Bixby: An Underwater Autonomous Vehicle for the 18th Annual RoboSub Competition

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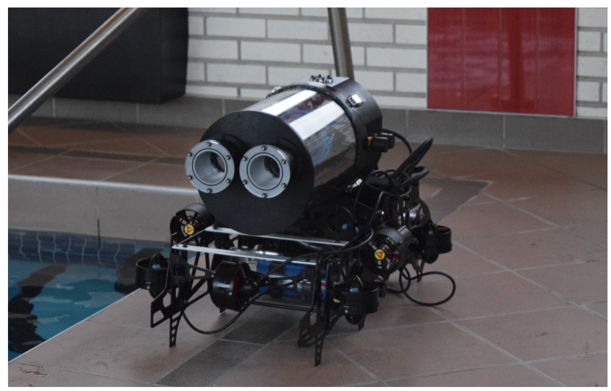
***Abstract*—McGill Robotics is competing for its second time in the AUVSI and ONRs International RoboSub Competition by building an entirely new Autonomous Underwater Vehicle. This year we used our experience from the previous competition to build a reliable platform that can be used for several years to come. Mechanical design focused on making a more durable design with room for additional sensors and control over six degrees of freedom. The electrical design centered on a unified backplane with card-edge pluggable PCBs. Software focused on object recognition and improving the mission planner to act on this information. The focus on integration of these systems will lead to a robot capable of improving on our previous competition. Most importantly, McGill Robotics has contributed to the engineering skills development of over 150 students.**

I. Introduction

McGill Robotics is an entirely student-run engineering organisation that grew from 98 to over 150 members forming three teams. The Rover design team contructed their Mars rover Artemis to compete for their first time in the University Rover Challenge. The AUV design team is returning for its second time to the AUVSI and ONR's 18th Annual RoboSub Competition with their Autonomous Underwater Vehicle (AUV) christened Bixby. The Business Team worked with both design teams handling McGill Robotics' marketing, social media, sponsorship, accounting, and outreach.



McGill Robotics prides itself on being a robotics community, where dozens of new university students are recruited every year and given the tools to excel. Technical excellence is balanced with professionalism as members are encouraged to give talks at local schools and participate in community outreach. It is with this spirit of community that McGill Robotics returns to San Diego to show off our new robot, Bixby.

II. Design Process

The AUV design Team was separated into three Divisions: Mechanical, Electrical, and Software. Each Division was again separated into Sections of 3-4 students that are responsible for one major feature of the robot. The

Section leaders coordinated with their division leaders to design a complete system. A Systems Team comprising the leader from each Division, plus the Project Manager, and several knowledgeable members oversaw the integration of all three Divisions into the cohesive system that is Bixby. Sections met weekly to coordinate specific tasks. Also weekly, the Section leaders met with their Division leader to plan future progress. Once a month the entire team came 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.

Fig. 1. McGill Robotics has over 150 members.

The design of Bixby began by reviewing the issues encountered last year. It was decided that the computer system, cameras and IMU could be reused, but that many of the sensors, thrusters, and the entire mechanical infrastructure needed to redesigned. This necessitated new motor controllers, power boards and a spacious new main hull to fit everything in. Early design decisions revolved around determining the features to be designed and their size estimates, allowing for the electrical and mechanical divisions to begin detailed design. Software was able to develop code in parallel physical components of robot using simulation or unit testing with isolated sensors. Once the rest of the systems were integrated around the main hull the entire robot's design was iterated to ensure that everything functioned together well.

III. System Overview

Bixby was developed by McGill Robotics between November 2014 and July 2015 and is a near-shore autonomous submersible designed for specific mission tasks. While designed to operate as an Autonomous Underwater Vehicle (AUV), Bixby more closely resembles a Remotely Operated Vehicle (ROV) with its compact, modular, and boxy design. This design intentionally models that of a mini work-class ROV, intended to carry out a various of tasks during shallow-depth, tethered missions, rather than typical long-range, streamlined, deep-water AUVs built to spend days traveling underwater. McGill Robotics' submersible vehicle, Bixby, features a small form factor, six 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 serve as a working platform for several years to come, allowing improvements in software and hardware. Just under

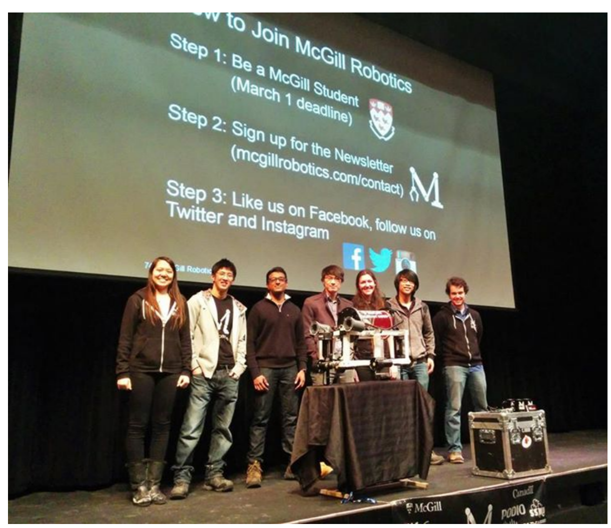


Fig. 2. McGill Robotics talk at Dawson College, Montreal.

70 pounds and measuring 32 inches long, 16 inches wide, and 20 inches high, Bixby is both 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 CO2 powered pneumatic manipulator system allows Bixby to fire torpedoes, drop markers and grab objects, while 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, 12V and 24V lines, which provide a run-time of up to two hours.

IV. Mechanical Systems

The Mechanical Division's goal for this year was to design a robot that integrated each system together in a way that was easy to access and assemble, but still kept the design modular enough to be able to work on each system separately. This resulted in an AUV featuring a cantilevered main hull, aluminum laser cut frame, standalone hydrophone system and a quick swap battery design. Bixby's torpedo launchers, grabbers and marker droppers are all actuated by a pneumatic system with the pressurized system and valves isolated from the rest of the robot.

Fig. 3. Bixby's CAD was done entirely with Autodesk Inventor.

A. Main Hull

The team faced many issues last year at competition but the biggest one was decidedly electrical connectivity. This year the problem was designed around by making the main hull bigger and placing many of the electrical sensors, including the cameras, inside. The main hull features a 9.5" diameter aluminum ring which seals to an acrylic tube with front camera ports on one side and a delrin plate with all the underwater connectors on the other. This larger main hull now houses the water cooled CPU, power board, motor controllers, 3 cameras, kill-switch and depth sensor.

Fig. 4. Bixby's CPU is cooled using a custom water cooling system.

The integration of components into the main hull was also major facet of the design. The aluminum ring has flats milled on its sides containing ports for the depth sensor, kill switch, and water cooling system. There is also a flat milled on the bottom to attach a small housing for the robot's down camera. The ring attaches to the frame and forming a cantilever with the electronics racks. This allows work to be done on the electronics while the robot is still assembled. The Bixby's two front cameras are mounted at the end of the rack, with their view-ports built into the robot's acrylic cover.

B. *Hydrophones Vessel*

This standalone pressure vessel was designed to contain all the functioning electronics needed to test and update the code for the hydrophone sensors. The pressure vessel features an acrylic body with two aluminum end-caps - one housing the four sensors in a small array, and the other for an underwater connector.

Fig. 5. Array of four hydrophones.

C. *Pneumatics*

The pneumatics system actuates Bixby's three moving components: the grabbers, torpedoes and marker droppers. The grabbers are integrated into slots in the frame and feature an accordion extending design actuated by a dual acting piston. The torpedoes and marker droppers will be fired using a burst of CO2. The valve housing itself was CNC'd out of an aluminum block, and has the regulator and mini CO2 tank fitted to the side of it.

D. *Thrusters*

Bixby 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 quad-copter formation along the vertical axis. The two thrusters in the surge direction are Seabotix BTD150 thrusters, while the other six are Blue Robotics T-100s.

E. *Battery Vessels*

The battery pressure vessels were designed to be easily swapped. The pressure vessel itself consists of an acrylic body and two aluminum end-caps with the battery sitting on an aluminum cantilever connected to one of the end-caps. The battery vessel is integrated into the frame - it mounts by sliding through the frame, rotating to lock its horizontal motion and then a quick release pin is inserted to stop rotation.

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F. *Frame*

A laser cut aluminum frame allowed for easy integration of various components of the robot directly into the frame. The design consists of two identical side panels with cross beams for mounting and support.

Fig. 6. Bixby's frame is made entirely of anodized aluminum.

V. Electrical Systems

The electrical system is divided into three sections: Power Distribution, Input/Output and Acoustics. This structure allowed the electrical design to be more easily distributed across our large team while making sure to coordinate each section. Bixby uses a total of 6 custom designed PCBs generously printed by local Montreal firm Labo Circuits. Each PCB was designed by our team members using Diptrace software.

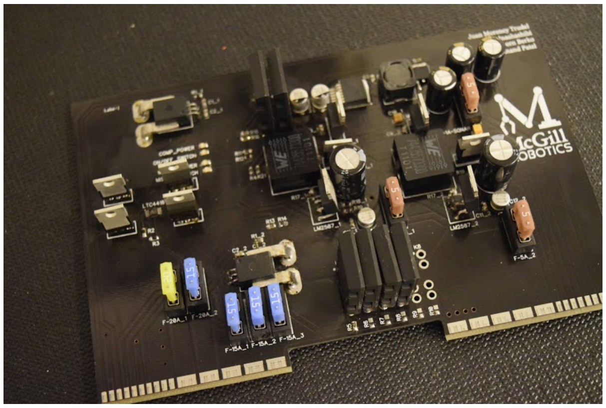

Fig. 7. The power board can handle up to 80 amps.

A. Power Distribution

Bixby is powered by two separate battery networks. One six-cell lithium polymer battery powers all the noise-sensitive sensors including: sonar, hydrophones, and depth sensor as well as powering the computer system. Another three-cell lithium polymer battery powers the more noisy thrusters thereby protecting our signal lines.

In each battery network voltage is regulated as needed for each of the loads; voltage and current monitoring ensures that both batteries are healthy; and automotive fuses protect our system from shorts or overload.

Bixby uses two physical switches to determine its power state. An emergency kill switch immediately disconnects power from all the thrusters while sending a signal to the computer to reset the mission. A second switch is simply used to toggle the computer system on and off.

B. Computer and I/O Systems

The on-board computer was built with a Z87 Mini ITX motherboard, Intel i7 4770k Quad-Core CPU, 8GB of DDR3-2400 RAM and a 250GB solid-state drive.

Most communications with sensors and actuators pass through the custom designed I/O Board which features two USB buses, and an RS232 converter for communication with the Sonar, and an RS485 converter for Router Raft communication. The I/O board also contains all of the micro-controllers and motor controllers as well as interfaces with the Power Board.

C. Micro-controllers

Bixby actually uses 3 different micro-controllers for all low level communications and control. An Arduino Leonardo clone is used for controlling Bixby's Status LEDs and a second micro-controller is used in our Router Raft for parsing the radio receiver and communicating with Bixby via serial.

Lastly a powerful Teensy 3.1 design is used for the majority of our controls. This controller features PWM signals for all 8 thrusters, the control of the pneumatic valves, an I2C bus for the depth sensor and secondary accelerometer gyroscope IC, the analog readings for both battery voltages and currents, and the mission switch input. Connected to the computer through the USB hub, the Teensy is ensured fast and reliable communication.

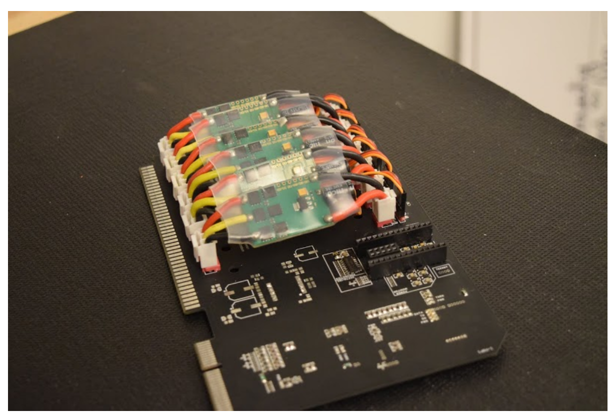

Fig. 8. The I/O board handles all low level communications.

D. Motor Controllers

Bixby uses six brushless motor controllers purchased off the shelf from Blue Robotics for use with their T100 thrusters. These controllers are connected directly to the I/O board for better integration. A custom designed dual channel brushed motor controller is incorporated into the circuit and used to control the two Seabotix thrusters. The pneumatics controller circuit is greatly simplified this year by using a single 7 channel, high voltage, high current NMOS array with an integrated inductive kickback diode

E. Sensors

Bixby features an array of four Teledyne Reson TC4013 hydrophones whose data is collected with a custom designed signal processing board. The signal from each hydrophone is amplified and filtered, then sampled by a MicroChip dsPIC33E series microcontroller. The collected data is passed to the computer through USB for processing. The X-IMU by X-IO Technologies is a versatile Inertial Measurement Unit (IMU) designed to provide easy access to orientation measurements. The onboard 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 with the hydrophones to reduce noise from the thrusters.

The depth sensor (MS5803) is a high resolution pressure sensor that measures the absolute pressure and temperature of fluids. It has a resolution of better than 1cm underwater and offers 24 bit pressure and temperature values.

F. Interfaces

Bixby uses several waterproof connectors from multiple companies for all electrical connection to exterior actuators, sensors and pressure vessels. We use wet mateable and sturdy Teledyne Impulse connectors for all our thruster connections, while MacArtney's Subconn ethernet connectors used for all our signals transmission underwater and high current purposes.

Status LEDs brightly communicate important information about the robot. When attempting autonomous runs they are the only feedback we get about Bixby's status and are invaluable for testing.

This year the long Ethernet cable was replaced with the so-called Router Raft which is composed of a high gain WiFi router and RF receiver housed in a waterproof Nanuk case. The WiFi router is connected to the main pressure vessel via a 20' Ethernet cable and provides wireless connection to the AUV. The radio receiver allows us to control Bixby with an RC controller for even more testing possibilities.

VI. Software Systems

A. Mission Planner

The mission planner is the brain of the robot, sending commands to the other software sections in order to complete the desired tasks. The mission planner was re-written this year to use the SMACH library. This allows the mission to be split up into states inside of states, similar to a hierarchical state machine. In addition, base actions can be reused within various tasks, and pieces of tasks can be reused in other tasks. Each state's outcomes can be specified to transition to other states, allowing the smach graph to be quickly rewired. The graph of all the states and their transitions is visualized, allowing the robot's conception of its progress through the course to be seen .

This year's mission plan is a substantial upgrade over last year's strategy of using just dead reckoning to pass through the gate, hit a buoy, and surface in the octagon. This year the planner will use computer vision to identify the lanes and visual servoing to position us over them. Using the positions and angles of the lanes for navigation should reduce the accumulation of errors and the need for precise initial aiming inherent in a dead reckoning approach.

Computer vision will also be used to identify the bins and the silhouettes contained in

Fig. 9. Computer vision recognizes a bin containing an image of a trident.

them. Visual servoing will be used to position ourselves over the bins, remove the cover from the main silhouette, and drop markers on the primary and secondary silhouettes. The uncovered targets of the torpedoes task can be identified and the strategy is to fire torpedoes through the small silhouettes.

Finally, the hydrophones will be used to navigate to and surface within the correct octagon. Computer vision will be used to locate and grab the objects. The objects will be dropped at our best estimate of halfway between the pingers in an attempt to place them on the tracks.

B. *Computer Vision*

The approach to recognising the bins, lanes, and torpedoes is as follows: first the images are preprocessed to remove noise and highlight the features of interest. For instance, in recognizing the lanes we look only at the red channel of the image. We then use the canny edge detector and OpenCVs findContours to generate possible candidates. Candidates are then eliminated based on shape, size, and intensity gradient. By adding many candidate elimination steps we can eliminate the vast majority of false positives. For good object recognition, it is necessary to have good footage. We adjust the color balance, exposure, and aperture of the camera to produce footage with brighter colors and little glare from the surface of the water. The images are rectified to help detection of straight lines.

C. *Controls*

There are two modes of the controls system: velocity mode, and position mode.

In velocity mode, the attitude and depth of the robot are controlled with PID loops, using feedback from the IMU and the depth sensor. The horizontal velocity of the robot is governed by open-loop control, as we have no measurements of velocity.

In position mode, the attitude and depth are controlled as before, and the horizontal position of the robot is controlled with PID loops, using position information from CVs object recognition.

Additionally the robot can be teleoperated with a remote control airplane controller for testing purposes.

D. *Simulation*

The Gazebo simulator is used to test our robot without requiring the pool. Simulated versions of all the robot systems and sensors have been created to allow testing of the Mission Planner and overall system integration. This year we switched from preamplified

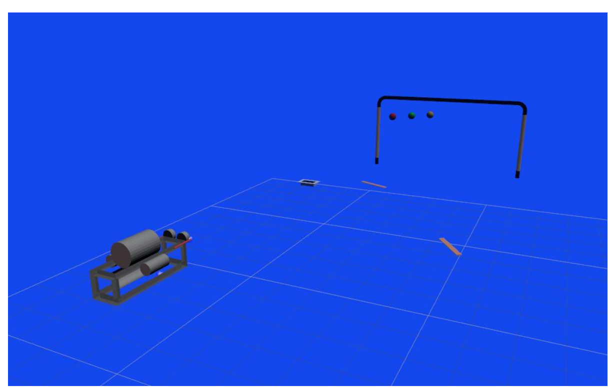

Fig. 10. Simulation environment containing the robot and tasks.

hydrophones in favour of four Teledyne Reson TC4013 hydrophones. The hydrophones are now mounted in a small square formation instead of the large rectangular formation used last year, in order to measure phase differences between them. The audio signals discretization has been off-loaded from the computers audio card to an external ADC by an ARM microcontroller to allow for higher precision. Finally, the time difference of arrival is determined by cross-correlating the signals and an estimated heading and distance is computed by multilateration.

E. Sonar

Fig. 11. The Tritech Micron sonar.

A new addition this year, the Tritech Micron sonar communicates with the on-board computer via RS232. A ROS driver was developed from scratch for the device to encode commands and decode the scan line data. A scan can then be visualized and the scan sector, range and resolution can be reconfigured dynamically to reduce scan time. In the future, we hope Bixby will use the sonar for object detection and recognition as well as localizing the robot in the pool.

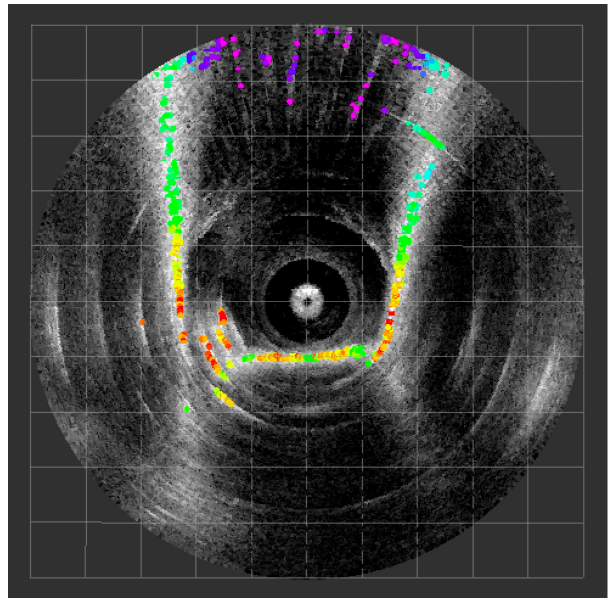

Fig. 12. A 360° scan from the sonar showing the edges of the pool, highlighted in color.

VII. CONCLUSION

For McGill Robotics 2015 was a year of historic growth. Not only was another team added but the overall size of McGill Robotics increased dramatically. This created many new challenges but also many opportunities and resulted in our solid AUV platform. We set out with a systems oriented approach that would ensure the different features would funciton well together. Today the Bixby is mechanically and electrically sound and has a solid software base that will serve McGill Robotics at competition as well as in the future.

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