McGill Robotics – Development of the Autonomous Underwater Vehicle: Asimov

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***Abstract*—McGill Robotics has built an Autonomous Underwater Vehicle as its first ever entry into the AUVSI and ONR's International RoboSub Competition. A forward-thinking strategy has led the team to prioritize skill development with the goal of making it into the final round after two years. Complete mechanical and electrical systems are ready for deployment at *TRANSDEC 17*, and a software infrastructure has been built so that more tasks can be added after completion of the Gate and Flight Path tasks is demonstrated in 2014. Systems were integrated seamlessly through a year-long review process and formal procedures for deployment. Four months of vehicle validation and optimization have ensured that Asimov is ready for competition.**

I. INTRODUCTION

McGill Robotics is a team of 98 students that has come together to gain hands-on engineering experience through the development of robots for several international competitions and educational outreach programs in the Montreal community. In its first-ever entry to the AUVSI and ONR's International RoboSub competition, McGill Robotics has built an Autonomous Underwater Vehicle (AUV) named Asimov, after the famous science fiction writer. *TRANSDEC 17* marks an important milestone towards the team's two-year goal of making it into the final round of the 2015 competition.

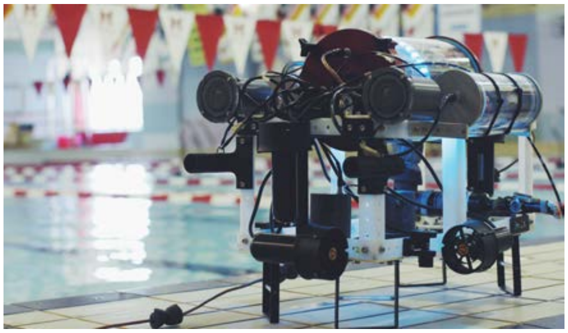

Fig. 1. Asimov on the pool deck

Over the course of the year, a long-term design philosophy has guided the growth of the team and the development of the AUV. First and foremost, we value *Team Before Machine.* Our goals parallel those of the AUVSI student competitions: "to provide opportunities for students to experience the challenges of system engineering, [and] to develop skills in accomplishing realistic missions with autonomous vehicles."[1] Furthermore, we understand that it takes a skilled and cohesive team to build a robot that is capable of earning a spot in the final round at such an esteemed competition. In order to do this, McGill Robotics set out to spend one year building a robust mobile

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[1] RoboSub Mission Final 2014 Draft.pdf

platform that can serve as a foundation upon which more features can be developed. Even during the first year, designs were converged upon through an iterative process of prototyping and review.

Fig. 2. The 2013-2014 McGill Robotics team

II. THE SYSTEMS ENGINEERING PROCESS

In order to extend opportunities to as many students as possible, a very large team was assembled. A strong team hierarchy was enforced to assign ownership of certain responsibilities to different people. McGill Robotics consists of four teams, with the AUV team and Business team contributing directly towards the RoboSub competition. The AUV Team was divided into Mechanical, Electrical, and Software Divisions, and a Systems Division was created during vehicle assembly to coordinate integration and testing. Each division contains sections of two to twelve members that are responsible for the development of one major feature. Sections meet at least once per week to assess progress and plan their work, and section leaders coordinate at weekly division integration meetings. The whole team comes together in one room every two weeks for a demonstration featuring updates on recent accomplishments.

McGill Robotics followed a seven phase process from concept to deployment, as outlined in the NASA Systems Engineering Handbook[2]. After a full month dedicated to building team relationships and developing some of the fundamental skills for working in robotics, we outlined the functional requirements for the vehicle and explored numerous possibilities on how to meet them. The remainder of the first semester was spent experimenting with different design embodiments through testing and simulations of each system. Each division also brought in expert advisors for a design review. Winter was spent building system components, including manufacturing in the machine tool laboratory, populating printed circuit boards (PCBs), and developing the software system. Countless unit tests were completed prior to submerging the entire vehicle in a tank on March 28. This accomplishment left four months before the competition to identify weaknesses in the design and iterate. Major revisions to the electrical and mechanical systems were completed for June 28, leaving a final month for testing and tweaking to ensure that the vehicle was reliable in time for *TRANSDEC 17*.

Fig. 3. Every part of Asimov was modeled in Autodesk Inventor

III. DESIGN OVERVIEW

The 2014 vehicle, developed by McGill Robotics between October 2013 and July 2014, is a near-shore type, mission-focused, autonomous submersible. While technically an Autonomous Underwater Vehicle (AUV), Asimov closely resembles a Remotely Operated Vehicle (ROV) in its compact, boxy, and agile design. This design intentionally models that of a mini work-class ROV, intended to carry

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[2] http://http://foiaelibrary.gsfc.nasa.gov/

out specific tasks as part of shallow-depth, tethered missions, rather than typical long-range, streamlined, deep-water AUVs built to spend days traveling underwater. McGill Robotics' submersible vehicle, Asimov, features a small form factor, five degree of freedom control, a computer-vision based navigation system, and external manipulators to autonomously navigate and interact with the underwater environment at the *TRANSDEC* facility in San Diego. The team strategically set out to design a vehicle that could successfully complete all challenges at the *RoboSub Competition* within a two-year period, striving to complete the first few challenges in 2014, but providing a robust test platform for 2015.

Just under 50 pounds and measuring 35 inches long, 17 inches wide, and 26 inches high, Asimov is light and compact. As the design focused on dexterity over speed, the vehicle can control five degrees of freedom (DoF) with its six thrusters, and has a top speed of 1.5 knots. A CO_2-powered pneumatic manipulator system allows Asimov to fire torpedoes, drop markers and grab objects, while navigation is facilitated with data from three cameras, an IMU, and two pressure sensors, processed through the on-board computer. The entire system is powered by two 24V lithium-polymer batteries, which provide a run-time of up to two hours.

IV. MECHANICAL SYSTEMS

Asimov's mechanical system incorporates the main hull, to house the majority of the electronic components; pressure vessels, to enclose external modules; manipulators, to interact with the environment; and a frame, to mount each system. The overall physical structure is optimized for balance, weight, modularity, and a net buoyancy of about 1% of the total weight.

A. Main Hull

The main hull pressure vessel houses the computer, power distribution boards, motor controllers, microcontrollers, indicator LED strips, and active water cooling system. The hull consists of an anodized aluminum and clear acrylic cylinder, with a face-sealing end cap that contains the electrical bulkhead fittings. The front end cap went through two iterations of design to accommodate new bulkhead fittings and reduce electrical cross-talk. The front cap changed from a fully aluminum plate to an aluminum ring with a non-conductive Delrin cover. Inside, acrylic electronics racks support the circuit boards and are lasercut to increase airflow and reduce weight. These racks are mounted on aluminum rails, which are fixed to the removable front cap and slide into the vessel to facilitate debugging. All electrical connections pass through the front cap via Fischer and Marshall Underwater bulkhead connectors. Because of the densely-packed interior and large thermal loads, an active water-cooling system is needed to exchange heat from the CPU and GPU to a radiator mounted on the exterior wall of the vessel.

B. Frame

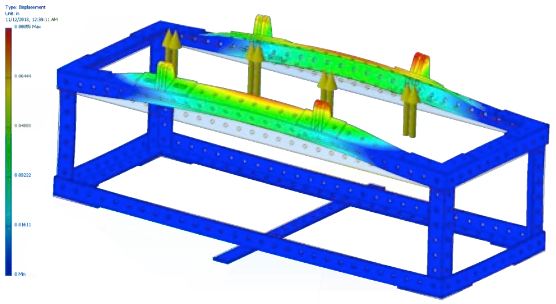

Fig. 4. The frame geometry was optimized using Finite Element Analysis

Asimov's rectangular-prism-shaped frame, made of drilled-out HDPE angle extrusions, was designed to be modular, light, and easy to manufacture. The simplicity and modularity of the frame allow for each component to be mounted in a number of configurations via aluminum brackets, and adjusted to account for balance and design changes. The frame design puts the center of buoyancy well above the center of mass, which increases stability and balances both list and trim of the vehicle. The frame's four bottom corners have simple U-shaped structures that double as feet and carrying points.

C. *Pressure Vessels*

Two main battery vessels, two swappable backup battery vessels, three camera vessels, a vessel for the pneumatic system, and a vessel for the IMU were all designed to enclose electronics that require isolation from the main hull. As the primary function of these enclosures is to ensure waterproofness extra care goes into ensuring the proper tolerances, lubrication, and sealing practices of each vessel. Each vessel is always transported and tested separately before being secured to the vehicle.

Fig. 5. Manufacturing seals to within 0.002" has prevented any leaks.

1) Battery Vessels: Each battery enclosure is made of a clear acrylic cylinder, with two bore-sealing PVC end caps—one fixed and one removable (See Figure 5). The removable cap has rails fixed to the inner wall, which cradle one battery, and a Fischer bulkhead fitting provides the electrical connection. Two active vessels sit on rails on either side of the vehicle, while two back up vessels can be swapped out when battery levels get low.

2) Camera Vessels: A unibody design is employed to enclose each of Asimov's cameras, providing the proper support, sealing, and connection while reducing complexity. The vessel is turned from PVC, with a face seal at the opening, and a clear acrylic cover to provide the seal and visual opening.

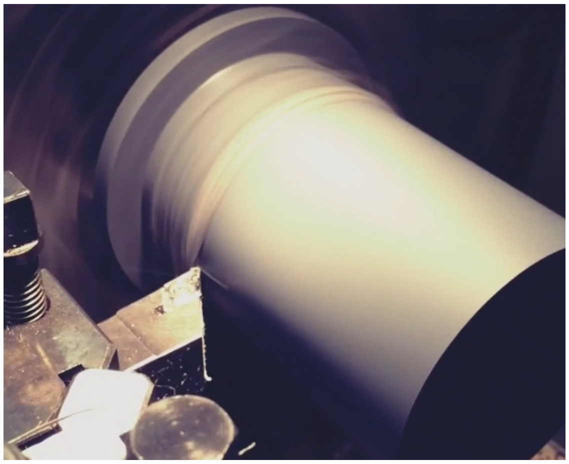

Fig. 6. The camera and IMU vessels were turned from a solid PVC rod

3) Pneumatic Vessel: The enclosure for the pneumatic system is designed similar to the main hull, but with two bore-seal end caps. The fixed end is CNCed from PVC for weight-saving, and the removable end is anodized aluminum to maintain structural support with the nine holes for bulkhead fittings. The six air valves and a valve manifold are mounted onto a rail system, which is fastened to the removable end cap, and a custom PCB sits on the manifold to control each valve. The vessel is mounted to the frame via a CNCed aluminum bracket with rails that allow it to slide fore and aft and provide list.

4) IMU Vessel: It is necessary to shield the Inertial Measurement Unit from the rest of the system's noise, so it has its own non-metallic enclosure–a unibody PVC vessel similar to the camera vessels. The enclosure uses a bore-sealing cap that doubles as the mounting bracket, and inside, a laser-cut housing for the IMU board seats it securely in place.

D. *Manipulators*

The manipulators designed for this year include two torpedo launchers, two marker droppers, and two claw mechanisms. All components were manufactured using 3D printing technology, most of which were printed for us by Stratasys. These components are all part of the pneumatic system that uses pistons, powered by a 3000 psi CO_2 tank and regulated down to 100 psi to actuate each mechanism.

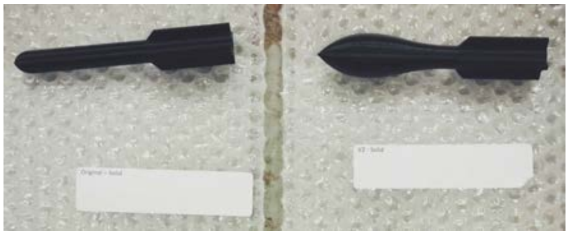

Fig. 7. Two variations of the torpedoes, printed by Stratasys

1) Torpedo Launchers: The launchers fire torpedo-shaped projectiles from the bow of the vehicle by means of a pneumatic piston powered by CO_2 gas. This design was preferred to using the actual gas as a propellant, as research showed it to provide more consistent thrust. The torpedoes were 3D printed with ABS plastic by Stratasys and designed to be both balanced and neutrally buoyant in order to fire in a straight path. The launchers were printed in the same way and were designed to be one piece; acting as the bracket, the fastener to the piston, and the torpedo chamber.

2) Marker Droppers: The marker droppers are also unibody 3D printed structures which act as the bracket, piston fastener, and marker socket, but were made on a FormLabs Form1 printer of a UV-curing resin. A reverse-acting piston, with a magnet at the tip, holds the ball-bearing marker in a socket until it is actuated and the magnet is pulled away.

3) Claw Mechanisms: The two parallel claw mechanisms that hang from the underside of the vehicle are shaped like fingers, made of printed ABS plastic, and powered by pneumatic actuators. The claws close down with just enough force to hold a K'nex® structure, and to detect when an object has been picked up, a reed switch is integrated into one of the fingers.

V. ELECTRICAL SYSTEMS

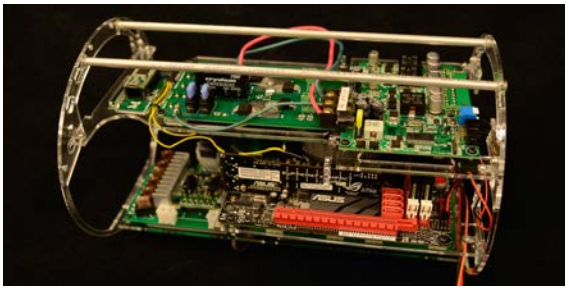

Fig. 8. The electrical system arranged across three racks

The electrical system is divided into four sections: power distribution and monitoring, computer systems, sensors, and electrical-mechanical interfaces. This structure allowed each module to be tested and iterated upon separately, and well-defined interfaces made integration effortless.

A. *Power Distribution and Monitoring*

Two 6-cell lithium-polymer batteries are connected in parallel to power Asimov. They fuel a custom-built power board, featuring two solid-state relays, indicator LEDs, fuse protection, and voltage-monitoring, to ensure that the batteries are never over-drained. The 24V, 5000 mAh batteries were chosen to assure 40 minutes of run-time, but have proven to last around two hours under typical usage.

The kill-switch circuit immediately cuts power to the thrusters and pneumatic actuators, while sending a signal to the computer to safely shut down. The push-button mechanism of a SEACON Underwater reed switch was modified to incorporate a ripcord and release-pin for easy access to a diver while the vehicle is underway.

B. *Computer Systems*

The on-board computer communicates with three cameras, the IMU, and the LED strip via USB; the poolside computer network via Ethernet; and the other sensors and actuators through a microcontroller with a custom PCB shield.

The computer was built with a a Z87 Mini ITX motherboard, Intel i7 4770k Quad-Core CPU, 8GB of DDR3-2400 RAM and a 60GB solid-state drive. For a low-level input/output controller, a Teensy 3.1 is used, as it has more memory and a smaller footprint than a standard Arduino Mega.

C. Sensors

The X-IMU by X-IO Technologies is a versatile Inertial Measurement Unit (IMU) designed to provide easy access to orientation measurements. The on-board *Attitude Heading Reference System* uses an Extended Kalman Filter to fuse the data from the accelerometers, gyroscopes, and magnetometer and generates a stable estimate of the orientation of the vehicle. The IMU is housed in its own enclosure and communicates with the on-board computer through a USB serial port.

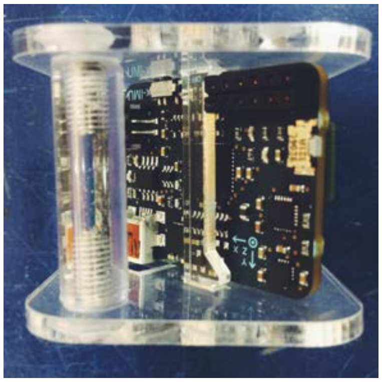

Fig. 9. The IMU uses a blind-mate serial USB connection.

To measure depth and provide pose in the z-direction, a Keller America pressure sensor is used, which generates an output current that varies with its depth. A moving-average filter is applied to the data, which isolates the DC component of the noisy signal, and makes it useful to the planner.

In order to locate the acoustic pinger, an array of four Sensor Technology SQ26-05 hydrophones is used. The receivers are mounted in a large rectangular arrangement on each of the corners under the frame. Localization is a four-stage process: data acquisition, digital filtering, time difference analysis, and multilateration.

Two algorithms were developed in simulation, using phase difference and time delay methods. The former method was ultimately rejected because the increased pinger frequency for *TRANSDEC 17* would have required placing the sensors closer together than their diameter allowed. The outcome is a system that can estimate the heading of the sound source with sub-degree accuracy in simulation.

D. Printed Circuit Boards

The power board, microcontroller shield, pneumatic valve controller and motor controller back plane were all designed in KiCAD to meet the vehicle's specific needs and were printed by Labo Circuits. Each board went through multiple iterations, after unit testing exposed areas to be improved. The distribution of components on each board was optimized for space and modularity of the systems.

Fig. 10. The power supply, power distribution board, and Teensy shield all fit on the top rack inside the main hull.

VI. SOFTWARE SYSTEMS

In developing the software system, the industry-standard *Agile* development methodology was implemented, with a series of small iterations and a demonstration of functionality at the end of each month. This method facilitates integration testing of early functional prototypes, shaping the direction of future development in ways that could not have been planned out at the beginning of a brand new project.

A. *Software Architecture*

The software architecture consists of the computer vision, state estimation, planner, controls, simulation environment, and front-end. The architecture is built with the Robot Operating System (ROS) framework on top of a Linux-based OS. This implementation provides optimal modularity by having distinct processes for each component and the communication between nodes is handled by ROS. This enables us to have a robust architecture where any component can be shutdown and respawned without affecting our overall performance. Figure 11 shows the design along with the flow of information:

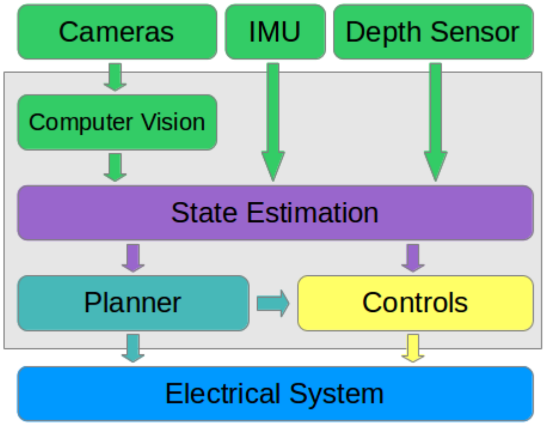

Fig. 11. Asimov's software architecture

To facilitate improvements and the reuse of components in future iterations, modularity and encapsulation were emphasized throughout the design. Multiple technologies were considered for the system's implementation, such as the Python and C++ programming languages. C++ was used because of the speed limitations of Python and the opportunity to develop skills in such a widely used language as C++.

B. *Computer Vision*

The computer vision system starts with three Point Grey Chameleon cameras coupled with Fujinon lenses. The strategy is to have one process for each axis on which there are cameras: forward and downward. This allows high modularity and encapsulation since they are independent of each other. The goal for the first year was to build up a framework for computer vision that robustly identifies the position of the Gate and Flight Path, and can be extendable to the other tasks in future years.

A series of filters is applied to each image as it is received from the cameras, starting with a Gaussian blur filter which helps us remove noise. Then, since the target objects have a distinct colour, each pixel is compared to a colour range. This process generates a binary image: the pixels that are matching the range are white, and the other ones are black. With this binary image, we can track the detected feature and apply logic algorithms to reject false positives and find the appropriate information. With the known focal length of our camera and the known size of the objects, we can then evaluate the relative distance between the robot and the feature. The image shown below demonstrates the multiple stages of our algorithm used to detect the gate:

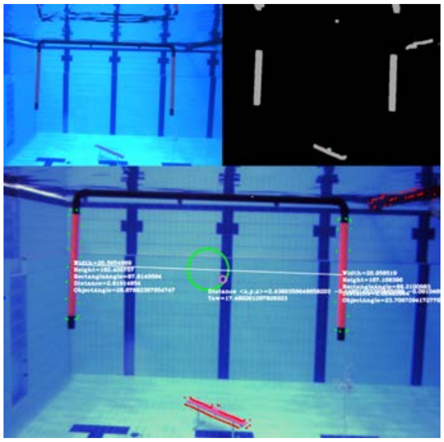

Fig. 12. Feature-detection image processing of the gate task

C. *State Estimation*

The state estimation system uses a Kalman filter to integrate the various sensors together. Its inputs are relative distance between the observed object and the robot, IMU pose, and depth. It's purpose is to evaluate the current state of the robot in the underwater world.

This state is then used by the planner and the control system to move the robot to the desired position.

D. Planner

Our planner system is the highest level of abstraction in the software system and is responsible for autonomously guiding the robot through the course. It is implemented as a finite state machine where each state corresponds to a challenge. Mini tasks within each state break down each challenge into a set of sequential actions. While there is a default ordering of the mini tasks, representing a perfect run, the order in which the robot executes these blocks can change in real time as more information becomes available, allowing it to correct mistakes without prematurely ending the run.

The planner provides visual feedback to poolside operators through the use of the four Blinky Tape LED strips. Two of the strips indicate battery levels, slowly changing color as the batteries drain. The other two strips, located toward the center of the robot, indicate which mini task is currently running. The lights flash brightly when errors occur, such as high temperatures in the main hull.

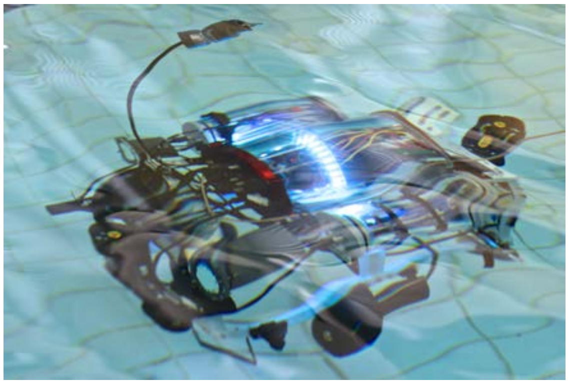

Fig. 13. Blinky Tape LED strips provide feedback underwater.

E. Propulsion & Controls

The propulsion and controls system closes the gap between the planner's desired position and the current estimated position. The placement of six brushed DC motors was chosen to achieve active control over five degrees of freedom. A zero-roll angle is passively maintained by arranging the vehicle components such that the center of buoyancy is above the center of mass.

Each degree of freedom is controlled with an independent PD controller. The estimated position is calculated using computer vision and other sensor data to determine the distance to the current object of interest, as measured in a body-fixed coordinate frame. The error is then computed as the deviation from the set point. The net force and torque that should applied by the vehicle is a linear function of this error and its rate of change.

The Thrust Mapper node converts the net force and torque into motor commands that should be sent to the motor controllers from the microcontroller. It is built upon models of the thrust-voltage characteristics of the thrusters and the command-voltage characteristics of the motor controllers, both of which were empirically determined through a series of tests.

F. Testing and Simulation Environment

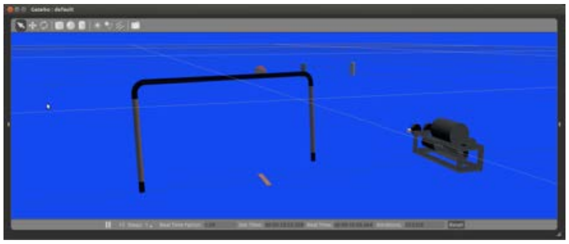

Fig. 14. The Gazebo simulator has the same software interfaces as the real hardware.

Development of a software system in our first year of competition without a physical robot to test with was made possible through the creation of a high-fidelity simulation environment. A popular open-source simulator called Gazebo was chosen because of its ease of integration with ROS. 3D models of the vehicle and competition challenges were assembled in a simulated world, and interfaces to the thrusters and sensors were defined to be the same as on the real vehicle. The image below shows the robot in front of the gate in the 3D simulated environment:

G. *Front-End*

Poolside testing is supported by a custom graphical user interface (GUI) that displays feedback from the vehicle and allows teleoperated control with a Playstation® controller when the vehicle is tethered via Ethernet. The front-end was implemented with the Python scripting language to enable quick prototyping and modification.

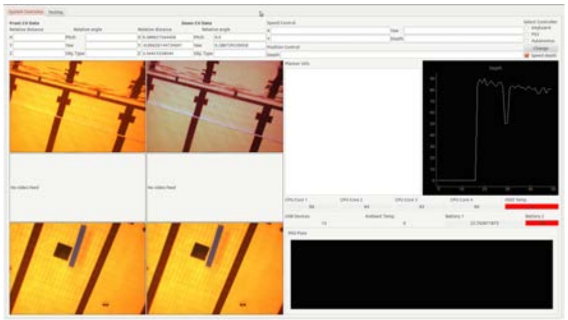

Fig. 15. Asimov's graphical interface for teleoperated missions

VII. SYSTEMS INTEGRATION

Systems integration has played a particularly important role in the design of a brand new AUV. There is a whole network of dependencies between all the components, and procedures for timing their development and ensuring interface compatibility have been paramount for this year's success. For example, the Mechanical Division needed to begin designing pressure vessels and mounting fixtures before the electronics were chosen and the software requirements were defined.

This is accomplished through an iterative design process where assumptions were made based on rough estimates and left easily modifiable as further detail became available. Every two weeks, the entire team comes together for presentations about the recent progress from the other sections, so that everybody is aware of the most up-to-date status of the development. Interface requirements are discussed at small weekly division integration meetings.

As assembly began in March, a new Systems Engineering Division was formed with a focus on the high-level integration of components. Its members coordinated the vehicle validation phase, starting with buoyancy tuning on March 28th. Formal procedures for sealing, individually leak-testing, and installing all eight pressure vessels before every test ensure safety and repeatability when negotiating the high risks of an underwater environment. Pool time efficiency is maximized by preparing rigorous documentation for each test, including roles, expectations, apparatus requirements, and contingency plans. A number of electrical and mechanical upgrades were made in response to testing results, and the process was carefully planned to minimize vehicle downtime.

VIII. OUTREACH

One of McGill Robotics' primary goals is to share our passion for robotics with others and to teach interested people about the technologies used in modern engineering. This was achieved through programs within the team, across larger social networks, and by reaching out to students in local schools. The RoboVentures Outreach Team was founded by McGill Robotics to develop skills among younger McGill students that will help them contribute towards competition teams in subsequent years. This year, the team built several robots, including a human-sized tuxedo-toting mobile platform that handed out roses around campus on Valentine's Day to raise money for the Heart and Stroke Foundation. Over 1400 students were reached through 18 visits to schools, fairs, robotics competitions, and more. Finally, we have made a deliberate effort to engage the larger McGill community through social media. A website, email newsletter, Facebook, Instagram, YouTube, LinkedIn, and Twitter accounts were used to target different audiences with different content, in order to present the excitement of robotics in an accessible manner.

IX. CONCLUSION

The primary goal for McGill Robotics 2014 has been to set up a foundation that can be built upon for years to come. This includes an emphasis on *Team Before Machine*, so that the future team will have not only the knowledge, skills, and experience required to excel, but also a culture that ties people together for the long-term. With 26 people attending the competition, we will learn a lot to fuel our passion for the next year.

Asimov is a strong contender for entry into the Semi-Final round of the *TRANSDEC 17* competition, and will serve as an excellent testing platform for the following year. Solid foundations for improvement were built, including a complete software architecture, and forward-thinking functionalities were prototyped for testing, such as the hydrophones and manipulators. The goals outlined for 2014 have been met, and hopes are high for future success.

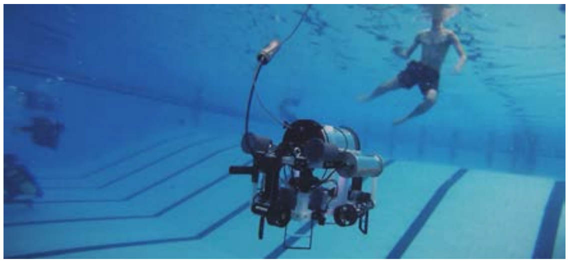

Fig. 16. In the water in March to prepare for *TRANSDEC 17*

X. ACKNOWLEDGEMENTS

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