University of Colorado Boulder RoboSub Team

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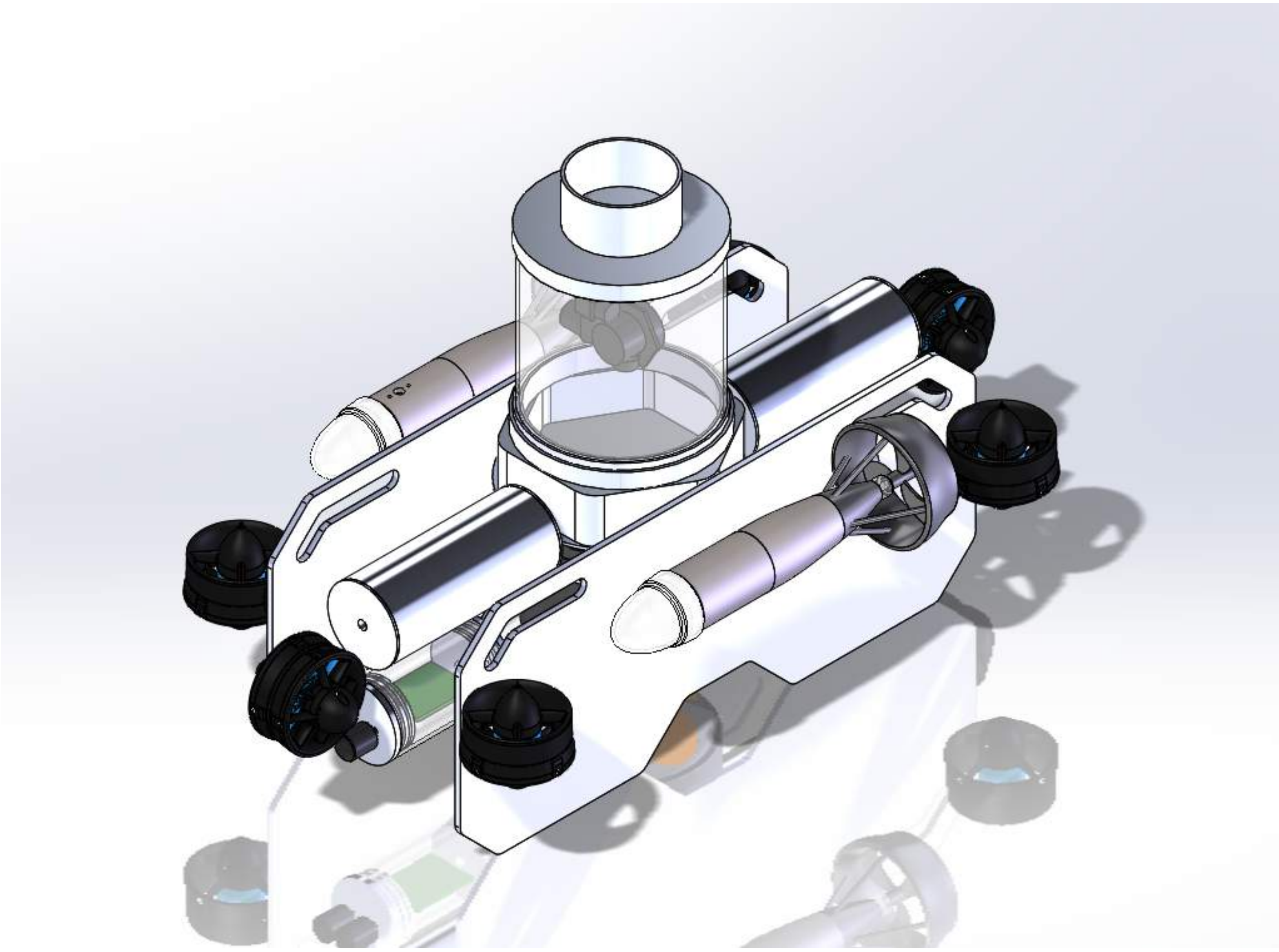

***Abstract*— The University of Colorado Boulder RoboSub team has worked diligently to create a novel robotic design for the 2016 RoboSub competition. The mechanical team designed a vertical hull to integrate with new panoramic cameras, as well as a side panel frame to support our six vehicle enclosures. The electrical team created custom printed circuit boards for power and hydrophones to meet the growing challenges of the vehicle and competition respectively. Finally, the software team designed a robust programming system using open source resources such as the Robot Operating System and OpenCV. These different systems have all been combined to create our 2016 vehicle Caligula.**

I. Introduction

The University of Colorado Boulder RoboSub has developed a robust autonomous underwater vehicle over the course of the year. The team's core design philosophy involved learning from the teams past mistakes, and analyzing how teams succeed at RoboSub. With this core philosophy in mind the team utilized its new knowledge and to design a unique robot from that information. In almost every aspect of the teams design there has been marked improvement from previous iterations.

II. Paper Contents

A. Design Strategy

The team's general design strategy is focused on improving vehicle capability and providing learning opportunities for its members. Given the team's young age, but relatively large budget, we focused on adding vehicle capability on a completely new platform, instead of refining the fundamentally flawed system used last year.

Last year our team encountered critical failures while integrating systems on WaterBuffalo II. After competition the team spent several weeks dissecting the flaws it discovered on the vehicle. From this analysis the team leaned many lessons. The team categorized each problem into supplier side, design side, and process side failures. Supplier side failures were components that arrived out of specification; these failures were out of the control of the team. The most notable failure in this category was the team's battery packs, which had significantly lower power levels than expected. Design side failures are failures of the design, portions of the vehicle design that were flawed. Process side failures were faults in the manufacture or integration process, which caused faults down the line.

In order to avoid the same problems faced last year, the team began testing isolated components as they are added to subsystems, prior to whole system integration. Additionally, every system is designed with alternative choices and backup plans in mind incase of subsystem failures. This gave our vehicle more modularity, and a more robust system to work from.

As with previous years the team commenced designing our 2016 vehicle Caligula after error analysis was complete. Key new sensing equipment guided the development for Caligula. In addition the team conducted a thorough evaluation of successful competition vehicles, categorizing the key features and design choices used by other teams that led to their success.

By analyzing the teams who have made it into the competition finals repeatedly in recent years we gained better insight into the capabilities of a top vehicles. From this we concluded that the DVL was the most important sensor; Amador Valley High School is the only team who has been in finals multiple times, in recent years, without a DVL. The next critical sensor that top vehicles consistently contained was a wide field-of-view machine-vision camera. Finally, having a quality hydrophone array seemed to be the most consistent method to reach finals.

The team applied the insights gained from WaterBuffalo II, analysis of top vehicles, along with a unique design flavor from our team, to develop our 2016 vehicle, Caligula.

B. Vehicle Design

Our vehicle design is broken down into three sections, Mechanical, Electrical, and Software.

1) Mechanical

WaterBuffalo II's mechanical systems were compromised during subsystem integration because tolerances on sealing surfaces of the main hull were too small. Even the slight addition of material from anodizing caused interference that left the team unable to close the main hull and protect critical electronic components. This problem was not discovered until final assembly at competition when the team no longer had access to a machine shop with the power equipment necessary to rectify the mistakes. Removing the extra material from the sealing surface required tens thousands of passes of sand paper and took team members 30 hours of continuous sanding to by hand to maintain concentricity. This was a major process failure in WaterBuffalo II. After this failure the team added an additional testing stage where all mated components must be tested prior to leaving the machine shop, and after being anodized. The team test fit all seals prior to marking them complete.

Caligula's newly designed mechanical structure consists of 6 waterproof electronics enclosures, 2 Video Ray pro-4 thrusters, and 6 Blue Robotics T100 thrusters, on a high-density polyethylene (H.D.P.E.) and aluminum frame.

In order to decrease the possible points of failure Caligula the team decreased the number of external enclosures. There are a total of 6 enclosures with 5 custom-designed enclosures for various electronics, and the pre-built DVL housing. The 5 custom enclosures include the main hull, down camera housing, hydrophone enclosure, and battery tubes.

The main hull of Caligula is a vertically oriented acrylic tube with aluminum end caps. A vertical cylinder is an atypical choice in the RoboSub competition, as the vast majority of teams use a horizontally cylinder for their main tube. We chose to use a vertical tube to accommodate our new 360° camera, the Occam Robotics Omni60. The clear acrylic tube allows the Omni60 to see all directions around the vehicle in the horizontal plane. The downside to the vertical tube it is slightly less stable orientation compared to a horizontal tube. This is accounted for in the vehicle enclosure layout, by keeping the center of mass directly below the center of buoyancy the vehicle is statically stable. Additionally, the vertical main tube orientation has a radially symmetric drag profile, reducing the thrust required to strafe and adjust heading (rotate about the vehicles central vertical axis).

One design side failure the team noticed during assembly of WaterBuffalo II was a failure to account for clearance between the connectors and frame spars. The vehicle design models did not accurately reflect minimum clearance for the SeaConn connectors used. To account for this the design, the bottom end cap deviates significantly from the typical RoboSub end caps. Since the tube is vertically oriented the team decided placing connectors parallel to the end cap along the main access of the tube would make the connections difficult to access, and would not provide proper clearance to place the DVL. Instead the team's solution was to have the connectors exit the main tube radially, allowing the team to easily access connectors on the side of the tube. Connectors on the bottom end cap of the main tube are a combination of SeaConn for data and battery power and SubConn split wet-mates for motor power. Additionally, the team chose to place a SubConn gigabit Ethernet connector on the top cap, in order to prevent the tether from becoming entangled during testing and tethered operation.

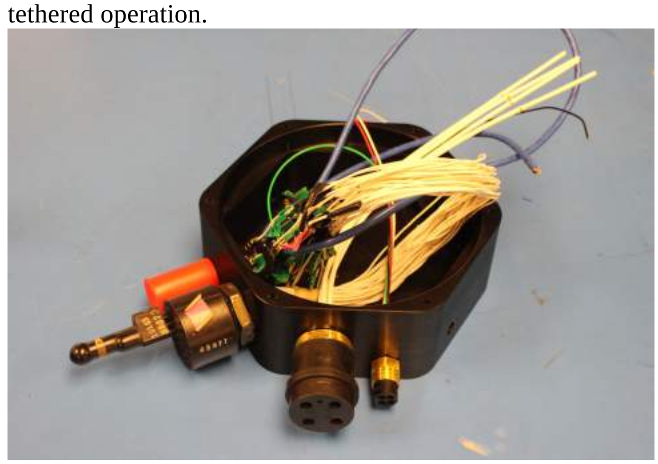

Figure 1: Bottom Endcap Durring Assembly

Caligula's ancillary enclosures include the two battery tubes, hydrophone enclosure, and down camera enclosure. The batteries are kept in a separate enclosure from the main electronics in order to make it easier for the team to change out batteries in between runs. By not having to open the main cull each time a batter change becomes necessary we get closer to the team goal of not needing to open the main enclosure throughout competition. This goal is in place because each time the main hull is opened there is a chance for electronics to be moved causing shorts, wires to unplug, and other potential dangers. Team lead Pierson Connors implemented this goal after his time as part of Amador Valley High School, where he noticed small electrical problems were caused by the team repeatedly opening and closing the main tube. The battery tubes use SubConn high power 4 contact connectors to move power between the battery pods and the main hull.

Because the team chose to place the DVL directly below its vertical main hull, there was no way for us to include the down camera inside of the main enclosure. This necessitates an ancillary enclosure for the down camera. The camera uses power over Ethernet (POE) for power and data. The team selected this communication protocol since there are few waterproof connectors capable of handling USB 3.0 or FireWire, other common vision communication protocols. SubConn, however has a gigabit Ethernet connecter, which the team placed on the rear of the camera housing to facilitate communication between the main computer in the main hull and camera.

Additionally the team designed an external enclosure to hold the hydrophones as interference can have large impacts on the sensitive analog electronics needed to record acoustic pings. The enclosure features a high precision, fixed mounting point for the hydrophone array, as well as storage space for multiple custom boards.

Caligula’s frame is inspired by the 2013-2015 Amador Valley High School design; team lead Pierson Connors originally created this design during his time on the Amador Valley Team and was inspired by the Reykjavik University design before that. The frame is made up of two half-inch thick HDPE panels with support and mounting struts connecting the two panels. This design reduces fabrication time, and design time. It is simple, robust, and easy to modify. And it is visually appealing as well as lightweight. The small cost of increased lateral drag is a small price to pay for the advantages.

8 thrusters propel Caligula through the water. 2 Video Ray pro-4 thrusters provide surge thrust and heading control. 6 Blue Robotics T100 are also used, 2 provide strafe and heading control, 4 provide vertical thrust, and roll and pitch control. This 8 thruster layout provides 6 degree of freedom control with redundant rotational control in all three rotational degrees of freedom. The redundant rotational control allows the vehicle to loose up to two thrusters and maintain 6 degree of freedom control. This thruster layout is the same as used by WaterBuffalo II and is popular in RoboSub, being used most notably by Cornell University in recent years.

2) Electrical

After encountering numerous difficulties integrating an entirely off the shelf electronics system in WaterBuffalo vehicle line, the team built Caligula’s electronics from the ground up. A custom passive sonar array and power distribution system were developed in addition to purchasing improved sensors for Caligula.

Caligula’s power distribution system is built around 2 custom designed printed circuit boards (PCBs). One custom PCB is for high current, battery merging and motor power. The second PCB is for low current, and voltage regulation to deliver power to the teams sensors and computing electronics as well as power monitoring.

The high current board uses two positive high voltage ideal diode controllers to balance the current drawn from each battery. Similar to an OR gate, the ideal diode controller enables the gate of an N-channel MOSFETs switching the current draw from one battery to another. By selecting the battery with the highest voltage, this system protects the batteries from becoming imbalanced, and only allows a single battery to be operated at a time, protecting the delicate lithium polymer batteries. The high voltage board also uses a single P-channel MOSFET as a kill switch to immediately kill all analog electronics connected to the robot. The MOSFET’s gate is attached to a double-pole single-throw switch that alternates between power at 14.8V and ground at 0V. When the gate is pulled to ground the MOSFET is on and allows current to flow to the motors. When it is connected to power the MOSFET disables the flow of current to the motors. This P-Channel MOSFET acts as a low side switch and was chosen due to its simple implementation over a high-side N-Channel switch, which would have required a voltage conversion to activate the gate.

The low current board uses a network of switching regulators to provide the required voltages for every digital system in the robot. Using the balanced 14.8 volts from the high current board, several Linear Technology integrated circuits (ICs) are used to step up or step down voltage. Each Linear IC is configured to use the SEPTIC mode, which protects against voltage drops. Voltage drops are especially common due to the motors significant power draw on startup, and during. As more current is drawn from the batteries, the 14.8 volts from the high current board drop. Since most digital components uses strict voltage levels to preform digital logic, stable voltage lines are extremely important. A SEPTIC boost or buck converter can provided a specific voltage output regardless of a shifting voltage input.

Also, the low current board uses a Teensy microcontroller to monitor current and voltage at various points in the power distribution system. The continuous monitoring allows real time diagnostics and can trigger the kill switch in case of dangerous fluctuations.

Caligula’s sensing has been significantly improved from WaterBuffalo II. Caligula has two new cameras, 3 inertial measurement units (IMU), a 9-hydrophone passive sonar array, pressure transducer, and a Doppler velocity logger (DVL). The cameras are a significant improvement over the webcams used on WaterBuffalo II. Horizontal vision is accomplished by an Occam Omni 60, a USB 3.0 machine vision camera system that combines the images from 5 cameras to give a 360° by 72° view around the vehicle in a horizontal plane. A Point Grey Blackfly camera body with a Theia SY125 ultra wide-angle lens provides the vehicle with down imaging. The Point Grey Blackfly uses a Power Over Ethernet (POE) communication protocol. POE is compatible with the wet mate gigabit Ethernet connectors commercially available. This enables the team to place the down camera outside the main hull giving an unobstructed view of the pool bottom. The team chose Ethernet over Fire Wire and USB 3.0 since they not compatible with widely available waterproof connectors, while Ethernet is. The team carefully selected these communication protocols to compatible connectors as many teams have had parts fail as a result.

Caligula's localization system is based around 3 inertial measurement units (IMU), and a DVL. Having 3 IMU is valuable, as MEMS IMU tend to be very noisy, 3 separate units allows for noise to be averaged out.

Figure 2: X-IO NGIMU

Caligula's hydrophone system consists of nine Aquarian AS-1 hydrophones designed to determine the heading, distance, and elevation of an incoming acoustic wave. The nine hydrophones are arranged in an orthogonal, cross pattern – where each arm of the array consists of five hydrophones. Figure 3 illustrates the geometry of the array.

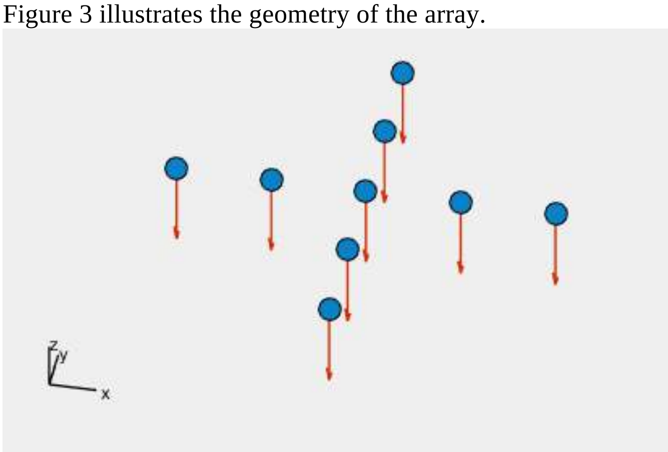

Figure 3: Hydrophone Array Geometry.

The location of the hydrophones relative to one another allows for the detection of acoustic waves between 20 kHz and 40 kHz while also preventing spatial aliasing.

The hydrophones interface directly to an embedded system that is independent from the submarine's primary computer. This system's sole responsibility is to determine the heading, distance, and elevation of an incoming acoustic wave relative to the vehicle's location. The embedded system consists of three, high-performance, ADCs, nine LNA's, an IMU, and a Xilinx FPGA SoC.

The FPGA is running a custom algorithm implemented in Verilog and VHDL. As a result, the hydrophone array – coupled with the custom algorithm – behaves as a passive sonar system rather than an acoustic point-source locator. In effect, the algorithm implements adaptive-beam forming, simultaneous multiple-source identification, and signal extraction.

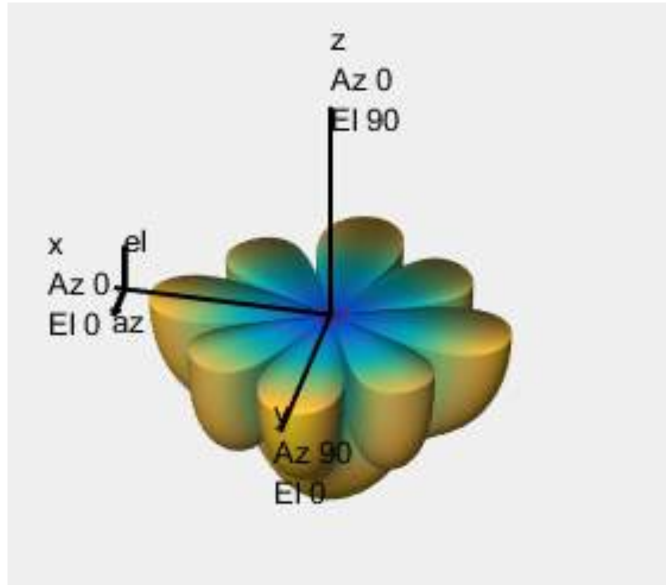

Figure 4: Hydrophone 3D Directivity Pattern at 40kHz.

Theoretically, the algorithm is capable of determining the heading, distance, and elevation of multiple sound sources to within a tenth of a degree. Once the telemetry of each identified acoustic signal is calculated, the data is packaged and sent to the submarine's primary computer in real-time. As the algorithm adapts via beam forming techniques, the resolution of the calculated telemetry of any given acoustic signal increases and therefore improves the ability to precisely navigate.

3) *Software*

WaterBuffalo II had limited software capabilities. Our team spent much of its time working on finishing the electrical and mechanical portions of the sub, that very little software was written by the time the competition began. Over the course of the competition the team's software rapidly developed allowing us to control the motors, cameras, and DVL. While this was an excellent start the team knew that more needed to be accomplished in future years.

Caligula's software system is designed to utilize the open source Robot Operating System (ROS). The team chose ROS because it allowed us to individually build and test software packages for our many sensors and then integrate quickly into a central mission planning setup. This enabled the team to avoid large delays in programming while waiting for hardware to be completed.

ROS provides tools for communication between both individual parts as well as languages making it easy for individuals to work on individual sensors, and packages. As a result Caligula's software was developed significantly faster. Figure 5 shows design flow of the vehicles software.

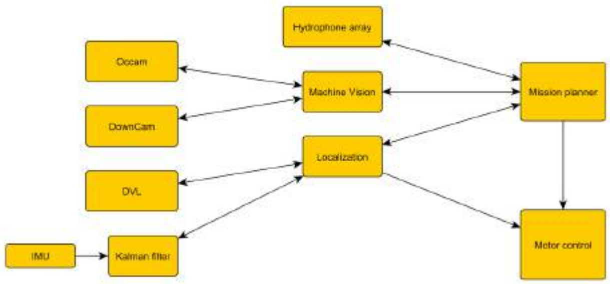

Figure 5: Software Block Diagram

The framework is designed around a central mission planner, which takes in input as a subscriber from different ROS packages and then outputs a desired location to our motor control package. The mission controller can be updated to account for different task times, and helps assist in transitions from one task to another.

The localization is based on a data input from serial communication from the DVL and the IMU's. The DVL takes care of both velocity and position outputs which can be compared to one another to verify accuracy. The IMU's are sent through a Kalman filter to average out errors and determine the vehicles orientation. Taking the data from each IMU and averaging it allows us to get even more accurate estimates of our orientation. The motor controller operates by controlling a Pololu Mini-Maestro 12 servo controller. It adjusts the heading, and velocity of the vehicle to match the desired output from the mission controller.

In addition to this sensor integration our software system contains significant vision capabilities. Our team is using OpenCV to identify objects such as buoys and to prepare headings based on the underwater guides. There are two cameras being used on the vehicle. The first is a forward facing camera, an Occam Robotics Omni60. The second is a downward facing cam, a Point Grey Blackfly. These will be implemented with three main ROS packages. The first packages, DownCam and Occam will read in video data from our machine vision cameras, and translate the image into a ROS mat message in the OpenCV mat image format. Then this message will be published for the machine vision package. Our machine vision package will accept image from both the downward and front facing camera and identify objects using blob detection algorithms, and a Hough transform to identify paths depending on the camera, and current stage of the mission planner.

Figure 6: Occam Robotics Omni 60, Panoramic Camera.

C. *Experimental Results*

Testing has been conducted at all stages of the design a building process of our vehicle. Each system was required to pass benchmarks prior to being integrated on the vehicle.

The mechanical team began testing in SolidWorks using the simulators provided to test how resistant to stress each enclosure was. Then after machining team members tested sealing surfaces with, and without O-rings to make sure tolerances were being met. Any additional machining was then conducted to allow for good fits. These tests were subsequently repeated after anodizing. Also, all threaded surfaces had at least one dummy connector placed inside to test that the correct taps had been used.

The electrical team conducted extensive tests of the custom boards. The high current board was tested for stability under a variety of heavy loads and battery input voltages. Through this testing the electrical team discovered key design changes that were implemented in a second revision of the board. The low power board was tested in a similar manner after the high voltage board had been verified. Once again this testing provided key insight to problems such as parasitic capacitance, which was rectified the boards second revision.

Finally the software team built and verified individual ROS packages as they were built. Each member of the team-designed packages in their own version controlled workspace. These workspaces were later combined. Light simulation in Gazebo is also being tested, as this simulator is a core reason why we chose to work in ROS.

The team plans to begin water based testing starting in early July with mechanical work completely finished, and motors working. The integration of our sensors will continue as we approach the competition.

D. *Acknowledgements*

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