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Autonomous Robotic Vehicle Project
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***Abstract*—The ARVP team has spent the 2012–2013 year developing a sweeping set of improvements to its AUV platform. The mechanical systems were completely redesigned for easy assembly, light-weight and to accomodate new features and instruments. The electrical hardware has been adapted for use with a reliable and easily assembled backplane system, as well as incorporating a much more sophisticated and adaptable microprocessor-based sonar system. New software has also been added, both to improve on previous vision systems and to adapt to changing competition requirements.**

I. INTRODUCTION

DRAWING FROM the lessons learned in previous competition years, the Autonomous Robotic Vehicle Project at the University of Alberta has developed a radically new autonomous underwater platform.

All of the physical hardware in ARVP's newest sub, "AquaUrsa," is new for RoboSub 16 (except for COTS parts such as thrusters). While the new hull and other mechanical changes will be immediately obvious to followers of ARVP's designs, the electrical hardware has undergone a similarly substantial evolution.

Key hardware improvements include a new mechanical platform integrating a clear tubular electronics compartment and rack, easily movable thrusters, clear camera cases, and marker droppers.

Improvements to the electrical systems include ARVP's first backplane-based connection system, a new display board to indicate the vehicle's status during testing and practice, and a new sonar system incorporating its own ARM microprocessor.

AquaUrsa's software systems have been largely carried over from the old SubmURSA platform, in a testament to the versatility of its "DisCo" software framework. The vision systems have been improved, in order to increase their effectiveness as well as to address changing competition requirements.

II. MECHANICAL

The completely redesigned hull and internals represent a huge step for the ARVP Mechanical team. 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 fully connected. The forward instrument assembly houses forward- and downward-facing cameras in a clear case, two marker droppers, and a resistive force sensor used in the "traffic light" task. The vehicle's thrusters are mounted on the end caps of the central cylinder, as well as on resin-infused carbon fibre tubes running the length of the hull. By mounting the thrusters on tubes, static and thrust balancing is as simple as sliding the thrusters to an approproate position along the hull. Another, longer tube holds the accelerometer/magnetometer at a distance from the hard- and soft-iron distortions created by the hull and thrusters, and four more extend radially from the hull, serving as "legs" when the vehicle is out of water, as well as convenient hydrophone mounting points.

Each of the vehicle's mechanical components are designed to withstand depths of up to 100 m ($\approx$981 kPa) with a minimum safety factor of 2. All materials used in the vehicle's construction were selected for their inertness as well as their strength, since corrosion and other reactions can easily destroy seals and connections.

In spite of its unusually porcine appearance, the "AquaUrsa" platform is the most rugged, manoeuvrable and light platform produced by ARVP to date. It also excels in safety: the platform is designed to be very stable and easy to manoeuvre outside of water, as well as within. The hull's many tubes and

TABLE I. "AQUAURSA" KEY MECHANICAL PROPERTIES

Length	120 cm
Width	60 cm
Height	60 cm
Weight	<22 kg
Safety Factor	>2.0
Max Depth	100 m
DOF*	5

*Degrees of freedom

legs, along with a dedicated crane attachment, make it very easy for RoboSub officials, divers, and ARVP members to move the vehicle.

A. Pressure Hull

The central pressure hull is the most crucial mechanical component of the vehicle, since it acts as a support for all other mechanical components as well as a waterproof vessel for the electronics. This year, ARVP opted for a cylindrical hull instead of the square vessels that have previously characterized the team's designs. The hull is composed of an extruded acrylic cylinder, sealed at each end by milled aluminium "caps," with O-ring seals. The tight manufacturing tolerance between the cylinder and caps ensures a watertight seal. Placing the end caps inside the tube causes the seal to be enhanced as pressure increases, due to the higher elastic modulus of aluminium.

Since the end caps of the hull are flat to allow for easy mounting options, they experience high stress when subjected to pressure. This issue is solved by the inclusion of carbon fibre supporting rods within the hull that bear the axial load on the end caps. The inner sides of the end caps are milled with a geometric pattern that helps to reduce the stresses and deflections caused by high pressure.

The aft end of the hull features a conical "cut-out" section that is removed to access the interior. Like the other seals on the hull, it is sealed against water by circular O-rings. This seal is also enhanced by increases in pressure. The carbon fibre supporting rods make contact with the opening end cap 1 mm after the cut-out makes a seal with the O-rings, allowing for small deflections in the end cap without compromising the seal.

Finally, the main hull is equipped with four additional carbon fibre rods mounted axially and equidistantly along the exterior. In addition to minimizing axial compression on the acrylic cylinder, these rods also serve as the mounting point for the sub's vertical and forward thrusters.

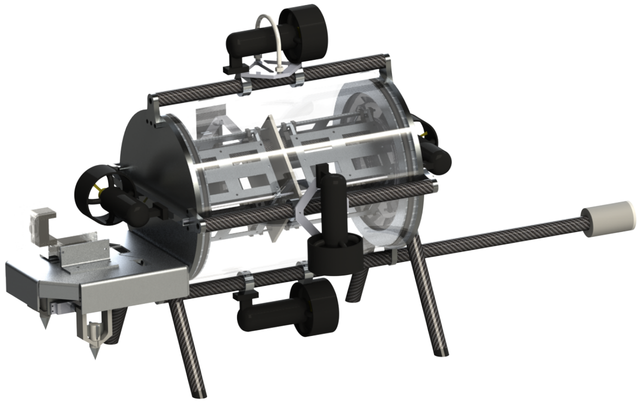


Fig. 1. Solid rendering of AquaUrsa's complete hull.

The lowest of these external rods also extends 1.8 m from the aft end cap of the hull, and is terminated by a waterproof case for an OceanServer OS5000-T digital compass/accelerometer. The design of this case allows the OS5000-T to be placed on standoffs, completely free from contact with other materials. The cylindrical case is sealed by a screw cap with an O-ring, and slides firmly into the end of the carbon rod.

B. Frontal Assembly

At the fore of the hull, a horizontal aluminium mounting plate is attached to the main hull's end cap, serving as a support for three pieces of competition equipment:

- A transparent case holding a forward- and downward-facing camera,
- A resistive force sensor used to detect physical contact with one of the competition's "traffic light" buoys, and
- A pair of torpedo-shaped markers used in the "speed trap" task, held within dual-purpose marker droppers and "pizza" grabbers.

This assembly can be removed to save weight if AquaUrsa is forced to run without vision capability.

The polycarbonate markers are built in a "torpedo" shape, with four fins and a weighted aluminium tip to cause them to drop in a straight line.

The claws that hold them are also built with small extrudes enabling them to lock a PVC pipe in place, making them useful for picking up objects once they have dropped their payload.

The camera case is constructed from polycarbonate, for its transparency and strength. The case holds a forward-facing and downward-facing camera in order to satisfy AquaUrsa's navigational requirements. Since the case is specially designed for AquaUrsa's specific requirements, it allows for lenses to be adjusted and interchanged without having to remove the camera from the case.

C. Electronics Tray

The electronic components within the hull are held in place by a square tray that holds the custom circuit boards, embedded computer, power electronics, batteries and wiring securely within the hull. Circuit boards are mounted on the outside of the tray, making them clearly visible through the acrylic hull. Other electronics, wiring, and batteries are stored within the centre of the tray.

III. ELECTRICAL

While the overall electrical systems architecture within "AquaUrsa" is similar to that used in ARVP's previous vehicles, many improvements have been made to the hardware's reliability, modularity and extensibility. The physical layout has been revised as well: in order to effectively utilize the dedicated electronics rack provided by the mechanical team, each of the custom PCBs used in "AquaUrsa" inserts into a backplane that distributes power and serial communications throughout the electrical system. The backplane-based approach simplifies design, improves reliability, and reduces the time required for wiring, testing, and troubleshooting, since almost every connection a given PCB might require is available on a standardized connector used by every other board.

The passive sonar system used to locate the "pizza" at the end of the competition course has been completely redesigned. While the analog zero-crossing detector implemented in previous years has been retained as a "fallback" approach, the hydrophone inputs are processed directly on-board by an ARM Cortex-M4 microprocessor, which determines the time differences of signal arrival that are used by the mainboard to estimate the distance and heading to the "pizza" beacon.

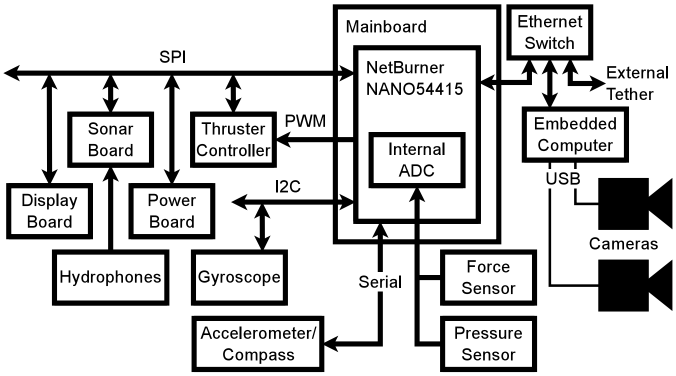


Fig. 2. Overview of electrical communication systems within AquaUrsa.

The power systems have been updated with higher capacity, greater reliability, and monitoring capabilities, which allows the software team to keep track of the power consumed within the electrical system. Redesigned thruster control boards also integrate power monitoring, giving a complete profile of power consumption within the entire vehicle.

Finally, ARVP has developed an optional display board that simplifies test and practice runs by visualizing important information in an easy-to-read format.

A. Backplane

Previous ARVP vehicles typically contained a variety of PCBs, representing both COTS and custom, in-house designs. Wherever a connection between boards was required, the team took the straightforward approach of running a cable within the hull from point-to-point. Since this approach becomes very unwieldy as more boards, connections and external devices are introduced to the vehicle, ARVP has developed a central backplane through which external connections, internal communications, and power are routed.

Using 50-pin card edge connectors, the backplane will provide the following connections to each connected board:

- Power voltages:
  - 12 V,
  - 5 V, and
  - 3.3 V,
- SPI data connections (MOSI, MISO and SCLK),

- I^2C data connections (SDA and SCLK),
- Raw PWM and direction signals used by thruster controllers,
- Generic manipulator controller pins (adaptable for use with marker droppers, item grabbers, torpedo launchers, etc.),
- Raw hydrophone signals,
- Serial UART connection,
- The output from the sonar board's analog zero-crossing detector (see section III-C), and
- A "kill" signal activated by the vehicle's hardware killswitch.

In addition, the backplane connects to all electronics external to the core electrical system, except for the USB cameras (connected directly to the embedded computer) and thrusters (conected directly to the thruster controllers). By condensing as many internal and external connections as possible into one location, AquaUrsa's internal wiring is tidier, faster to assemble, quicker to debug, and has less risk of an inadvertent break in a connection caused by stretched or bent cables.

Two backplane boards face outward from the centre of AquaUrsa's hull, each equipped with four card slots arranged in a square. A unique characteristic of the backplane is that it mounts the PCBs radially, near the outside of the hull, in contrast with other tube-hull vehicles seen at RoboSub that stack their electronics in layers. This approach makes all electronics visible from outside the hull, while batteries, power electronics and external wiring can be stored in the centre of the hull.

B. Display Board

During autonomous testing runs, it can be difficult to verify that an AUV's mission control software is performing as designed, or where trouble might be coming from. ARVP has developed an optional display board to be used during testing. This board will be mounted in a visible location, and will provide detailed status information to the ARVP member handling the vehicle in the pool. Under normal condidions, the board can display the following information:

- 4x20 OLED display for textual information:
  - ○ Current measured depth, heading, tilt, acceleration, and velocity,
  - ○ Current task being attempted (e.g. "go through gate"),
  - ○ Estimated bearing and distance to sonar beacon (when sonar mission is active),
  - ○ Battery cell voltage, charge level, and discharge rate
- LED lamps for statuses:
  - ○ SPI communications OK,
  - ○ I^2C communications OK,
  - ○ Bus voltage issues (5 V, 3.3 V out-of-range), and
- LED battery meters that provide quick verification of battery status at a glance.

Along with this "normal" information, the mainboard can also take direct control of the OLED display and show other information on a priority basis. This can provide useful diagnostic information to testers. Common, but frustrating, problems such as loose connections or dead batteries can be diagnosed immediately, instead of requiring tools, multimeters, and precious testing time to discover.

C. Sonar Board

ARVP's new sonar system is an important addition to AquaUrsa. The functionality of previous systems has been extended to create a more effective and accurate positioning system used to locate the end of the course.

An array of four Cetacean Research SQ26 hydrophones is arranged at the ends of the vehicle's four legs. Since the team relies on a time difference of arrival (TDOA) algorithm, this arrangement provides the maximum hydrophone spacing needed to accurately measure time differences. Once the hydrophone wiring enters the hull, it can be connected either to the backplane (for faster wiring, used in competition) or directly to the sonar board (a useful arrangement for testing). In either case, hydrophone signals enter the sonar system through a buffering amplifier, and are then filtered using an eighth-order elliptic bandpass filter that attenuates unwanted signals outside of the 20–30kHz band. The filtered signal is passed through another, programmable-gain amplifier. The sonar system can adjust the amplitude of its input signals on the fly, to adjust to changing pool conditions and hydrophone locations.

From this point, the filtered sonar signal branches to two paths. The first, and most basic, of these uses an analog comparator to implement a zero-crossing detector. The output of this detector is a square wave with an equivalent frequency to its input—essentially stripping the sonar signal of all information except for its fundamental frequency. This signal can be monitored by a microcontroller with accurate timing capabilities.

While an analog zero-crossing detector is an effective sonar solution on paper, it is easily thrown off by common real-world interference. For this reason, the zero-crossing detector has been relegated to “Plan B” status in AquaUrsa’s sonar system. A more effective, stand-alone sonar system has been developed by the electrical team that independently determines time-differences-of-arrival of sonar beacon signals, and passes them to the mainboard when commanded via SPI. By compartmentalizing the sonar functionality in separate hardware, the team achieves improved results without adding to the computational load borne by the mainboard. In addition, the sonar system can be tested quickly, easily, and anytime, without having to assemble any other hardware.

The sonar board is equipped with an STM32F4Discovery development board that uses its internal ADCs to sample the four hydrophone channels at 70 kHz. The firmware on this development board passes each channel through a Goertzel filter [1] used to detect the target frequency at the end of the course. Once one of the four filters detects the target frequency, the time at which it arrived is recorded. When commanded via SPI, the firmware will transmit the most recent set of sonar times-of-arrival, allowing the mainboard to estimate the heading and distance to the sonar beacon. These coordinates can then be compared against previous calculations to determine whether the last sonar pulse emanated from the actual beacon being tracked.

The sonar board optionally supports capture of raw hydrophone data to an SD card, allowing team members to test differrent algorithms and filters easily using “stock” data.

D. Mainboard

AquaUrsa’s mainboard design is largely similar to that of its previous two AUVs, Bearacuda and SubmURSA. This board holds a NetBurner NANO54415 microcontroller core module running uClinux, that acts as the functional heart of AquaUrsa. The mainboard is directly responsible for:

- Processing analog sensor inputs from ADCs distributed throughout the vehicle:
  - ○ Pressure and temperature sensors, and
  - ○ Current and voltage sensors on each thruster controller and the power board, used to monitor battery status,
- Controlling the SPI, I^2C and RS232 serial interfaces used by:
  - ○ The sonar board,
  - ○ The OceanServer OS5000-T accelerometer/compass mounted at the aft of the hull,
  - ○ The display board, and
  - ○ the gyroscope mounted on the mainboard,
- Providing PWM and direction signals to the thruster controllers,
- Interfacing with the onboard embedded computer, and optionally with a tethered PC, via Ethernet, and
- Running mission control software (if the embedded computer is unavailable).

E. Thruster Controllers

ARVP’s unique in-house thruster controllers are another design largely carried over from the 2012 competition. The overall topology remains the same: Each board uses three L298 H-bridge ICs to control three 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.

Such a simple design results not from inexperience with more complicated commercial controllers, but from too much experience! In the past, the team struggled with the reliability and power output of commercial motor controller designs, which often lacked the exact combination of features required for a given vehicle. In addition, the rare problems that do occur with H-bridges and discrete logic gates are easily diagnosed and repaired, instead of being hidden inside the complex schematics and proprietary firmware of commercial devices.

The thruster controllers are also capable of feeding power consumption data back to the mainboard through onboard ADCs. These ADCs monitor the current output to each thruster using the L298's built-in current-sense pin, as well as the terminal voltage of the battery connected to the controller, to allow the mainboard to track battery status during runs.

F. 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 third 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 within AquaUrsa. These voltage rails are connected to the backplane through a 20-pin ATX power connector, which allows the backplane to be powered by an ordinary PC power supply during bench testing.

Like the thruster controllers, the power board is also capable of reporting the battery terminal voltage and load current to the mainboard through an onboard ADC.

IV. SOFTWARE

The software systems in AquaUrsa operate on a framework called "DisCo," developed at the Department of Computing Science at the University of Alberta. The aim of DisCo is to provide an effective, modular and adaptable communication framework for software components of robotics systems. Adaptability is the key feature of AquaUrsa's software system. It is based on a number of independent components that communicate using small packets of information, making it possible for components running on different networked devices to inter-operate as easily as those running on the same device. The software components are typically distributed between the microcontroller, embedded computer, and an external development computer, but can be moved from one device to another as competition conditions change.

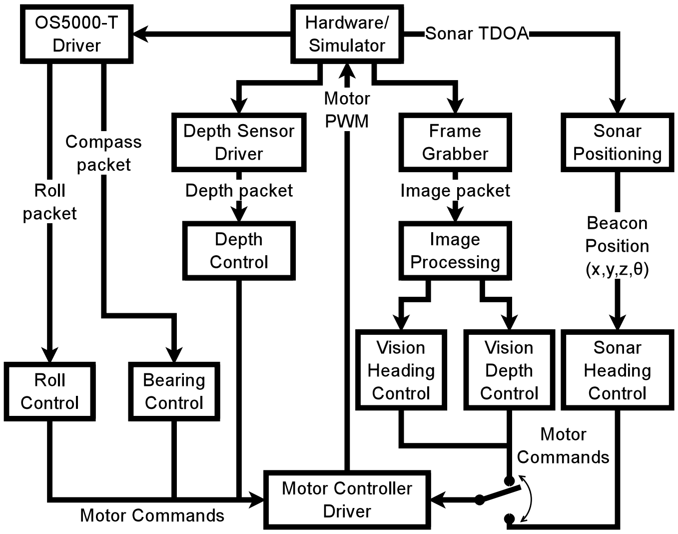


Fig. 3. Overview of software components within AquaUrsa's embedded hardware.

A. Drivers

Several driver components allow the DisCo framework to interface with actual hardware devices in the vehicle. All drivers are abstract, so that their operation appears the same to other components, regardless of their exact implementation, allowing easy migration to new hardware platforms. 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. In addition, each driver supports a simulation mode used during testing and debugging. A special “log driver” allows one of AquaUrsa’s runs to be “replayed,” also for debugging purposes.

B. 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
- Various methods of extracting information from the object’s shape: edge detection, locating contours, Hough line analysis.
- A cascade classifier, using Haar-like features for object recognition

The implementation of the algorithms themselves is provided by OpenCV [2].

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 first performs canny edge detection (after preliminary hue-based analysis has been done). Then, it attempts to locate the image contours and uses Hough line analysis to find lines in the image. After that it performs task-specific processing, using the expected configuration of lines and contours for the object that is currently being tracked.

The Haar features-based detection is based on the ViolaJones object detection framework [6] with additions by Lienhart [5]. This method is traditionally used for face detection but can be applied to detection of arbitrary objects, including the objects in the missions. It utilizes simple features, combined together using a cascade of boosted classifiers [6]. The types of features include edge, line and center-surround features (as described in the OpenCV manual [3]).

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.

C. Sonar

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 a 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 [4]. Once the relative position of the pinger has been calculated, the sonar component calculates the relative heading and updates the horizontal controller component with a new target heading, causing it to turn AquaUrsa towards the acoustic pinger.

D. 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 higher level components can use the controllers by requesting that the target of the controller be changed as well as starting or stopping individual controllers and changing the gains and other parameters.

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.

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 and 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 ±10% from the center of the frame) of the target and the rest of the time it corrects its orientation and 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.

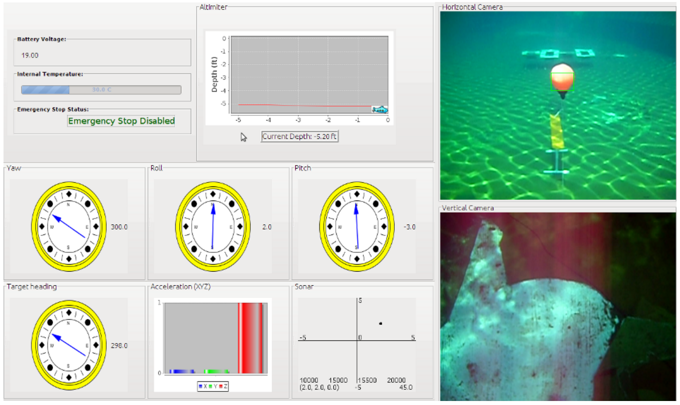
E. *Mission Planning*

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.

Parameters for each mission are stored in XML files that are automatically reloaded upon being changed. This allows the parameters to be quickly updated during development, testing and competition.

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 and data from the various other sensors, as shown in Figure 4. This can be performed in real-time while AquaUrsa is being tested, or with recorded data from a previous run.



Battery Voltage: 19.00

Internal Temperature: 30.0 C

Emergency Stop Status: Emergency Stop Disabled

Current Depth: -5.20 ft

Fig. 4. Visualization of sensor data

In addition to visualizing important data at a glance, this interface can also act as a remote control. The operator can issue a target value for the depth controller component, and can also control AquaUrsa’s yaw in one of two ways: by directly issuing a turning effort command, or by adjusting the target of the heading controller component, causing the vehicle to turn to face a specific direction.

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 as the 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 2012–2013 academic year, ARVP has conducted such diverse activities as classroom visits and demonstrations, soldering and microelectronics workshops, 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

The latest AUV platform developed by ARVP allows for an extended set of competition tasks to be attempted. AquaUrsa will visit San Diego with vision, sonar, and marker dropping capabilities, a huge addition to the team’s possible sources of competition points.

The new competition features have been integrated into redesigned, improved mechanical and electrical systems that will allow AquaUrsa's mission control software to reach the limits of its capability. In particular, the re-worked vision and sonar systems provide great opportunities for the team to increase its standing in the competition.

Given the hours of design, fabrication and testing that have been poured into AquaUrsa over the past year, ARVP is confident in representing western Canada with pride at RoboSub 16, and in having developed a solid foundation on which further improvements can be made for future competitions.

ACKNOWLEDGMENT

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In addition to the valued assistance of the U of A, ARVP is grateful for the assistance of its other 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 2012–2013 season are, in alphabetical order:

- Abma Machine (services)
- Alberta Printed Circuits (services)
- ASA Alloys (materials)
- MARL Technologies
- Shell Canada (via Shell Enhanced Learning Fund)

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

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