each hydrophone.

Bandpass filters are designed using Sallen Key topology to attenuate low frequency noise generated by our thrusters and provide a maximum gain at the frequencies of interest (Figure 14).

Two AD7264 analog to digital converters (ADC) were selected for their high precision (14 bit), configurable, high-speed sampling and SPI communication interface, high input impedance, low signal-to-noise ratio, and programmable gain amplifiers. These ADCs allow us to scale our digital signal according to the distance from the pinger. The final digital output from the ADCs is then buffered before being sent to the main stack connector.

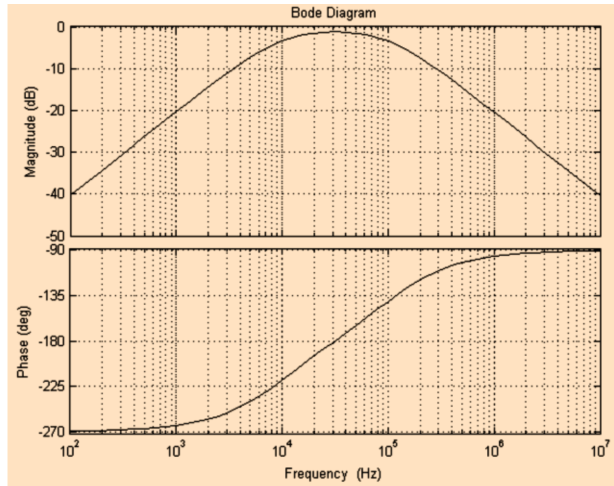

Figure 14. A Bode plot of Sallen Key bandpass filter transfer function, with the bandwidth and centre frequency matching the pinger frequency.

IV. EMBEDDED SYSTEMS

At the heart of SubZero's electronic subsystem is a Terasic DE0-Nano, an Altera Cyclone IV field programmable gate array (FPGA) development board that encompasses all of the embedded systems. Its purpose is to link SubZero's netbook with all of the internal circuitry through a single, centralized board. This removes the necessity to interface several different microcontrollers. The DE0 was chosen for its availability of general purpose input/output pins, small form-factor (3x2 inches) and flexibility—optimizing performance and configurability.

A. Sonar Processing System. The sonar system triangulates the bearing towards a sonar pinger by determining the time delays between hydrophones. A cross-correlation operation is performed on each combination of hydrophone signals to determine the difference in phase between them (Figure 15).

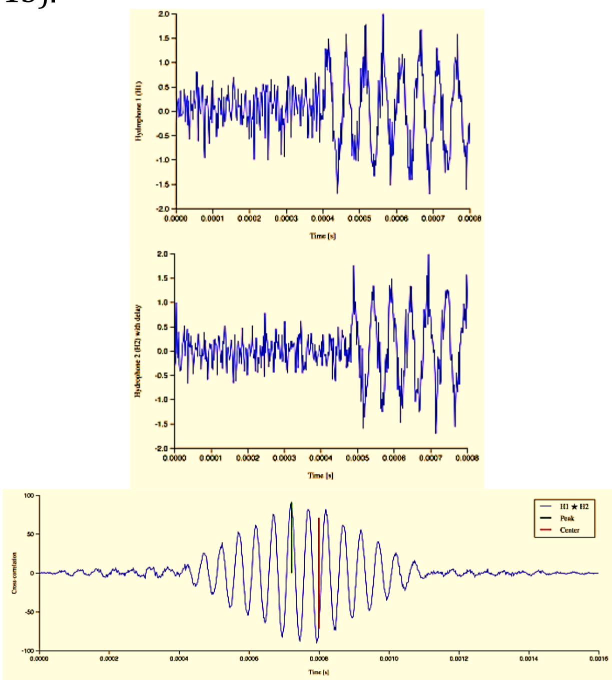

Figure 15. Cross-correlation peak shifted by time delay.

A Fast Fourier Transform (FFT) based convolution is then used to determine the time delays between the hydrophones. With knowledge of the time delays and the hydrophone array's geometry, a bearing towards the sonar pinger can be determined.

B. Embedded Soft Processor. NIOS II, the FPGA soft processor, exposes high level commands to the netbook, giving access to the electronic peripherals. These include the IMU and depth sensor, which provide attitude readings, and the motors. Proportional-integral-derivative (PID) controllers are implemented on the NIOS to give them immediate access to the IMU depth readings and the motor driver boards. The netbook interface sets a target speed, yaw, and depth, which become the inputs to the PID controllers.

V. SOFTWARE SYSTEMS

SubZero's software serves as the interface between the user and SubZero. It houses all of the custom C/C++ algorithms and functionality that allow the submarine to carry out its tasks autonomously. This year, the software was completely redesigned to follow the Agile Manifesto principle of creating adaptive code. This was achieved primarily through the use of several design patterns and the graphical Model-View-Controller (MVC) approach.

A. Computer Hardware. All software is stored and run on an ASUS VivoBook X200MA netbook powered by an Intel Bay Trail-M N2830 2.4GHz dual core processor and 4GB of RAM. Several 2.0 and 3.0 USB ports are also used to connect to the on board FPGA and webcams (Figure 16).

Figure 16. ASUS VivoBook X200MA.

The netbook weighs 1.24kg, making it flexible and lightweight. It is remote controlled through an Ethernet tether SSH X11 connection using an ARCFOUR protocol to enhance the transfer speed.

B. Software Organization. The software can be broken down into three major abstractions: the Model, the View, and the Controller. These make up the skeleton of the graphical MVC framework used in SubZero (Figure 16).

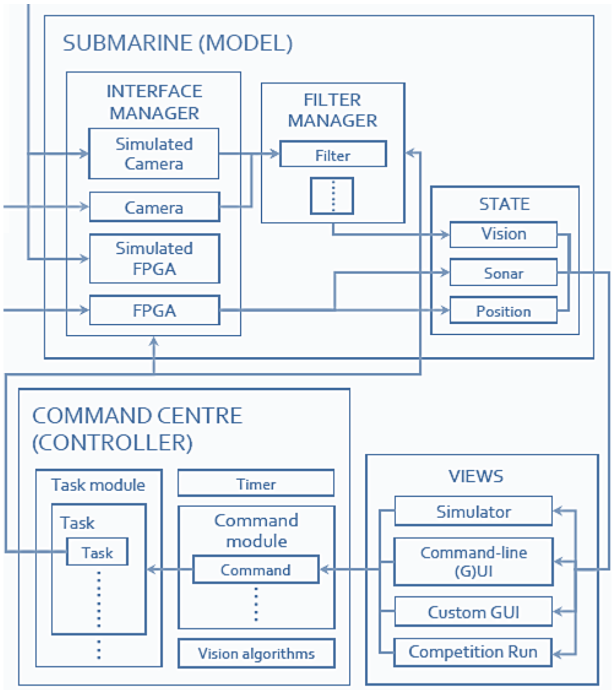

Figure 16. SubZero schematic of MVC architecture.

Model. The models represent information about SubZero and its surrounding environment. They also encapsulate the connection and the information source, which consists of the webcam and FPGA connections.

Not only do these models gather and store this information, they also provide a line of communication outwards to the FPGA and the webcams. This allows the software to communicate to the FPGA to control any external components, such as the thrusters.

View. Views, in the context of the Model-View-Controller approach, are the interfaces between the software and the user. They provide graphics to the user and obtain user input. Views are an abstraction of UI that can be customized based on the user's needs. This flexibility allows users to easily test and debug the submarine (Figure 17).

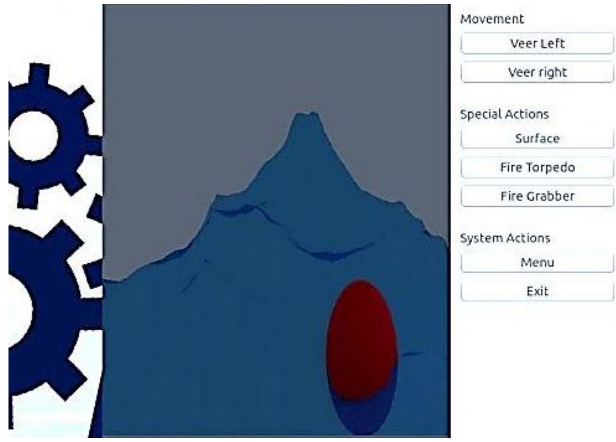

Figure 17. Example view of a custom-made GUI for simulating task runs.

Controller. Controllers act as the mediators between the Models and the Views. They serve to interpret the user's input received from the Views and determine which task to carry out. These tasks involve "controlling" and manipulating the Models and Views to achieve the desired outcome.

C. Vision. SubZero's vision heavily emphasizes the ability to provide up-to-date images, while carrying out customized pre-processing filtering and post-processing analysis. Two Logitech Webcam 9000 Pro webcams pointed forward and downwards are used to gather the images. These cameras were chosen for their Linux driver support as well as their low cost. The OpenCV library is used for all image gathering and processing functionality.

Filtering. The pre-processing filtering module is designed to be fully customizable. Filters can be created or modified with minimal refactoring. Once created, filters can easily be swapped for another or chained together in any specified order during run-time. This gives SubZero the ability to adapt to the environment as needed, even during a run.

Once the desired filter set is specified, all subsequently acquired images are passed through these filters and stored for other modules to use (Figure 18).

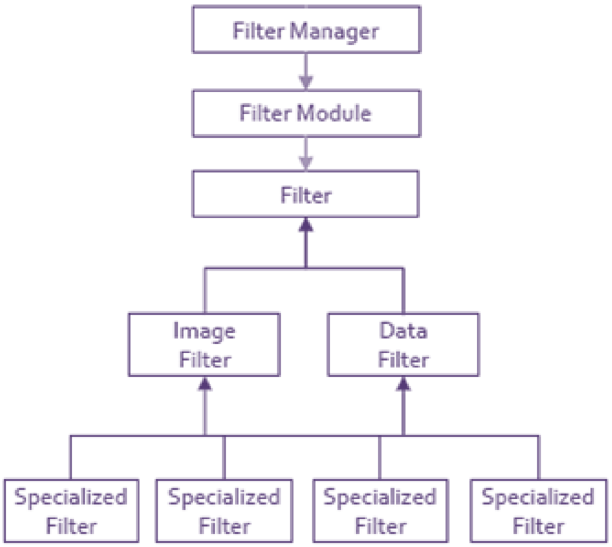

Figure 18. SubZero schematic of filter module.

D. Software Control. The "brain" of SubZero is held in the controller module. All the post-processing and algorithms that determine the submarine's next movements are run in the controller module. These algorithms and post-processing are encapsulated into modules called tasks. Using the composite design pattern, we represent higher level tasks with a composition of other tasks. This inherently makes each task easy to call individually or as a group. Ultimately, tasks will communicate to the model module to make SubZero move.

E. Simulator Testing. A simulator for testing SubZero was developed to test different functionalities of the submarine prior to pool tests. The simulator is created by loading a model of the test environment into the Qt framework. The model of the sub is also loaded into the Qt framework to serves as a camera in the simulated environment. The Qt library is used to create all of our user interfaces and is held in the view module. The components of the simulation were made using Blender, which was chosen for its ease of use and low cost (Figure 19).

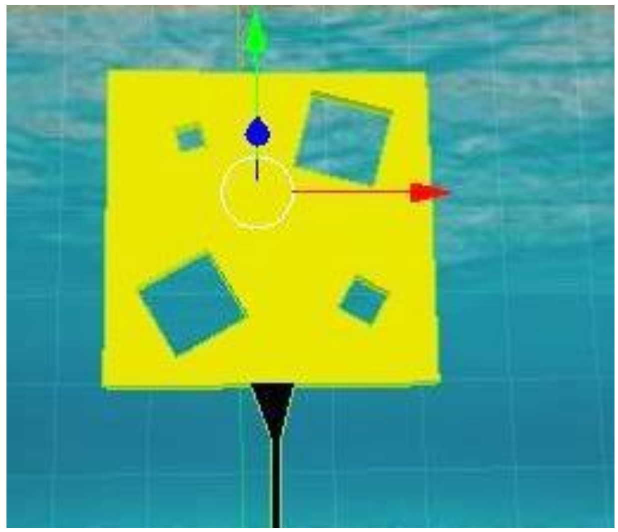

Figure 19. Blender model of the Set Date task used in the simulator.

VI. CONCLUSION

SubZero is a modular AUV developed by the University of Toronto's Mechatronics Design Association after this year's development. Using the design concepts and experience from previously developing the AquaTux AUV platform, attention was placed on improving the structural integrity and agility of the AUV. Future projects will aim to expand MDA's AUV capabilities through design and completion of peripherals. MDA members have been able to participate in large and extensive engineering projects over a 11 month AUV development cycle. The valuable experience in complex mechanical, electrical and software engineering design has been a challenging yet rewarding team-building experience for MDA members who hope to participate in the next RoboSub competition with its next AUV iteration.

ACKNOWLEDGEMENTS

The University of Toronto Mechatronics Design Association would like to thank our friends and family at the University of Toronto for their generous contributions that made our project possible: the Engineering Society, Department of Electrical and Computer Engineering, Department of Mechanical and Industrial Engineering, Department of Engineering Science, and Skule Alumni.