University of Alberta Autonomous Robotic Vehicle Project RoboSub Journal Paper 2015

Alvin Ly, *Team Leader - Administrative,* Michael Bujold, *Team Leader - Technical,* Veselin Ganev, *Team Leader - Software,* Michael Bonot, *Team Leader - Mechanical,* Rumman Waqar, *Team Leader - Electrical,* Jamie Lee, *Team Leader - COPPER,* Randi Derbyshire, Josh Robertson, Michael Yu

***Abstract*—The University of Alberta's Autonomous Robotic Vehicle Project (ARVP) team continues to improve on their development of an Autonomous Underwater Vehicle (AUV) with a focus on a robust, easy to expand, reliable platform that can gradually extend it's functionality from a solid foundation over time. Small but significant modifications were made to the physical assembly for ease-of-handling and to contribute to it's robustness. Electrical systems and software design continues to move towards using a unified architecture based on standard communication models.**

I. Introduction

IF EXPERIENCE is what one calls mistakes, then the Autonomous Robotic Vehicle Project team has a seemingly limitless supply of it. As a result of last year's 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. The overall software control system for this year was based on the Robot Operating System (ROS), which necessitated redesigning some of the hardware components. The thruster control system and power supply have remained unchanged from last year, as they are now a proven design with excellent reliability, but the control and user interface modules are new for this year.

Further changes have been made to the mechanical assembly. Difficulties operating the computer vision cameras outside the main pressure hull forced a change to move them inside the pressure hull with the rest of the AUV's electronics. This simplifies wiring and eliminates communication problems that had plagued the team in previous years. More thought has also been put into protecting the integrity of the external-mounted components, as it was discovered through repeated handling of the AUV that the thrusters could be easily damaged if absolute care was not taken. To this end, the external frame was redesigned in an attempt to mitigate any possible damage.

AquaUrsa's software PID controllers required an extensive re-write this year with the transition to ROS, but many hours of testing have resulted in an extremely stable and reliable control system. The vision systems continue to be tested under labratory conditions, with adjustments made in order to increase their effectiveness in the changing competition environment.

II. Mechanical

The new exterior frame support and interior camera integration adds a new level of robustness to AquaUrsa's mechanical design while still complementing the fundamental characteristics of the previous hull. The forward instrument assembly is now replaced with two large aluminium sheets on either side of the hull with horizontal-running aluminium bars holding the two sheets together. The new frame assembly not only adds more reliability and structural integrity to the AUV but also allows for increased modularity in mounting thrusters and other accessories. The vehicle's six thrusters are now mounted on the aluminium sheet frame while also being shrouded by custom-formed aluminum cowlins to protect the thrusters from external contact damage. A clear acrylic tube houses the electronics in plain view, and allows the entire electronics support tray to be removed from and inserted into the hull while still being fully connected. A long resin-infused carbon fiber tube runs along the bottom of the hull holding the inertial measurement unit at a

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

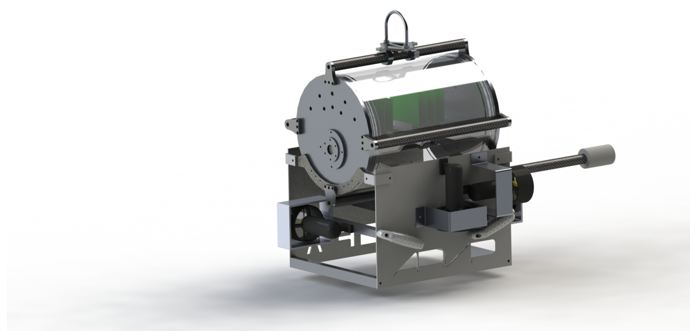

Fig. 1. Solid rendering of AquaUrsa's complete hull.

distance that is not affected by the hard and soft iron distortions created by the hull and thrusters. The camera is now integrated in the interior of the hull to provide greater wired connectivity and remove the requirement for a secondary camera housing thus eliminating another potential for water infiltration.

This new iteration of the AquaUrsa platform is the most rugged, manoeuvrable and expandable platform produced by ARVP to date. It is readily expandable, provides a rugged enclosure for protecting the more sensitive electronic components, and is easy to maneuver outside of water and within water. The hull frame handles, along with a dedicated crane attachment, make it very easy for RoboSub officials, divers, and ARVP members to transport the vehicle.

A. Pressure Hull

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 toleranced 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. 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 connect to a bracket and is mounted onto the frame's aluminium side sheets. There are also threaded holes that have sub-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

The electronics tray is divided into 2 distinguishable sections with the whole assembly able to slide out of the hull, as well as batteries that are able to separately slide out of the electronics tray platform. The electronic components within the hull are held vertically onto the backplane with approximately equal spacing between each electrical component. The card slots provide the support to keep the components in an upright position with the aid of aluminum side supports helping prevent any jarring to occur when AquaUrsa is set in motion. The backplane is fixated onto an aluminum platform, which are rested upon two 1-inch carbon fibre rods that placed parallel amongst each other. The batteries are kept in a 2-battery aluminum holder, with a bearing-axle assembly attached above the holder.

2 battery holders are placed below the back plane platform and in-between the carbon fibre rods with the bearings resting onto a stepped aluminum guide.

C. *Frame Assembly*

The new 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. *Interior Cameras*

Previously, the camera was enclosed in a waterproof case mounted on the frontal assembly. Now, the camera is mounted on the electronics tray inside the hull, removing any wire connectivity issues while still maintaining efficient waterproofing. A two-and-a-half inch hole is drilled through the front lid to provide space and transparency for the camera. This hole is sealed by a large aluminium disk that is bolted onto the lid with proper o-ring seals. Another o-ring is then squeezed by a transparent plastic lens onto the disk. The lens is held securely by another smaller aluminium disk that is bolted uniformly along the larger disk. This assembly gives proper parker standard o-ring seals while giving ease of replacment of the lens if it ever becomes scratched or damaged.

III. Electrical

The main goals for AquaUrsa's electrical architecture this year was to make it a modular, plug and play 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. *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.

B. *Thruster Controllers*

The thruster control system comprises of three thruster controller boards and the thruster processing board connected together using a backplane. Using 50-pin card edge connectors, the backplane provides the following connections to each board:

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

ARVP's unique in-house thruster controllers are another design largely carried over from the design developed for the 2014 year. The overall topology remains the same: Each board uses two L298 H-bridge ICs to control two thrusters, providing up to 4 A to each from a 5-cell lithium battery connected directly to the controller board. The L298s are controlled by raw PWM signals provided by the mainboard. In addition to the six PWM signals, the mainboard also provides six binary direction signals used to control the direction in which the thrusters fire. A simple network of discrete logical ICs translates the PWM and direction signals into the correct signals required to drive a thruster.

The thruster processing board houses a Teensy 3.1 ARM Cortex-M4 microcontroller which subscribes to various ROS messages from PID controllers, and maps these signals properly to the thrusters. In addition, it also publishes the statuses of all the thrusters, and the kill signal using ROS messages.

C. 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

D. 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.

E. 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.

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.

F. Battery Monitoring System

AquaUrsa is powered by four 5-cell Lithium Polymer batteries. Three of these are used to power the thrusters and the last one is used to power the electronics. Before attaching the batteries to the their respective loads, they are connected to the battery monitoring board. This board uses four DS2438 battery monitoring ICs to calculate the current battery voltages and currents. This is sent to the onboard

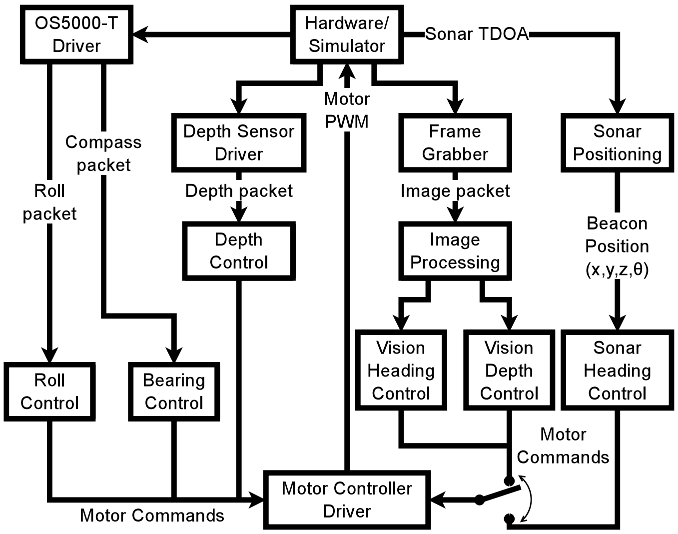

Fig. 2. Overview of software components and their interaction.

Teensy 3.1 ARM Cortex-M4 microcontroller. The microcontroller packages the data into ROS messages and sends it to the main Intel computer over USB. The microcontroller also drives four bar graph displays to show the current voltage levels of each battery. The batteries are then connected to their respective loads.

IV. Software

The software systems in AquaUrsa utilize the ROS (Robot Operating System) [2] framework. ROS is an open-source framework that provides a variety of features, including support for highly distributed systems, a unified communication system between components 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 components running different networked devices to inter-operate as easily as those running on the same device. The software components are distributed between microcontrollers, embedded computer, 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 [3], 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

AquaUrsa's Vision subsystem implements several different image processing algorithms that can be used to locate the various objects necessary to complete the vision tasks. The vision processing system locates the center and/or the angle of the current object and passes that information to the Navigation and Mission Planning components, which will determine the AUV's actions based on this information.

The utilized algorithms include:

- Hue-based colour analysis
- Shape-related information: edge detection, locating contours, Hough line and circle transforms.

The implementation of the algorithms themselves is provided by OpenCV [1].

The Hue-based analysis consists of two main components. The simpler one looks for significant deltas between the hues of neighbouring regions. The other one involves normalized cross-correlation between the hue of the latest camera image and a template image, which has been manually provided to the algorithm.

The image processing component that deals with shape-related information, combines several algorithms, together with the known information about the target object's properties. It performs one or more of the following: canny edge detection (after preliminary hue-based analysis has been done); finding location of the image contours; using Hough line and/or circle transforms. After that it performs task-specific processing, using the expected configuration of lines/contours/circles for the object that is currently being tracked.

Different tasks use different combinations of these algorithms in order to perform the most suitable analysis for the particular task. In addition, for most tasks there are several alternative processing methods available, which attempts to address the frequently changing competition conditions.

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. 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 component is responsible for running and supervising the missions AquaUrsa performs. Each mission, e.g. "pass through gate," "locate pinger," has a completion condition (which describes the criteria for success) and a time-out time (the maximum time to take on a mission before giving up). When either the completion condition or time-out time of a given mission is reached, the Field Commander terminates it and moves to the next mission.

The lower-level components utilized by the mission planner (e.g. the PID controllers, the image processing tasks, etc.) implement ROS actions [3]. The mission planner implements an Action Client, which allows it to send goals, start/stop actions and receive feedback from the action components with detailed information about the current task.

F. Graphical Display / Remote Control

During testing, various sensor data can be visualized, including live video annotated with image processing information, sonar data annotated with pinger position and orientation information as well as data from the various other sensors. Additionally, data can be graphed so that the performance of the controllers and other related components can be evaluated during testing. This can be performed in real-time while AquaUrsa is being tested, or with recorded data from a previous run and utilizes visualization components provided by ROS.

Another component acts as remote control as well as a quick way of configuring components and specifying mission parameters. It allows the operator to tune the gains of the controllers and to specify timings and ordering of the missions. It can also enable ”ROV mode”, in which the operator can manually move and steer AquaUrsa during testing.

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, enginering and technology.

ARVP regularly makes appearances at public events hosted by the University of Alberta and its Faculty of Engineering, such it's Open House, Dean's Engineering Reception, and Faculty of Enginering CO_2 Car Races, with demonstrations and information about robotics.

Classroom visits and mentoring sessions are an especially effective way to connect with future engineers. In the 2014–2015 academic year, ARVP has conducted such diverse activities as classroom visits and demonstrations, hosting high school students for a tour of Engineering labs, and interactive sessions using Lego MindStorms kits. 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

ARVP's newest iteration of the AquaUrsa platform takes many of the lessons learned over the past year and integrates them into a package with excellent reliability. As it is important to always move forward, AquaUrsa is capable of everything it was in previous years and then some.

Some risks were taken in completely redesigning the software control system, but it is expected that this will pay dividends in the long run. It has been proven with many hours of testing that it is a reliable system, and RoboSub will the the penultimate test.

After all the time and dedication put in over the past year, the ARVP team is excited to represent Alberta and Canada at RoboSub 18, and looks forward to pushing AquaUrsa to the limits of it's capability.

Acknowledgment

The members of ARVP wish to extend their thanks and acknowledgement to the University of Alberta Faculty of Engineering, Department of Mechanical Engineering, and Students' Union for their administrative support, and for the financial assistance provided via the Engineering Students' Project Fund. The team would also like to thank Aassem Askari for his generous donation of a GoPro video camera to the team. As well, special thanks to the team's faculty advisor, Dr. Walied Moussa.

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 2014–2015 season are, in alphabetical order:

- Alberta Printed Circuits
- Hi-Tech Seals Inc.
- MARL Technologies
- MacArtney Underwater Technology
- Metal Supermarkets
- Schlumberger
- Shell Canada (via Shell Enhanced Learning Fund)
- Virgin Technologies Inc. (services)

ARVP could not exist without the outstanding external support the team receives from each of these organizations. Their support is hugely appreciated!

References

[1] OpenCV. [Online.] Available: http://opencv.willowgarage.com/.
[2] ROS. [Online.] Available: http://www.ros.org/.
[3] ROS actionlib. [Online.] Available: http://wiki.ros.org/actionlib.