Development of an Autonomous Underwater Vehicle for the 19th Annual RoboSub Competition: Bradbury

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***Abstract*—McGill Robotics is competing for its third year in the AUVSI and ONR's International RoboSub Competition with its latest Autonomous Underwater Vehicle (AUV): Bradbury. This year, the software systems have been developed through extensive field testing while improvements have been made to the existing mechanical and electrical designs. The main hull of the previous year was preserved; however, a new frame and battery vessel were machined to improve buoyancy. The computer system was also reused and interfaced with a new, unified, back-plane with card-edge plugable Printed Circuit Boards (PCB). The software architecture was overhauled to allow new tasks to be attempted at competition and allow the same code base to be used in McGill Robotics' new drone project. This year, McGill Robotics presents its most capable AUV to date and is expected to show significantly improved performance at RoboSub. Most importantly, however, McGill Robotics has contributed to the engineering skills development of over 240 university students while promoting science and technology to thousands of students across Canada.**

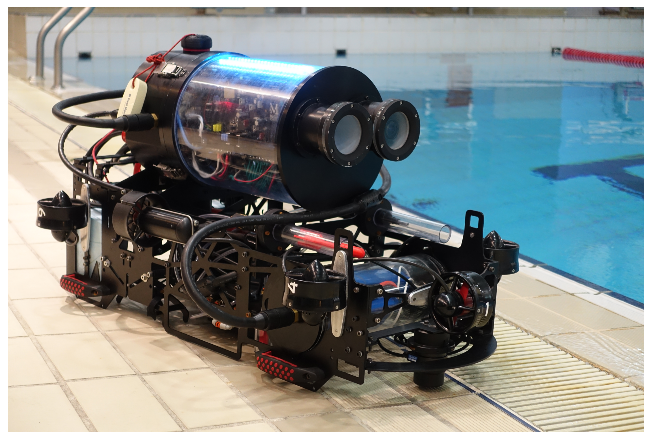

Fig. 1: Bradbury on the Pool deck

I. Introduction

McGill Robotics is an entirely student-run robotics engineering organization that has grown in three years to include over 240 dedicated students working on three different projects: a Mars Rover, an Autonomous Drone, and an Autonomous Underwater Vehicle. This year an entirely new Mars Rover was constructed for the 2016 University Rover Challenge and European Rover Challenge. A new Drone project was started this year for the AUVSI Seafarer Chapters SUAS competition. The AUV design team returns for its third year at the AUVSI and ONR's 19th Annual RoboSub Competition with their Autonomous Underwater Vehicle (AUV) Bradbury shown in figure 1. In figure 2 McGill Robotics can be seen hosting their new event RoboHacks, an annual robotics focused hackathon open to all university and college students. McGill Robotics' Business Team works with all of these projects, handling McGill Robotics' marketing, social media, sponsorship, accounting, and outreach. McGill Robotics takes prides in nurturing a robotics community in the Montreal area where dozens of new university students are recruited for the team each year. In addition to providing new members instruction and tutorials, the entire team participates in talks at local schools and community centres. From visiting primary and secondary schools in lower-income areas to hosting a competition for local college students, McGill Robotics is dedicated to this growing community and has adopted its new motto: Building robots to inspire students, and inspiring students to build robots. It is with this sincere spirit of community that McGill Robotics presents its most advanced AUV: Bradbury.

II. Design Process

The AUV team, shown in figure 3, is separated into three Divisions: Mechanical, Electrical, and Software. The Software Division is a unified Division that develops a high-level architecture for all three robots. All Divisions are again separated into Sections of 3-4 students that are each responsible for one major feature of the robot. Within the Software Division, the Software Systems Section is responsible for code specific to the AUV, such as Controls, State Estimation, and robot operation at pool tests. Sections meet weekly to coordinate designs and manufacturing. Also weekly, the Section leaders meet with their Division leader to plan future progress.

The Division leaders and Project Manager are responsible for systems engineering as well as planning field tests. The Project Managers for each of the three robots as well as the Business Team leader represent McGill Robotics publicly and manage larger team issues such as outreach events, university and faculty interaction, and finances.

Fig. 2: McGill Robotics hosting RoboHacks

Once a month, a Demo is organized, in which the entire 240-person team from all projects come together for team bonding and to show off work to other Sections and Divisions. The entirety of McGill Robotics relies on the project management software Podio for all intra-team communications and planning as well as Team Gantt for time management. The design of Bradbury is entirely focused on preserving the previous year's robot for use in field testing and software development [1]. Bi-weekly pool tests are held at the McGill Athletics Center where data is gathered using targets and obstacles built by the team and new features are continuously implemented. The mechanical and electrical Divisions focused on redesigning specific systems to make them more reliable and flexible. Design also began on next year's C class AUV which is expected to be manufactured in September, thus allowing continuous round-year software testing.

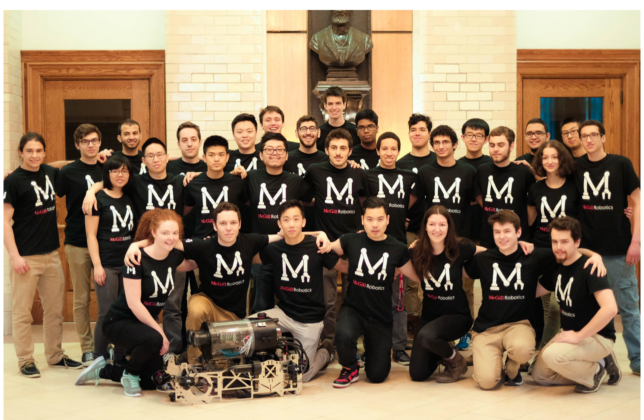

Fig. 3: McGill Robotics 2016 AUV Team Photo

III. System Overview

McGill Robotics developed the Bradbury AUV between September 2015 and July 2016, resulting in a near-shore autonomous submersible designed for specific mission tasks. While designed to operate as an AUV, Bradbury more closely resembles a Remotely Operated Vehicle (ROV) with its compact, modular, and boxy profile. This design intentionally models that of a small work-class ROV, intended to carry out a wide range of tasks during shallow-depth, short-term missions, rather than a typical long-range, deep-water AUV built to spend days traveling underwater. Bradbury features a powerful computer, six degree of freedom control, a fused sonar and computer-vision navigation system, and external manipulators to autonomously interact with the underwater environment at the TRANSDEC facility in San Diego. The team strategically set out to design a vehicle that could serve as a working platform for several years to come, allowing improvements in software and hardware.

Weighing just under 80 pounds and measuring 42 inches long, 20½ inches wide and 20 inches high, Bradbury is slightly larger and heavier than its predecessor. As the design focused on dexterity over speed, the vehicle can control six degrees of freedom (DoF) with its eight thrusters. A CO_2 powered pneumatic system allows Bradbury to fire torpedoes, drop markers and grab objects in front and below. Navigation is facilitated with data from three cameras, an Inertial Measurement Unit (IMU), a depth sensor, and a sonar, all processed through the on-board computer. The entire system is powered by two lithium-polymer batteries, one 12V and one 24V, which provide a run-time of over two hours.

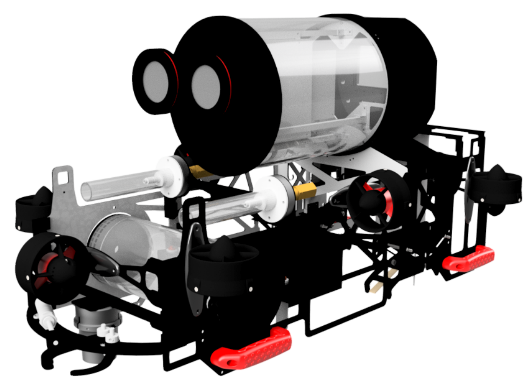

Fig. 4: CAD of final Bradbury design

IV. Mechanical Systems

After the 2015 RoboSub Competition, it was clear that maximizing testing time would have the most significant impact on further development and success. The Mechanical Division focused on revisions and upgrades to the design of the robot rather than a complete re-design so that it would be available as a testing platform throughout the year. A CAD of the final design is shown in figure 4. After these upgrades, Bradbury features the same cantilevered main hull as the previous robot, a reconfigured, laser cut aluminum frame, one swappable battery pressure vessel, a standalone hydrophone pressure vessel, dual pneumatic marker droppers and torpedo launchers, pneumatic piston actuated down and forward manipulators, and a compact pneumatic valve housing.

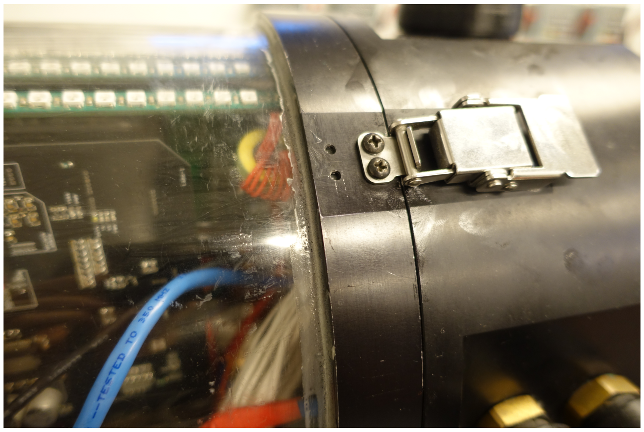

Fig. 5: Aluminum collar fastened to endcap

A. Main Hull

The main hull of last years AUV has been reused and modified this year. The enclosure starts with a large aluminum ring, which on one end is sealed by a Delrin connector plate, and at the other by an acrylic housing secured by draw latches. The ring has flat surfaces milled into its outside diameter to accommodate additional connectors, a mission kill switch, and a downward facing camera pod. From this ring racks to mount the AUVs electronics, computer, and forward facing cameras are cantilever supported. Inside, a water cooling system is utilized to transfer heat from the AUVs CPU through the connector plate to a radiator exposed to the pool water and mounted on the frame. This year, the connector plate was modified to accommodate a change in thrusters and to make the connections more ergonomic. The rack supports were also updated to be more compact and stronger, and the camera pods were redesigned to fit the new Chameleon3 camera. Finally, the aluminum collar which is used to secure the acrylic housing to the aluminum ring can be seen in figure 5. In the future, a longer smaller diameter vessel with a mid-cap design would be more optimal as the large aluminum ring was heavy, difficult to machine, and the cantilever design was not as rigid at intended.

B. Pressure Vessels

1) Battery Vessel: The battery pressure vessel was designed to be easily removable or mountable and houses the AUVs 12V and 24V batteries. This was achieved by designing the vessel to interlock with the frame, secured by a quick-release pin. Both endcaps of the vessel have a port for a waterproof high power electrical connector and, to make assembly of the vessel easier, an NPT plug was incorporated into one endcap so that the internal pressure could be equalized with atmospheric pressure. This ensures that there is minimal resistance to opening or sealing the pressure vessel. This feature was added because it was observed at past tests and competitions that a change in internal pressure could make it physically difficult to open a radially sealed vessel.

2) Hydrophone Vessel: This standalone pressure vessel contains all of the components necessary to operate and test the hydrophones sensors. This has made it possible to test the system much more frequently as space for the entire AUV is no longer required. The vessel is made up of an acrylic housing and two aluminum endcaps: one to mount the hydrophone array, and the second with a bulkhead connector. Utilizing a separate vessel makes it possible to isolate the sensors from interference created by the other electrical systems on the robot.

C. Frame

This years frame uses the same style of design as the previous AUV. Lasercut aluminum is used to provide structure and support to Bradburys pressure vessels and systems. After RoboSub 2015, it was apparent that the trim of the AUV needed to be improved. By redesigning the layout of the frame, the trim was adjusted to be much more level, making the AUV more stable. Additionally, dedicated mounts for buoyancy tuning masses were incorporated into the frame to provide further and more delicate control over the AUVs buoyancy and balance. It was also clear that the frame could be made much more ergonomic and accessible. For ease of transportation, comfortable handles were added, access ports were built into the frame panels for pneumatic and electrical connections, and a front bumper was added for protection and to avoid entanglement. To minimize the size and mass of the frame, Finite Element Analysis (FEA) was used to estimate the maximum stress experienced by the frame during expected loading. Finally, for style and corrosion protection, the frame was anodized black.

D. Pneumatic system

1) Valve Housing: The pneumatic system valve housing (figure 6) was redesigned as a cuboid vessel; to be more space efficient, and to simplify the mounting system required. To eliminate bulky compressed air tanks and larger regulators the pneumatic system is supplied by 16 gram CO2 cartridges. This supply is regulated down to 100 psi and routed into the valve manifold. The housing was Computer Numerical Control (CNC) machined from a solid block of aluminum reducing the number of joints and potential leaks. All inlets and outlets on the vessel are sealed with either: an o-ring, a gasket, or an NPT tapered thread with Teflon tape. Use of push connect fittings has made tubing assembly repeatable and reliable, and a lever actuated valve makes it possible to seal the cartridge off from the rest of the system. The valve and manifold assembly exhausts directly into the valve housing which has a check valve protected exhaust port. So even in the case of a high pressure gas leak at any point in the system, the valve housing seal will not be compromised.

2) Torpedo System: The torpedo system uses a short burst of CO2 to launch the torpedo off of a nozzle and rail assembly. The launch rail and polycarbonate shroud ensure that the torpedo will fly accurately at the intended target. Because the system is open to the water, a check valve is used to ensure that water does not flow back and damage sensitive components. To prevent the torpedo from falling out of the launcher prematurely, an o-ring was fitted to the

Fig. 6: Pneumatic valve housing

rail and presses against the stabilizing fins of the torpedo, holding it in place. To make iterative designs and testing feasible, the torpedoes were 3D printed. This allowed for low cost and rapid fine tuning of the design leading to greater flight stability by designing the center of mass to be in front of the center of pressure, and by manipulating the buoyancy with the number of shell layers and infill percentage. This iterative process is displayed in figure 7 where two years of design are displayed.

3) Marker Dropper: The design reasoning of the marker dropper system were very similar to that of the torpedo launcher. Using off the shelf components and with the majority of necessary machining done by students, a reliable dropper system was developed. A magnet tipped nozzle is used to guide and hold the marker in place. The marker was designed and 3D printed to hold a steel ball bearing in place with a press fit at the tip. Using a ball bearing greatly increases the density of the marker and guarantees the center of mass will be in front of the center of pressure producing rapid and stable descent in water. Like the torpedo system, a short burst of CO2 pushes the marker off of the magnet allowing it to free fall toward the target.

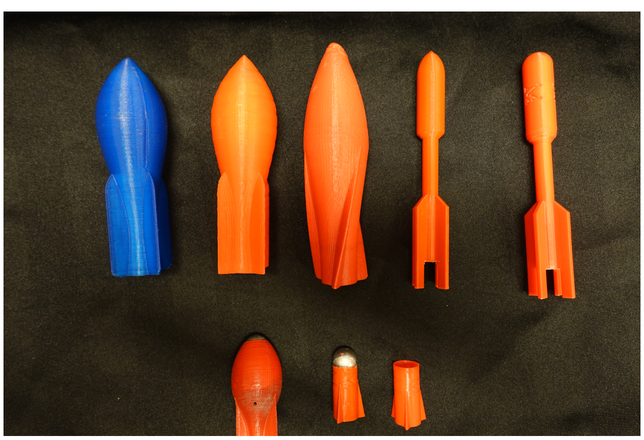

Fig. 7: Different torpedo and marker designs

4) Manipulators: Bradbury is equipped with two down and one forward manipulator. All three are actuated by double-acting pneumatic pistons and are made of laser cut aluminum for a strong yet compact design. The downward facing manipulators are connected to a scissor-jack assembly to increase the reach of the system while using very little additional space. The forward manipulator is mounted on the front bumper of the AUV, with one driven arm and a gear and shaft assembly to drive the second. This layout made use of the available width of the frame and did not interfere with the sonar and battery vessel mounted aft it. Both manipulators use a three finger claw system, so that anything that is grasped is held in a firm three contact point grip. This style of grip was selected to reduce the risk of an object being dropped unintentionally.

E. Thrusters

Bradbury uses 8 thrusters to control all six degrees of freedom. The thrusters are arranged with two along each of the horizontal axes, and four thrusters arranged in a quadcopter formation along the vertical axis. This layout was utilized with Bixby and proved to be effective and so was used again with Bradbury. The two thrusters in the surge direction are Blue Robotics T-200 thrusters, while the other six are Blue Robotics T-100s.

V. Electrical System

The electrical system is comprised of a main computer system, a power and distribution system and various input and output peripherals. The Electrical Division's main goal for RoboSub 2016 was to reduce interface of all the different hardware units by reducing the amount of wiring inside the robot. A large number of wires makes the robot harder to troubleshoot and increases electromagnetic interference[2]. To alleviate this problem, a set of custom Printed Circuit Boards (PCB) that interconnect through back-planes have been designed. In addition to reducing the number of wires, it allows the electrical system to be completely modular, facilitating quick debugging or board replacement. Another goal of the Division was to increase our presence in the electronic robotics community by designing an open source Arduino-based platform for which we allow anyone to use and improve. Our platform, the Isoduino, features power isolation, something not present in the original Arduino platform. Anyone is free to download the design files and print their own board. A printed Isoduino can be seen in figure 8.

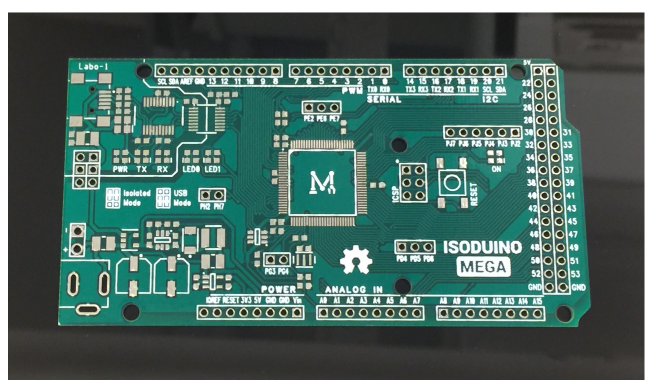

Fig. 8: A Printed Isoduino

A. Computer System

The computer system features an Asus Z87 Mini ATX motherboard along with an Intel i7 4770k Quad-Core processor. It also posses 8GB of DDR3-2400 memory and a 256GB solid state drive as storage. The operating system of the computer is the Ubuntu 14.04 LTS, and the Robot Operating System (ROS) provides the main framework of the software systems.

B. Power System

The power system has been separated in two different voltage rails in order to avoid interference between the thrusters and the more sensitive sensors. An overview of the system is shown in figure 9. For safety purposes, both subsystems are equipped with a physical kill switch along with voltage and current monitoring and protection circuitry. Bradbury's 12V LiPo battery is directly used to

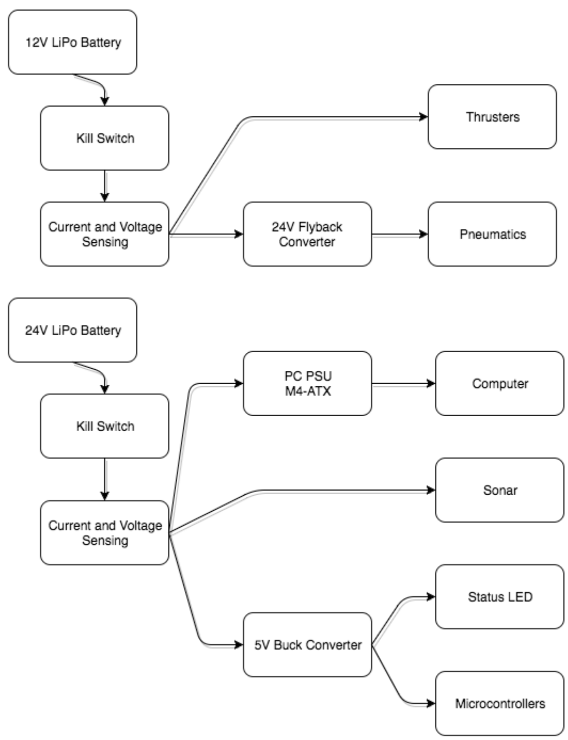

Fig. 9: Power system diagram

power the thrusters, and a flyback converter is used to step up the voltage to 24v in order to power the pneumatic system. The 24V LiPo battery is directly used to power the sonar. A buck converter is then used to step down the voltage to 5V in order to power all the microcontrollers. Additionally, the battery powers the M4-ATX PSU which supplies the main computer.

C. Input/Output

The Input/Output (IO) system allows the robot to sense various parameters of its surrounding, as well as transmitting information to the user. A diagram of the system is depicted in figure 10.

1) Status LEDs: The AVU's custom Status LED strips are an array of WS2812B RGB LEDs which convey important information about the robots state to operators on the poolside. They display specific patterns for battery level, IMU initialization, and which task being performed.

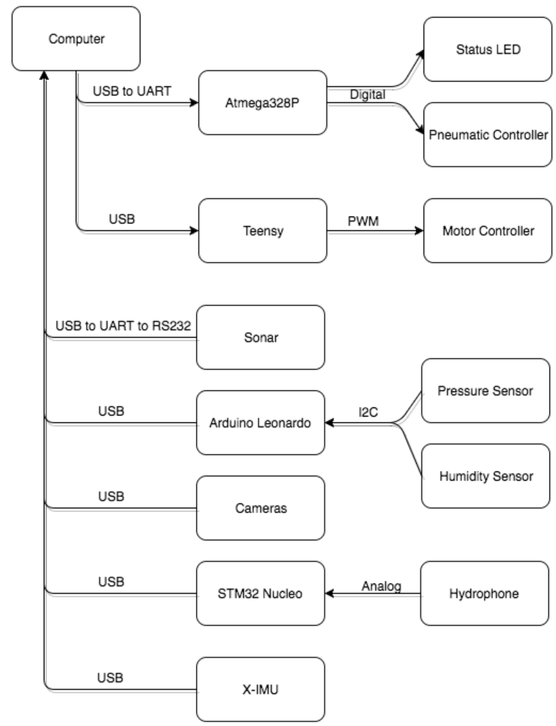

Fig. 10: Input/Output system diagram

2) Sonar: The RS232 signal coming from the Tritech Micron Sonar is translated into UART using a custom PCB featuring a ISO7142CC chip. This is done to digitally isolate the signal which is then translated to USB to interface with the main computer.

3) Hydrophone: The pinger localisation system of Bradbury is comprised of an array of four Teledyne Reson TC4013 hydrophones. Before being sampled by the STM32 Nucleo microcontroller, the signal coming from the hydrophone is filtered and amplified by a three stage amplifier of OPA2350 op-amps. Figure 11 displays a SPICE simulation of the frequency response of the amplifier. With the

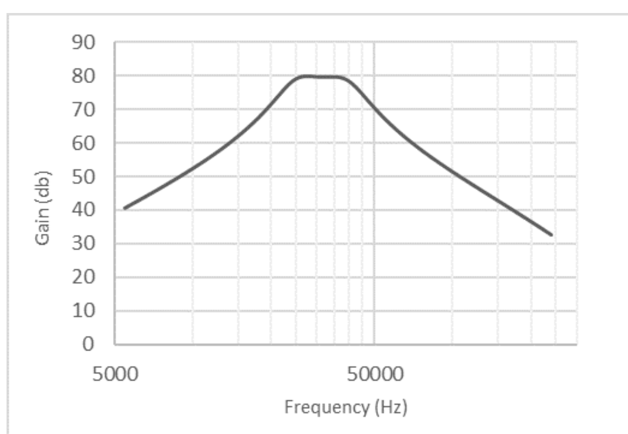

Fig. 11: SPICE simulation of amplifier frequency response

sampled signal we perform a time delay estimation between the the signal of each hydrophone using generalised cross correlation. Then, simple trigonometry is used to triangulate the sound. Figure 12 presents a zoomed in view of the sampled signal which permits visualisation of the time difference.

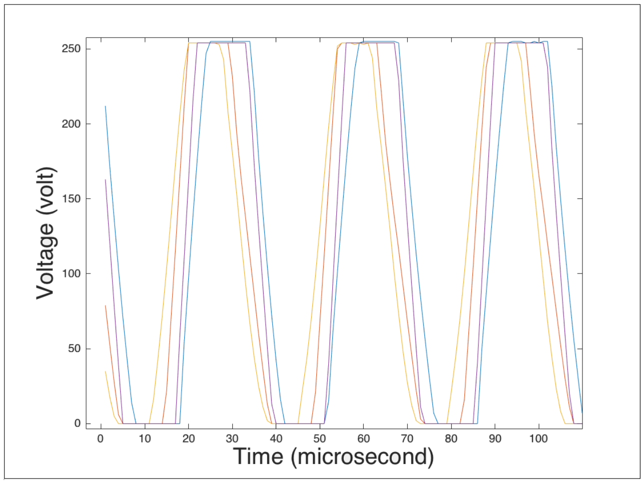

Fig. 12: Sampled Pinger pulse over time

4) Pneumatic Controller: Bradbury's pneumatic pistons are actuated using an array of NMOS (TPL7407L) which is controlled by a Teensy microcontroller.

5) Motor Controller: Bradbury's T100 and T200 thrusters, which feature brushless motors, are controlled by off-the-self ESCs. The control signal is sent from the main computer and translated to a pulse width modulated signal by the Teensy.

6) Pressure and Humidity sensor: The MS5803 high resolution pressure sensor allows depth to be measured from the pressure exerted by the surrounding water. Moreover, the HH10D humidity sensor is used as a leak detection mechanism. Data from both sensors are gathered using an Arduino Leonardo before being sent to the main computer through USB.

VI. Software Systems

Bradbury's software system was improved significantly this year, iterating over last year's design and architecture to allow for the reusability of high level components on McGill Robotics' new autonomous Drone with a minimal amount of modification.

A. Computer Vision

Having acquired hours of footage in past competitions, the computer vision pipeline was completely rewritten this year to make use of a machine learning approach rather than a filter based approach. This allows for a more flexible object recognition module applicable to any image classification problem. By preprocessing the image using a single image fusion filter [3], we first intensify the features of the image to recover details lost due to underwater haze and color cast. A single frame has been enhanced in figure 13. The artificial neural network then takes the SURF [4] features of multiple areas of the preprocessed image and classifies them based on previously seen data from past competitions to locate regions of interest in the frame.

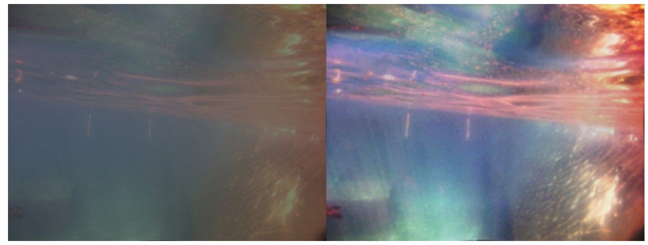

Fig. 13: Underwater image before and after preprocessing

B. Sonar

Having acquired a Tritech Micron sonar and developed a custom ROS driver to encode commands and decode line scan data in the last year, McGill Robotics has leveraged the data collected in previous years to develop a sonar scan processing pipeline. A single 360 scan is shown in figure 14. By first stitching together each consecutive line scan, a circular sector scan is obtained. An adaptive threshold technique is then used to filter the sonar scans, followed by a mean shift clustering algorithm to localize points of interest from the obtained pointclouds.

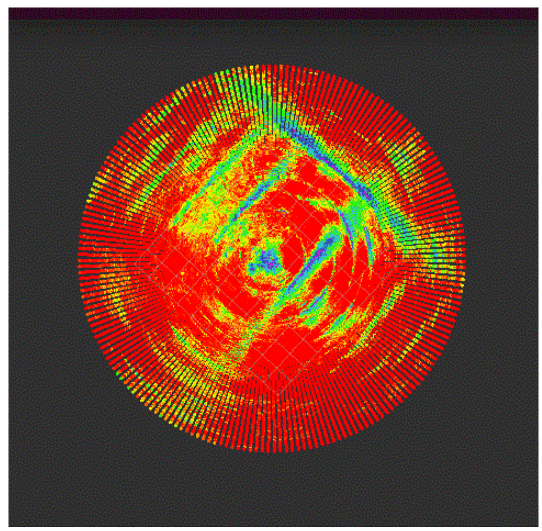

Fig. 14: 360° scan of the McGill Pool

C. State Estimation

The State Estimation system receives data from the Inertial Measurement Unit, Sonar, depth sensor and cameras to synthesize useful information for the Autonomy and Controls systems.

The on-board IMU, the X-IMU from x-io Technologies, provides 9 degrees of freedom measurements directly to the main computer through USB. Its 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.

Using the downward facing camera with a Visual SLAM algorithm [5], the position and pose of the robot is estimated.

Using the Sonar, the relative position of the points of interest are also tracked to measure changes in position of the robot, which provide a low frequency but accurate

odometry estimate.
By fusing all the odometry estimates in a SLAM algorithm, the AUV can reliably localize itself in most environments.

D. Planner and Controls

The planner is the strategical component of the robot, sending commands to the other software modules in order to complete the desired tasks. The mission planner was re-written using ROS' SMACH library this year to be robot-agnostic, allowing it to be used on McGill Robotics' Autonomous Drone as well.
This library allows the mission to be split up into states which we can be nested into each other. Each states outcomes can be specified to transition to other states, allowing the state graph to be quickly rewired, giving us the strategical flexibility to reorganise which tasks are attempted as well as how they are attempted at competition. The relationship of all the states and their transitions can then be graphed, allowing the robots conception of its progress through the course to be visualised easily.
A software component called Taskr now implements each robot specific action sequences, composed of reusable basic low-level actions as building blocks.
To carry out each task, the Taskr then communicates with Bradbury's controls system, a six Degrees Of Freedom closed-loop PID controller designed and tuned for stable and precise motion in the presence of disturbance flows.

VII. Field Testing

A. Environment

Field tests are conducted bi-weekly at the McGill Athletics Center in a 25 meter swimming pool. To ensure realistic scenarios many of the obstacles and tasks have been replicated according to competition rules. During a field test a minimum of four designated roles must be filled: Swimmer, who is responsible for handling the robot in the water; Coordinator, who is responsible for scheduling and communication; and at least 2 Robot Operators who control the robot and collect data.

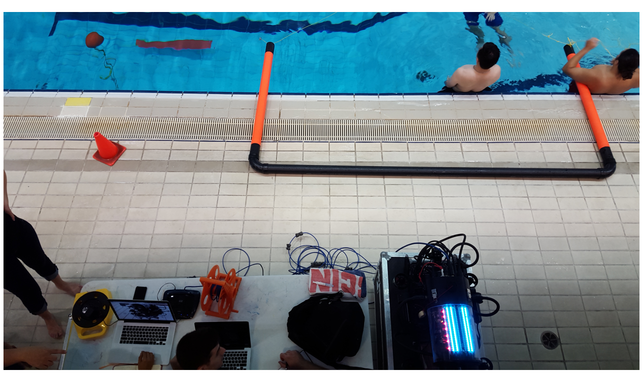

Fig. 15: McGill Robotics during a field test

B. Experimentation

To date, over 30 hours of pool time has been spent testing software features and gathering data. Several hours were spent tuning various parameters for both software and mechanical systems such as: overall buoyancy distribution, torpedo and marker buoyancy, PID control gains, and camera calibration. To ensure the hyrophones tests were as representative as possible the team purchased a Benthos ALP-365 pinger identical to the one used at RoboSub. Different team members are encouraged to operate the robot at each test which is important for transferring knowledge to newer members.

VIII. Conclusion

The technical focus for this year was to improve on past success and to develop a more reliable and stable robot. Significant time has been invested in developing the software and hydrophone systems. Today Bradbury is McGill Robotics' most advanced and capable AUV and is expected to attempt more tasks than ever before.

McGill Robotics continues to grow exponentially both in terms of members and projects. Not only did membership explode from 150 to 240 and another robotics project was added but the team also began hosting its own robotics competition: RoboHacks. This created many new challenges but also many opportunities which have allowed McGill Robotics to give back to the community through several outreach efforts, holding true its motto: Building robots to inspire students, and inspiring students to build robots..

Acknowledgments

McGill Robotics is very grateful for all the support received each year. The entire team would like to thank the experts for their constructive feedback on our designs: Prof. Meyer Nahon, Prof. David Meger, Marwan Kanaan, Robert-Eric Gaskell and Michael Grizenko-Vida. Additionally, Bradbury could not have been built without the manufacturing guidance of Donald Pavlasek. Thank you to Peter Carpenter, Jason Boivin and all the lifeguards at the McGill Athletics Center for access to the pool for testing. Cheers to the McGill Racing Team, McGill Electric Vehicle Team and the McGill Baja Racing Team for borrowed tools and advice in our shared workshop. We are so appreciative of all of our sponsors, especially our platinum and gold sponsors: Podio, Digital Ocean, McGill Engineering Student Centre, SBG Systems, Maxon Motor, IEEE, and Diptrace. Finally, thank you to everybody at the AUVSI and ONR who worked so hard to make this competition possible. See you at TRANSDEC!

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