University of Alberta Autonomous Robotic Vehicle Project RoboSub Journal Paper 2016

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***Abstract*—The Alberta's Autonomous Robotic Vehicle Project (ARVP) team at the University of Alberta continues refinement of their Autonomous Underwater Vehicle (AUV) platform, named AquaUrsa. With few major changes to the physical structure of the AUV this year, the emphasis was placed on maintaining reliability while at the same time expanding the capabilities of the robot with an eye towards accomplishing more course objectives at RoboSub 2016.**

I. Introduction

THIS YEAR the Autonomous Robotic Vehicle Project (ARVP) has taken major steps to incorporate new systems to our autonomous underwater vehicle in order to accomplish more task consistently. As a result of last years competition, and the many hours of testing done over the course of the year, the ARVP team has made significant strides in our goal of constructing a robust, easy-to-use, easy-to-expand platform for years to come.

The basic design is the next iteration of the platform called AquaUrsa. This year the electrical team of ARVP is altering the previously proven power supply system to incorporate power monitoring capabilities. There are several new boards that have been used in the electrical system this year to incorporate additional task which includes the marker, projectile and underwater sound source task. Since these boards are new, rigorous testing has been done to ensure their reliability. The thruster control system has remained unchanged from last year, as they are now a proven design with excellent reliability.

Further minor but significant changes were made to the mechanical assembly of AquaUrsa. As the electrical system of AquaUrsa becomes more robust, additional room inside the hull is required for the electrical hardware therefore battery pods were manufactured to allow for a quick change battery system that freed up space within the pressure hull. Last years change of placing the cameras inside the hull proved to be a step in the right direction, but the limited view from inside the hull needed to be fixed. The flat plastic window in the front was changed to a dome shaped window which drastically increased the viewing area of the camera. Many of the basic navigating systems of AquaUrsa has been worked, reworked and again reworked where it is near perfection, therefore ARVP is attempting new and more difficult task by installing a torpedo launcher, marker dropper and a hydrophone box for the sonar task.

II. Mechanical

The previous rendition of AquaUrsa had yielded a reliable mechanical platform for ARVP to work off. The vehicle was at its most rugged and manouever-able state ever since its conception. The main foundation of AquaUrsa has undergone little alterations since last year. A clear acrylic hull protects the electronic components from the underwater environment, while providing plain view of the components inside. The hull remains mounted onto the exterior frame support, which also holds the vehicle's six thrusters. Custom-made aluminum cowlings were installed for each thruster to absorb any sudden impacts the vehicle may endure. A long carbon fibre tube is attached to the back end of the vehicle, holding the inertial measurement unit at a distance that is not affected by the hard and soft iron distortions created by the hull and thrusters. The electronics are able to slide in and out of the hull through the use of the carbon fibre rods inside the hull, which act as

TABLE I. "AQUAURSA" KEY MECHANICAL PROPERTIES

Length	100 cm
Width	60 cm
Height	65 cm
Weight	<30 kg
Safety Factor	>2.0
Max Depth	22 m
DOF*	5

*Degrees of freedom

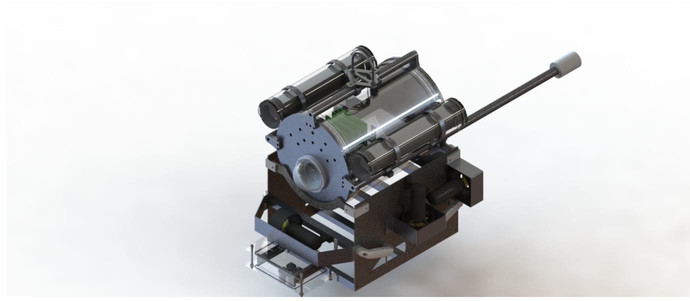

Fig. 1. Solid rendering of AquaUrsa's complete assembly.

a rail system for the electronics tray and the forward facing camera mount.

One notable change to the current AquaUrsa design is the relocation of the AUVs battery supply. Originally located inside the pressure hull, the batteries are now located outside of the pressure hull and encased within two cylindrical water-tight enclosures. As result of this relocation, space has been created to allow easier access to the electronics tray and cameras. The previous camera apperature for the forward facing camera has also been replaced with a hemispherical acrylic lens. This change has vastly increased the field of view for the forward facing camera. New to AquaUrsa, the vehicle is equipped with two projectile systems- a torpedo launching mechanism and marker release mechanism. Both mechanisms are mounted between the two sheets of aluminum from the frame support and below the hull. Through learning from the successes and failures of previous mechanical design choices, this years rendition of AquaUrsa has remain reliable and robust, while becoming one of ARVPs most versatile robot to date.

A. Pressure Hull Assembly

The central pressure hull is the most crucial mechanical component of the vehicle, because it acts as a support for all other mechanical components as well as protecting the electrical components from the external environment. The hull is composed of an extruded acrylic cylinder sealed at each end by machined aluminum lids and o-ring seals with proper o-ring grooves. The hull and lids are tolerance to Parker standards to ensure standard o-ring sizes can be used and the electronics are properly sealed within the hull. The lids of the hull are flat to allow easy mounting options, but this would result in higher hydrostatic pressure in the water. This issue is solved by including carbon fiber rods within the hull that supports each lid. The back end of the lid has a removable cut out that has standard external o-ring grooves. This removable section allows easy access to the electronics within the hull. There are also threaded holes on the removable lid that allows u-channels to be attached to create a simple and efficient handle. There are also two cut extrudes on either end of the interior back lid that fits the emergency shut-down switch of the robot. A breather vent was incorporated onto the removable lid section, allowing air to circulate out of the hull for ease of sealing. The outer section of the back lid has four equally spaced tabs that ensure the interior lid is concentric to the exterior one. The front and back lid have mounting holes that connects to a bracket and is mounted onto the frames aluminum side sheets. There are also threaded holes for mounting the SubConn waterproof connectors that connect the electronics within the hull to the components external to the hull. Lastly there are four carbon fiber rods that are mounted axially and equidistantly along the exterior to minimize the axial compression force on the acrylic cylinder. The bottom carbon fiber rod extends 1.8m from the end of the back lid and has a waterproof case at the end for a digital inertial measurement unit. This waterproof case holds the inertial measurement unit on standoffs. One side is permanently sealed with a wire that connects to the unit and the other side has threads and an o-ring to seal it from water.

B. Electronics Tray

Inside the hull assembly, the electronic boards and components rest on top of two distinguishable platforms that slide on two 1-inch diametre carbon fibre rods. The electronics tray close to the front of the AUV acts as the mounting location for the forward facing camera and the motor controller boards. . The card slots provide the support to keep the components in an upright position. The second tray, which is located near the removable section of the hull assembly, contains the electronics that require immediate attention and the most handling. The electronic components within the hull are held vertically onto a backplane with approximately equal spacing between each electrical component. The backplane is fixated onto an aluminum platform, which are rested upon two 1-inch carbon fibre rods that placed parallel amongst each other.

C. Frame Assembly

The frame assembly consists of two large aluminium sheets held on either side of the hull by horizontal running aluminium bars. Attached to the aluminium sheets are four L-shaped tabs which are connected to a mounting bracket that has been bolted onto the hull itself. On the frame, there are bent aluminum sheets that are mounted around the thrusters to prevent any contact damage being done onto the thrusters themselves. Two nylon grip handles are installed on either side of the aluminium sheets to provide greater ease in transporting the AUV. The horizontal aluminium bars create never before seen modularity in mounting task completion components such as the gripping claw, marker dropper, and sonar sensor. The bars can be arranged into any location of the sheets to provide better spacing and remove interference.

D. Battery Enclosures

In previous years, the batteries of AquaUrsa were housed inside the acrylic pressure hull. In order reduce the wiring inside the hull and provide more spacing for the electronics, the batteries were moved outside of the hull and placed into cylindrical, waterproof enclosures. Two enclosures rest on top of the axial carbon fibre framing, with aluminum sleeves built to keep the enclosures upright. The battery enclosure is made out of 3.5-inch acrylic cylinders, which is sealed at both ends with aluminum o-ring flanges. The caps of the assembly are designed with 1/2-inch acrylic ends.

E. Hydrophone Box

The hydrophone box is an enclosure that contains four hydrophones and their respective electronic boards. The hydrophone box is located at the front of the robot to reduce the noise on the receiving signals. The electronic boards are located inside the watertight containment. The upper part of the box is made by gluing six pieces of acrylic to each other. On the bottom face of the part, a groove was machined to fit an o-ring and produce a tongue and groove seal. At the bottom, a flat acrylic sheet is used as a lid to close the box. The two parts of the box are bolted together by a 12 pairs of bolts, nuts and washers. Hydrophones are connected to an aluminum plate this attached to the bottom of the box.

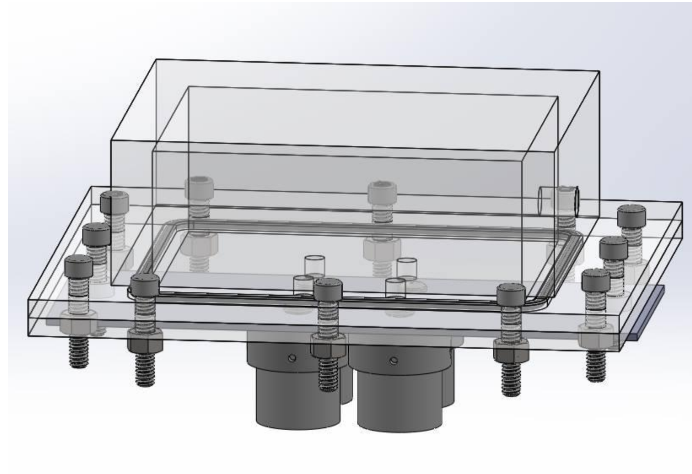

Fig. 2. Rendering of the Hydrophone Box

F. Marker Release Mechanism

In order to complete another task in the competition, AquaUrsa has been equipped with two markers located underneath the pressure hull. The markers themselves are torpedo shaped steel tubes fitted with acrylic fins to ensure stability and optimum accuracy. The marker release mechanism used involves holding the steel markers in place by a magnet. When the target area is identified by the interior cameras, a waterproof servo will move the magnetic field away from the dropper causing it to fall onto the target area. The housing for these components was 3D printed out of ABS plastic. This ensures that the magnetic nature of the system is not compromised by other ferromagnetic metals as well as makes for a simple machining process.

G. Torpedoes

The launching module consists of a 13 Ci 3000 PSI air tank connected via macroline hose to a regulator. The regulator has a 90 degree fitting attached on two sides opposite of one another. Macroline hose is used to connect both fittings to their own 2-way general service solenoid valve. Mounted on both solenoid valves is a solenoid to tube connector that is press fitted with a 123mm stainless steel pipe. The torpedoes are held on these pipes with the aid of o-rings. After the entire system is pressurized with air, an electrical signal is sent to the appropriate solenoid valve. This signal opens the valve allowing for air to escape from the launch pipe to propel the torpedo forward. The torpedoes were 3D printed using PLA as the filament.

H. Camera Dome

In the previous year, the front-facing camera looked through a 2.5-inch circular aperture through the front of the hull. Aluminum disks with o-rings were used to seal the camera lens assembly, but the design obstructed majority of the cameras vision. A 4-inch diameter dome lens replaced the original camera lens assembly and optimized the front-facing cameras vision. This also opens up cameras peripheral vision, allowing for a wider scope of the vehicles surroundings. To seal the dome, a silicone gasket maker was used to fill in the spacing in-between the camera flanges and front surface.

III. Electrical

The main goals for AquaUrsa's electrical architecture this year was maintain the modularity of the system. The core functionality was kept the same, however improvements were made to increase reliability and monitoring capability of the systems. To this end, Robot Operating System (ROS) was employed for the robot, where all electrical systems communicate to the main computer using serial-over-USB. This allows all systems to communicate with each other using a unified communication model.

A. Power Monitoring

The goal of the power board was to improve the power delivering and monitoring system to the different components of the robot. Before, there was no way of telling how much power and current was being used by each of the peripherals connected to the power board. At the same time, the way the peripherals are connected to the board is by specific voltages (ranging from 3.3 V, 5 V, and 12 V). This can make it an issue when trying to troubleshoot the components of the robot. In order to make troubleshooting easier, new channels will be incorporated on the board. Each of these channels will be able to supply any of the three different voltages needed for each specific component to work (either 3.3 V, 5 V, or 12 V). New sensing ICs will also be installed in each of the channels in order to monitor power consumption from each of the peripherals. This will allow us to determine if there is way too much power going into a single peripheral, for instance, the motor controllers.

B. Marker/Torpedo Release Board

This board uses a Teensy 3.1 microcontroller to collect serial information from the main computer. This information is then processed to determine which system is required between the marker release system and the torpedo release system. For the marker release system a desired angle will sent as a PWM signal to the waterproof servos, causing them to rotate to the specified angle. For the torpedo release system a PWM signal will be used to switch a NPN transistor on for a desired period of time. This will allow the mass amount of current required for the solenoid to flow through the transistor, shooting compressed air into the torpedo.

C. Thruster Controllers

The thruster controllers design is the same design as the previous years robot. Three thruster controller boards are controlled by a thruster processor board and they are all connected together using 50-pin card edge connectors and a backplane. Each thruster controller receives:

- Power voltages:
  - 12 V
  - 5 V
  - 3.3 V
- Raw PWM and direction signals
- A kill signal activated by the vehicles hardware kill switch

Each thruster controller board has two L298 H-bridge integrated circuits (ICs) providing up to 4 A to their respective motors. To control the ICs the processing board passes PWM signals and the directional signals through a network of logic ICs, which will output the needed waveforms to spin the motors in the desired speed and direction.

The thruster processor board contains a Teensy 3.1, which listens to various PID controllers and publishes the efforts to their respective motors. The Teensy also publishes the status of each motor and monitors the hardware kill switch.

D. Sensor Board

This board uses a Teensy 3.1 ARM Cortex-M4 microcontroller to collect sensor information from various devices and packet it into ROS messages. This board is responsible for:

- Acquiring the IMU data from OceanServer OS5000-T accelerometer/compass mounted at the aft of the hull.
- Acquiring and processing the depth data over I2C from MS5803 pressure sensor.
- Acquiring and processing touch data for resistive touch sensor mounted in front of the robot.

E. Display Board

During autonomous testing runs, it can be difficult to verify if the AUV's mission control software is performing as designed, or if a component is malfunctioning. Therefore, we designed a diagnostic display board to be used during testing. This board uses an Arduino Duemilanove board to subscribe to various ROS messages to provide detailed information about the vehicle. The board can display the following information:

- 320x240 TFT display for textual information:
  - Status of every hardware system
  - Measured depth, heading, pitch and roll.
  - Feedback from thrusters
  - Battery voltages
  - CPU and memory usage on the main computer
- RGB LED strips are used to signal AUV status from afar:
  - Red indicates a problem
  - Green indicates 'OK' system status
  - Blue indicates completion of current task

F. Sonar Board

AquaUrsa features a brand new sonar system hardware design this year, yet the basic mathematical concepts of the software portion are the same. The functionality of previously designed systems was used to create a more effective and accurate positioning system to locate the pinger underwater. Four Cetacean Research SQ26 hydrophones are mounted in a square array in which the maximum distance between each pair of hydrophones is less than 5 cm. Such a setup ensures that the time difference of arrival (TDOA) between each pair of hydrophones is less than one wave period of the signal. This simplifies the positioning algorithm and computational manipulations.

The signal from the hydrophones is passed on to the signal conditioning unit. It provides three basic functions:

- It provides dynamic amplification of the hydrophone signals before they are sent for processing.
- It converts the single ended signals from the hydrophones into differential format which preserves the signal qualities in transmission.
- It runs the signal through a bandpass filter to remove noise.

The conditioned signal is then passed on to the data acquisition unit. It keeps the signal voltages are within the specified voltage limits of the ADC and then passes the signals on to two ADS7861E analog to digital converters. These two channel simultaneous ADCs are used to sample the four bipolar hydrophone signals at 250 Ksps to ensure relatively high definition results through the mathematical processing. The digital signal is captured by the programmable realtime units (PRUs) on Beaglebone Black where all the digital signal processing is performed. This functionality is further described in the software section.

G. Power Systems

AquaUrsa's main power system is responsible for providing power to all vehicle components except the thruster controllers. Because of the broad range of voltage levels and power requirements of different hardware, ARVP has centralized all of this functionality into a single power board, reducing the complexity of the entire system to simplify design, troubleshooting, and repair.

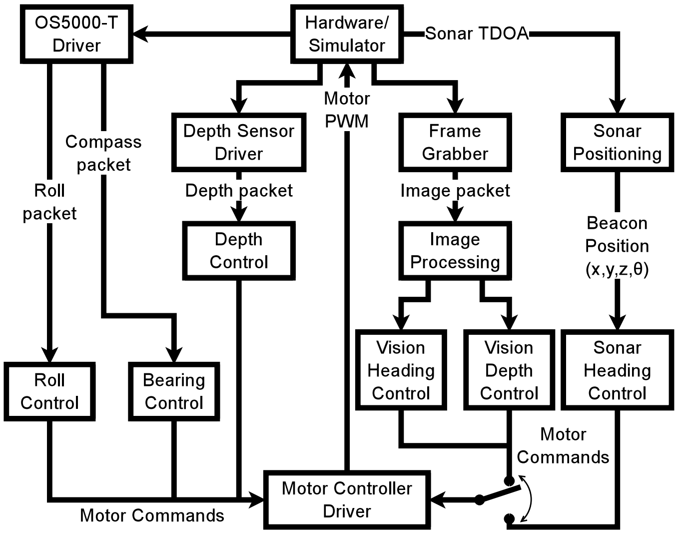

Fig. 3. Overview of software components and their interaction.

The power board is supplied by a 18.5 V lithium battery, which supplies power to an intelligent power converter that steps the battery voltage down to a constant 12 V, up to a maximum power of 200 W. This voltage is further converted to 5 and 3.3 V by a separate converter that provides a combined 30 W to both rails. These three standard voltages are sufficient to power all electronics inside AquaUrsa.

IV. Software

The software components of AquaUrsa include sensor and motor drivers, navigation controllers, Computer Vision algorithms, sonar algorithms, mission planning systems and graphical display. These components all work together using the ROS (Robot Operating System) framework [5]. ROS provides a variety of features, including support for highly distributed systems, a unified communication system, ready to use device drivers and tools for testing/troubleshooting/visualization.

A key feature of AquaUrsa's software is a modular design. It is based on a number of independent components that communicate using ROS messages, making it possible for processes running on different networked devices to inter-operate easily. The modular design allows AquaUrsa's components to be tested in isolation making debugging easier. The software components are distributed between microcontrollers, embedded computers, and an external computer used during testing.

A. Drivers

Currently implemented drivers include:

- A depth sensor driver that interfaces with the pressure transducer and informs other components of the measured depth.
- A heading and acceleration driver that communicates with the compass, accelerometer, and gyroscope, providing other components with tilt-compensated heading and acceleration information.
- A motor controller driver that accepts motor commands and generates the PWM and direction signals required by each of the thrusters.
- A sonar driver that receives the time-differences-of-arrival of the four sonar signals, and provides the results to the high-level sonar localization components
- A frame grabber driver that captures camera stills and provides them to the image processing components.

The driver components are responsible for initializing a device, communicating with it via the appropriate protocol, and passing information between devices and higher-level software components, using ROS messages.

B. Navigation

The software team developed a generic PID controller in order to be able make decisions about how to control AquaUrsa's actuators based on current mission requirements and sensor readings. The controller component itself is independent of the actual item being controlled, allowing it to control different items and making it easier to maintain. The controller implements a ROS action server [6], allowing other components (such as the mission planner) to use ROS actions for setting goals, starting/stopping the controller and getting information about the current status of the controller. It also allows other components to change gains and other parameters as needed during the testing and tuning processes.

Heading and depth control are done by monitoring the current output from the digital compass and the depth sensor, and feeding them to the respective controller instances which determine the appropriate power for the thrusters in order to maintain a particular heading and the specified depth.

When performing a vision oriented task, the vision processing component produces a location and/or relative orientation for the object being tracked and sends that information to the appropriate controller. The target of the position-based vision controllers is the middle of the frame. The heading-based vision controllers typically target being parallel to the object. AquaUrsa only moves forward when the actual position of the object is within a certain threshold (usually set to $\pm 10\%$ from the center of the frame) of the target and the rest of the time it corrects its orientation and vertical position without moving forwards. This is done to make it easier for the controllers to achieve their goal and to reduce the chance of completely losing the object.

Similarly, for the sonar mission, the Sonar component updates the target of the heading controller by taking into account both the current heading (from the digital compass) and the heading of the pinger relative to AquaUrsa, as calculated by the Sonar component.

C. *Vision*

Underwater image processing is affected by light attenuation and scattering, which results in poor contrast and non-uniform colors [1]. AquaUrsas vision algorithms have been designed to overcome these challenges. Firstly to balance out the colors in the image, contrast color correction of the RGB colour model is applied [1]. The contrast correction operation reduces the blue in the image and enhances the red and green.

Since the shapes and colours of the competition objects (eg, Buoy, path, gate) are known, the vision algorithms take advantage of this consistency. The two main vision algorithms used for target localization are:

- HSV colour space thresholding
- OpenCV Blob Detector
- Adaptive Thresholding

The vision algorithms are implemented using the OpenCV library [3]. To utilize the TX1's NVIDIA GPU the algorithms are designed to use the OpenCV4Tegra optimized functions [4].

Several methods were experimented with for HSV thresholding, a naive method was to take the mean Hue of the target and threshold within a standard deviation of that value. Given the dynamic illumination of the competition pool this method is not robust in all situations. Another solution was to take a Hue Histogram for a target and train a SVM classifier, then use a sliding window to match objects with similar Hue histograms. This method is better at recognizing outliers but is computationally expensive due to the sliding window operation.

In order to analyze shape OpenCV's adaptive thresholding algorithm was used. With Adaptive Thresholding, the threshold is calculated for smaller regions of the image, making it more robust for images with a variety of illuminations. Adaptive Thresholding uses a grayscale image as its input, after experimentation it was found that the saturation channel of the HSV colorspace provided the best output. From these processed images contours are found using OpenCV, then various constraints (eg. Circularity, aspect ratio, area, color) are applied to filter out false positives.

After the target has been localized using one of the above algorithms, tracking begins. For example with the buoy task the CamShift tracking algorithm is used, which is less computationally expensive to perform than localization.

The path algorithm contains two parts, one is HSV color matching, and the other is a Random Forest Classifier. Since using only HSV did not work situations underwater, and in competition there will be similar objects with such colors, the Random Forest Classifier was added.

D. *Sonar*

The hydrophone signal from the ADCs is fed into the programmable realtime unit (PRU) on Beaglebone Black. This data is sent to AM335x ARM Cortex-A8 processor on Beaglebone Black using shared memory.

In order to determine the position of the sonar pinger relative to AquaUrsa, the time-difference-of-arrival (TDOA) of the four hydrophones is used, by performing multilateration calculation. Given the four times of arrival, an analytical solution of the multilateration equations is calculated using the method developed by R. Bucher and D. Misra [2]. Once the relative position of the pinger has been calculated, the sonar component calculates the relative heading and updates the horizontal controller with a new heading, causing it to turn AquaUrsa towards the acoustic pinger.

E. *Mission Planning*

The Mission Planner controls which tasks AquaUrsa attempts and monitors if tasks have been completed. For each task there is a state which has the run loop for that task. If the task is completed based off a logical condition or the task time-out occurs, then Mission Planner leaves that state and starts another. Certain tasks consist of multiple sub states, for example the buoy task, where all three buoys are located and touched.

For some tasks the Mission planner uses the heading and depth PID controllers. The PID controllers use ROS Action Servers [6] which can be sent goals by Action Clients. In this case the various Mission Planner states implement Action Clients. For vision tasks the mission planner uses the vision PID controllers. These controllers use the difference between the estimated buoy location, and the center of the camera image to center the buoy in the image.

F. Graphical Display / Remote Control

For testing, ROS rqt [7] is used to visualize sensor data and test robot subsystems. For example rqt's plot view is used to view depth and heading data in order to verify those sensors are calibrated properly. In addition rqt image view is used to check the front and bottom facing cameras are working. To test the motors, rqt's message publisher is used to publish motor speeds at each motor topic separately and verify each is functioning correctly. All sensor data is recorded using rosbag during competitions and pool tests. With the recorded bag files sensor data can be played back and used to test and debug.

During tests it is nice to modify algorithm parameters without having to update the code and restart subsystems. In order to do this ROS *dynamic_reconfigure* [8] is used. Using rqt as the GUI and *dynamic_reconfigure*, parameters can be changed and different algorithms selected. For instance, when testing buoy detection algorithms, changes to the algorithm parameters can be made and then the results of those changes viewed using rqt's image view. In addition the PID controller constants are tuned using dynamic reconfigure to get the right amount of damping. Being able to dynamically change parameters speeds up testing and helps to identify bugs in the code.

Another component that is used for testing is teleoperation using a joypad. Using a joypad is a intuitive and easy way to test AquaUrsa's PID controllers, and makes it easy to identify issues. The teleoperation code works by sending goals to PID action servers when the joysticks are moved. Depth and strafing are controlled using the left stick and heading and horizontal speed are controlled with the right.

V. Community Outreach

ARVP has a mandated community outreach program in addition to its technical activities. ARVP members donate their time in an effort to educate the public about robotics and engineering. The primary audience of the outreach program is school-age children, who are encouraged to pursue careers in science, engineering and technology. ARVP regularly makes appearances at public events hosted by the University of Alberta and its Faculty of Engineering, such as the Open House and the Deans Engineering Reception with demonstrations and information about robotics. Summer camp visits and mentoring sessions are an especially effective way to connect with future engineers. In the 2015-2016 academic year, ARVP has conducted such diverse activities as attending summer camps and teaching the kids about robotics, and presenting our robot at ROS meetings to technology enthusiasts. These sessions provide an encouraging, up-close look at the opportunities available in the robotics field, and more importantly, are thoroughly entertaining to the participants!

VI. Conclusion

Although ARVP's AquaUrsa has not undergone major changes in its systems this year, much of the team's effort was to perform the small changes and continue rigorous testing to ensure the consistency of the new AquaUrsa. Most of the changes this year were creating additional subsystems to allow AquaUrsa to advance further at the competition. This year's focus was consistency, where every new system added must be tested to the point of near perfection prior to attending competition.

After all the time and dedication put in over the past year, the ARVP team is excited to represent Alberta and Canada at RoboSub 19, and looks forward to presenting all the new innovative systems in AquaUrsa.

Acknowledgment

The members of ARVP wish to extend their thanks and acknowledgement to the University of

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In addition to the valued assistance of the U of A, ARVP is grateful for the assistance of external sponsors. Their generous donations of money, materials, deferred services, and discounted hardware are an important reason for the team's success this season.

ARVP's sponsors for the 2015–2016 season are, in alphabetical order:

- Alberta Printed Circuits
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- Hi-Tech Seals Inc.
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- Metal Supermarkets
- Paintball Action Games (services)
- Redwood Plastics
- Schlumberger
- Shell Canada (via Shell Enhanced Learning Fund)
- Virgin Technologies Inc. (services)

And the team would like to give special recognition to Jamil Kara, who assisted in producing the team video.

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