University of Alberta AUV: "SubmURSA"

Autonomous Robotic Vehicle Project: 2012 RoboSub Competition

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Abstract - The ARVP entry to the 2012 RoboSub Competition, "SubmURSA," has been refined and improved based on experience from the 2011 competition. While the overall system architecture is essentially the same, key improvements were made to the mainboard, sonar board and power distribution board, and the old "off-the-shelf" motor controllers have been replaced by an in-house design. Most software systems are similar to those from previous years, retaining the modularity and adaptability of the "DisCo" framework. New image-processing algorithms will improve performance in vision tasks. The existing pressure hull has been retained, but with a new lid to protect its contents. The most noticeable change is the complete re-design of the frame surrounding the main pressure hull, which now has more adaptability, strength, and utility.

I. INTRODUCTION

The Autonomous Robotic Vehicle Project at the University of Alberta exists to develop, apply, and promote robotics technology. The principal activity of ARVP is the development of robotic vehicles for entry into the annual RoboSub Competition organized by the Association for Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research (ONR).

The "SubmURSA" vehicle platform used in the 2011 competition experienced several problems that affected its performance:

- The centrifugal pumps intended to be used for diving and movement had insufficient power to move the vehicle effectively.
- The vehicle hull was not designed in such a way that it would float level in the water. This problem was exacerbated by the lack of static balancing capability.
- The frame's narrow beams and few anchoring joints made it quite flexible and unstable.
- The hand-made lid of the pressure hull sealed poorly, and deflected inwards at depth.
- The Sabertooth motor controllers were unreliable. One of the controllers failed completely, and the others did not respond to the "kill switch" signal during one of the competition runs.

- The embedded computer, tasked with high-level mission decisions and image processing, failed to communicate with the mainboard.
- The inertial measurement unit (IMU) failed.

The combination of these problems resulted in a vehicle that was unable to effectively move, sense its surroundings, or act autonomously - all major requirements of the RoboSub competition. Fortunately, each problem has been addressed, along with other concerns, in the revised and improved SubmURSA platform.

II. Electrical Systems

The overall electrical system architecture is similar to what was used on the 2011 platform. Its main components are:

- A mainboard that features a NetBurner MOD5234 microcontroller, responsible for processing all sensor inputs except video, and controlling the thrusters used for movement.
- An embedded computer (EC) that uses processed sensor data provided by the mainboard, and video from USB cameras, to make mission-level decisions, e.g. "move to buoy," "move to surface," etc., and instruct the mainboard accordingly.
- A power distribution board that steps the 18.5 V lithium-polymer battery output to 12, 5, and 3.3 V to power all electronic components.
- Motor controllers that translate control signals from the mainboard into power signals that operate the thrusters.
- A sonar board that conditions and processes hydrophone input before it's processed on the mainboard.

Numerous electrical difficulties in the 2011 competition sparked a re-imagining of the implementation of these systems. Poorly-performing elements have been scrubbed from the system. Upgrades were made with modularity and expandability in mind, since new components are often "piggy-backed" on

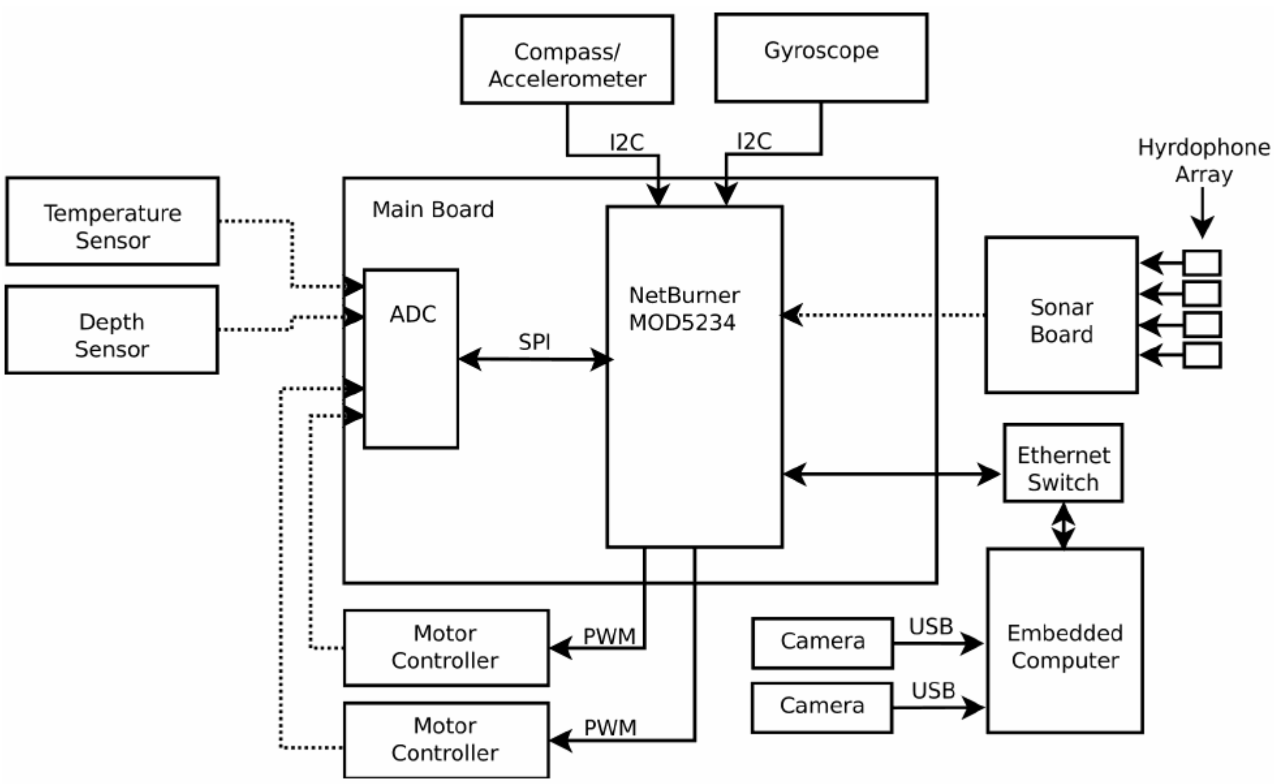

Figure 1: Overwiew of electrical systems used in SubmURSA.

previous hardware during testing and design.

A. Motor Controllers

Without adequate, robust motor control, SubmURSA would literally be dead in the water. This is indeed the lynch-pin of the entire electrical system. In past years, off-the-shelf components were used, but these devices often required unnecessary compromises. Commercial devices often lacked required features like feedback, had an excess of features that complicated their integration, and generally larger form factors.

To address these concerns, ARVP has developed a purpose-built motor controller based on the L298 H-bridge integrated circuit. This IC can drive one motor at 2 A or two motors at 4 A in a “bridged” configuration. Two motor control boards, each with three L298 ICs, are used, allowing up to six thrusters to be operated. Each channel accepts a PWM signal for thrust level and a binary direction signal. Power is passed directly from the 18.5 V batteries to the motor controller boards. In addition to these inputs, a “sense” pin feeds an analog voltage, proportional to motor current draw, back to the mainboard, and an active-high “enable” pin disables the load when pulled low, to implement required kill-switch functionality.

B. Mainboard

The mainboard acts as the control hub for each peripheral board. It houses a NetBurner MOD5234 microcontroller running microLinux, loaded from an on-board SD card, and is responsible for:

- Processing several sensor inputs.
- Providing PWM and direction signals to the motor controllers.
- Interfacing with the embedded computer via Ethernet.
- Running the mission control software, if required by EC failure.
- Interfacing with a development PC via USB during testing and debugging.
- Handling input from the kill-switch: when the switch is actuated, the motor controllers’ “enable” pin is pulled low and an active-low “RUN” pin on the mainboard is pulled high, resetting the MOD5234.

C. Sensor System

Numerous sensors allow SubmURSA to determine its orientation, bearing, and depth, and other mission-specific information:

- An LSM303DLM 3-axis compass and accelerometer to determine orientation and heading.
- An L3G4200D gyroscope to compensate for error and drift in the compass/accelerometer.
- A TDH30 analog pressure transducer to determine depth.
- Four SQ26R1 hydrophones positioned at the corners of the frame, for passive sonar.
- A Microchip MCP9700 Linear Active Thermistor to measure internal hull temperature.
- Two USB video cameras used by the embedded computer for image processing.

Since some of these sensors provide analog outputs, a Maxim MAX1300 analog-digital converter, which communicates with the NetBurner via SPI, is mounted on the mainboard to free up microcontroller pins.

D. Power Distribution Board

In previous years, voltages required to power the different electrical components were provided by separate boards. To simplify SubmURSA’s internal wiring and reduce assembly and troubleshooting times during competition, all of these boards’ functionality has been rolled into a single power distribution board. A dedicated 18.5 V lithium-polymer battery provides input to a Vicor V24A12E400BG voltage regulator module, which steps the battery voltage down to the 12 V required by the embedded computer. Also connected to the 12 V bus are LM7805 and LM1117-3.3 regulators, which provide 5 and 3.3 V, at up to 1 and 0.8 A, respectively. Each of the 12, 5, and 3.3 V outputs can be connected to up to five loads through Molex Minifit connectors. Standardizing electronics power to use these connectors will improve organization and consistency of electrical wiring, as well as allowing all of the electronics to be powered by an ATX 2.0 compliant PC power supply during testing.

E. Sonar system

SubmURSA's passive sonar system enables it to detect to detect the acoustic pinger located at the end of the RoboSub course. Four SQ26R1 hydrophones measure audio from the environment. The signal from the hydrophones passes through a high-pass filter to remove the 60 Hz power signal "buzz." Since these piezoelectric devices are not externally powered, their output signal is passed though an adjustable-gain pre-amplifier, with a default gain of -70 V/V.

From this point, each signal is split into two paths that allow for two distinct modes of operation. The first mode passes the raw sinusoidal wave through a rectifier that eliminates the negative half of the pinger signal (to avoid damaging other components), leaving the positive half unchanged. The second mode of operation performs additional conditioning on the signal: it is first passed through a zero-crossing detector, which converts the sinusoidal wave to a square wave. The square wave is positive when the sine wave is positive, and vice versa. This signal is rectified to remove negative voltages; the end result is a logical signal that is "high" when the sonar input is positive and "low" when the sonar input is negative. Both signals from all four hydrophones are sampled by an analog-digital converter, and all eight digital signals are passed to the mainboard via SPI for processing and interpretation.

The frequency of the hydrophone input can be determined in software by either measuring the time between pulses of the conditioned hydrophone output, or by digitally filtering the raw, rectified sinusoidal signal. The MOD5234 microcontroller logs the instants at which a desired frequency has been detected by each hydrophone. This time-difference-of-arrival (TDOA) data is passed to the embedded computer for interpretation.

III. SOFTWARE

The software systems in SubmURSA 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 SubmURSA's software system. It is based on a number of independent components that communicate using small packets of information – however, it is irrelevant whether components are running on the same device, or on different devices which are networked together. 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.

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. 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 determines 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 SubmURSA’s runs to be “replayed,” also for debugging purposes.

B. Vision

Previous vision processing systems used by ARVP implemented only a simple RGB-thresholding algorithm, which determined which pixels in a frame were close enough to a target’s colour, and to direct the vehicle towards the largest concentration of target colour. This approach is generally effective, but suffers from the major drawback that its performance can be affected by times of day, when the same object may appear to be a different colour. To implement more robust target identification, an additional processing method was applied in order to use information about the shape of a target object, as well as its colour.

Image processing involves normalized cross-correlation of hue between the target image and a template, and application of a cascade classifier by using Haar-like features for object recognition, both implemented in OpenCV [1].

The colour-based approach must be retained since the Haar method is not appropriate for all cases. Normalized cross-correlation is performed between the hue of the latest camera image and a template image. Adaptive thresholding is used to single out the object being tracked. A template image can be provided to the algorithm by a user of a PC connected to the system, who can select the target from the current camera feed.

The Haar features-based detection is based on the Viola-Jones object detection framework [2] with additions by Lienhart [3]. 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 [2]. The types of features include edge, line and center-surround features (as described in the OpenCV manual [4]).

C. Sonar

In order to determine the position of the sonar pinger relative to SubmURSA, the four hydrophone signals are analyzed to retrieve their time-difference-of-arrival (TDOA) information, to which a multilateration calculation can be applied. 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 [5]. Once the heading to 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 SubmURSA 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 SubmURSA'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 for the object being tracked and sends it to the appropriate controller. The target of the vision controllers is always the middle of the frame. SubmURSA 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 vertical position without moving forwards.

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 SubmURSA, as calculated by the Sonar component.

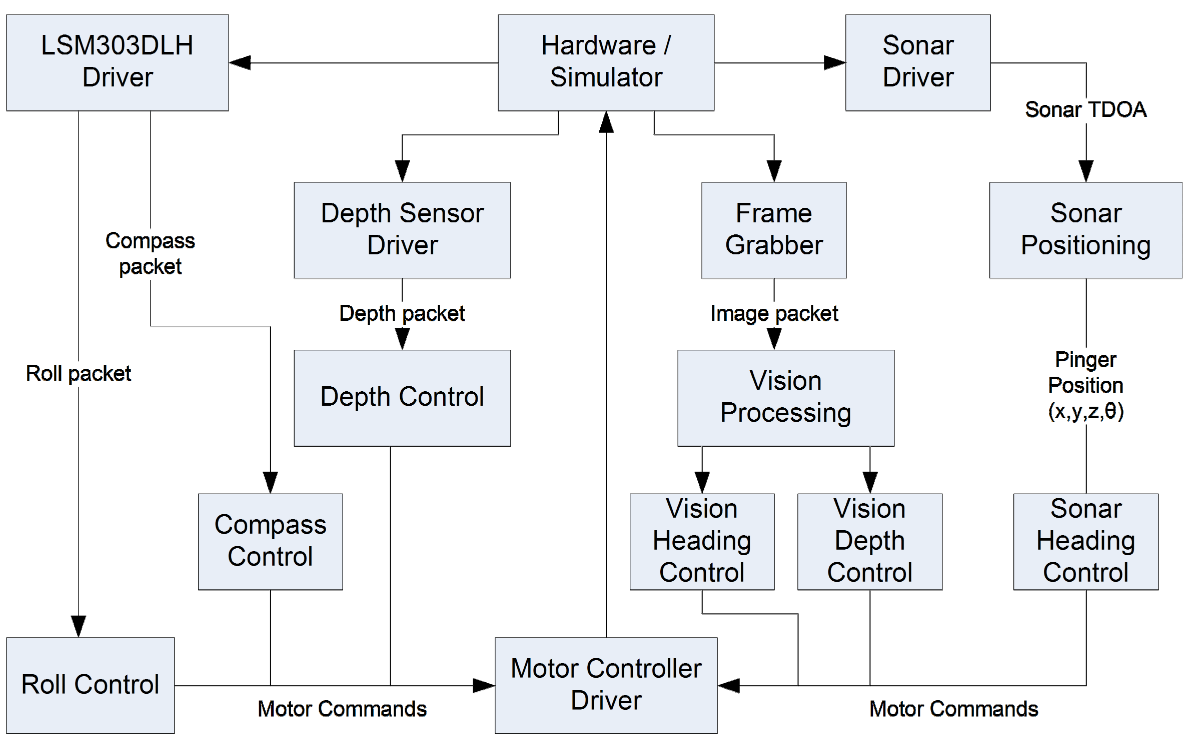

Figure 2: Overview of SubmURSA's software components.

E. Mission Planning

The Mission Planner component is responsible for running and supervising the missions SubmURSA 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. This can be performed in real-time while SubmURSA is being tested, or with recorded data from a previous run.

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 SubmURSA’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.

IV. MECHANICAL

SubmURSA’s mechanical systems were largely successful at the 2011 RoboSub Competition, but many opportunities for improvement were identified. The central rectangular pressure hull that houses the electronic components was very effective, but the frame to which it was attached was quite pliable and not very adaptable. By having the pressure hull slide into the frame on rails, it

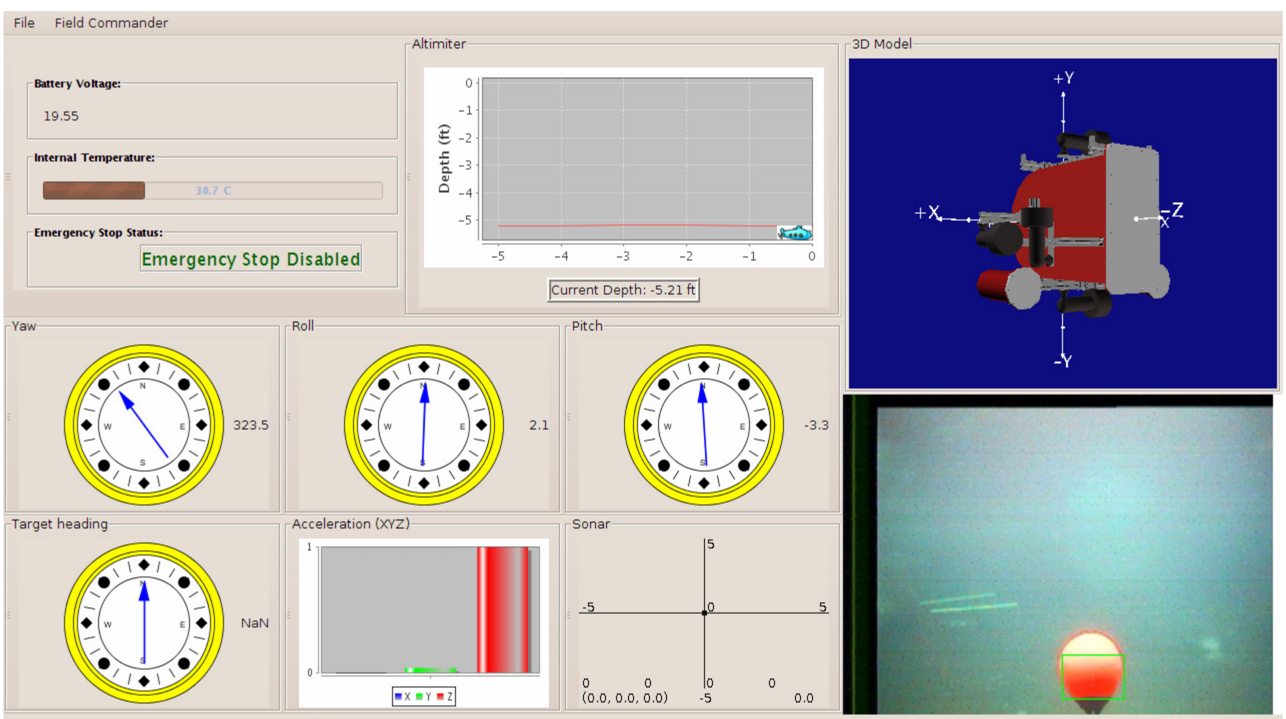

Figure 3: Screen capture of graphical display / remote control interface.

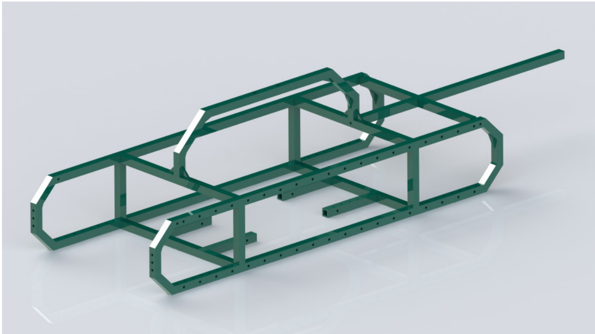

Figure 4: Isometric rendering of SubmURSA's new frame.

was intended that static balancing could be achieved easily, but the hasty addition of two vertical thrusters made this impossible. The hand-made Lexan pressure hull lid sealed poorly and deflected downwards at high pressures. These issues framed the mechanical team's design philosophy approaching the 2012 Competition.

A. Frame

To address the concerns identified at the previous Competition, the mechanical team elected to retain the pressure hull, but re-design and re-build the frame, with the following key requirements in mind:

- Maintain high adaptability. The frame must accept various parts in various configurations as competition requirements change.
- Design a carry handle for safe, easy transportation and hoisting.
- Maintain a minimum distance of 18" between the inertial measurement unit (IMU) housing and any source of magnetic interference.
- Minimize weight while retaining sufficient rigidity to withstand thrust forces.
- Use readily available materials, and uncomplicated design, to expedite construction.

Based on these requirements, the frame was designed to be constructed from 3/4" square aluminium tubing with 1/8" thick walls, with numerous threaded holes for attachment of components such as thrusters, hydrophones, and future additions like torpedo launchers and grabber arms. Previous designs had successfully used 6061 aluminium, but when tested by immersion in Edmonton city water for several days, this material experienced significant corrosion. The 2012 frame design uses 6063 aluminium, which trades some mechanical strength for lower cost, improved weldability, and excellent corrosion resistance.

Wherever a tube was required to make a 90° bend, it was divided into two 45° bends to reduce the stress concentration at individual welds. The geometry is simple to construct, and is as light as possible while maintaining an absolute worst-case safety factor of 2 before any part of the frame will fail.

The frame typically mounts six Seabotix BTD-150 thrusters: two in each axial direction. Their arrangement allows for five degrees of freedom (surge, sway, heave, yaw, and roll).

B. Lid

SubmURSA's pressure hull requires a lid to protect its contents from the aquatic environment, which is known to be somewhat hostile to electronics. It was originally assumed that an adequate lid could be cheaply hand-made by forming a clear Lexan sheet

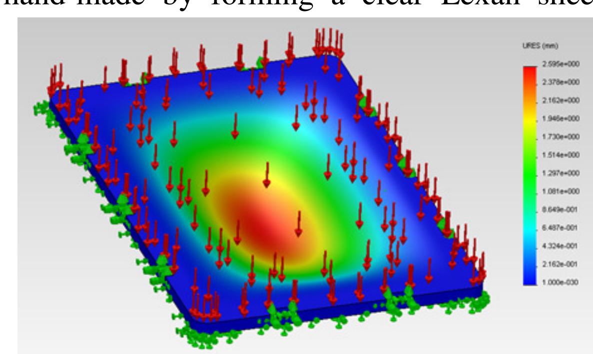

Figure 5: Simulated deflection mapped over lid at 10 m.

over the hull with a heat gun, but this solution lacked the mechanical strength and watertight seal required to protect the hull contents.

A much-improved lid has been designed for use in the 2012 Competition, made from 1/2" clear polycarbonate. Ten jaw clamps on the pressure hull latch onto notches in the lid to pull it onto two rubber O-rings lining the hull rim, and a groove in the lid fits snugly over the hull lip, with an allowance for the lid's expansion when moved from Edmonton's sub-arctic climate to the balmy temperatures of San Diego.

Assuming a worst-case depth of 10 m, the lid will experience a maximum deflection of 2.6 mm, clear of the 10 mm distance between lid and hull contents. In this situation, the lid's deflection and stress are well within the limits of the material, giving a safety factor of 3 before failure.

C. Electronics Trays

The pressure hull contents can generally be freely arranged within the available space, but some design attention was given to simple trays capable of organizing and retaining the electronics within the hull. The electronics racks were not as exhaustively simulated as the other mechanical components, due to the trivial loads they will be required to support. Special attention was paid to the trays' modularity, to allow them to be moved based on wire length considerations or for static balancing. The trays are generically sized to accept various future boards, and, like the lid, are clear to maximize visibility into the hull.

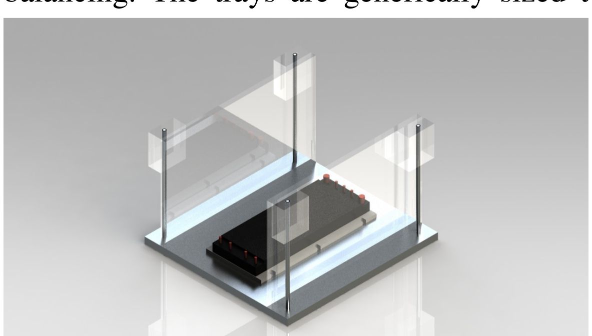

Figure 6: Electronics tray design.

V. ACKNOWLEDGEMENT

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REFERENCES

[1] OpenCV. http://opencv.willowgarage.com/.
[2] P. Viola and M. Jones. Rapid object detection using a boosted cascade of simple features. In Computer Vision and Pattern Recognition, 2001. CVPR 2001. Proceedings of the 2001 IEEE Computer Society Conference on, volume 1, pages I–511 – I–518 vol.1, 2001.
[3] R. Lienhart and J. Maydt. An extended set of Haar-like features for rapid object detection. In Image Processing. 2002. Proceedings. 2002 International Conference on, volume 1, pages I–900 – I–903 vol.1, 2002.
[4] OpenCV Object Detection using Haar-like features. http://opencv.willowgarage.com/documentation/object_detection.html#haar-feature-based-cascade-classifier-for-object-detection.

[5] R. Bucher and D. Misra. A Synthesizable VHDL Model of the Exact Solution for Three-dimensional Hyperbolic Positioning System. VLSI Design, 15(2):507–520, 2002.