Cornell University Autonomous Underwater Vehicle: Design, Implementation, and Strategy of the Polaris and Leviathan AUVs

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***Abstract*—Polaris and Leviathan are Cornell University's vehicles for the AUVSI RoboSub 2023 competition. Our focus this year was on improving the reliability of the vehicles, which involved a tradeoff between simplicity and cost. Polaris represents a daring step forward, with numerous subsystems redesigned for reliability. Its mechanical frame allows for easy access to core components, strength, and maneuverability. We added a new ZED depth-sensing camera enclosure to enhance mission reliability, and the mechanical actuator systems now utilize a hydraulic system. The electrical system has been redesigned with a stronger power delivery system. Software improvements include optimizations and new libraries to enhance task completion consistency. In terms of strategy, Leviathan's role was modified to complement Polaris' capabilities.**

I. Acknowledgments

CUAUV would like to thank all the individuals and organizations who have supported us over the past year, including Cornell's MAE, ECE, and CS departments.

Thank you to the Fischell family for their ongoing support and for sparking a lifelong interest in AUVs in our team members. CUAUV would especially like to thank our adviser: Professor Hunter Adams. Special thanks to the Director of Cornell Aquatics, Brigitta Putnam; the MAE Director of Instructional Laboratories, Matt Ulinski; Cornell Engineering's administrative staff, especially Kae-Lynn Buchanan Wilson and Karen Prosser, and last but not least, the Cornell Rapid Prototyping Lab (RPL). For their tremendous support in the absence of a Swanson Project Team Director, we would like to give special thanks to Lauren Stulgis, Kate Reiter, and Gibran el-Sulayman.

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References

[1] Kim J-H, Kim N, Park YW, Won CS. Object Detection and Classification Based on YOLO-V5 with Improved Maritime Dataset. Journal of Marine Science and Engineering. 2022; 10(3):377. https://doi.org/10.3390/jmse10030377

II. Competition Goals

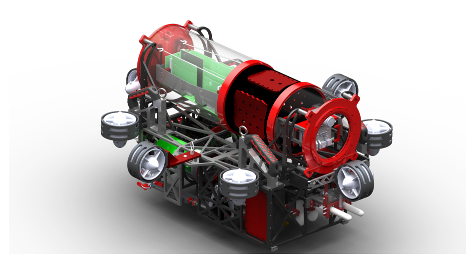

Fig. 1. Polaris

CUAUV continues to be a team that prioritizes learning. By rebuilding our vehicles each year, we can maximize how much our members can learn and ensure that the knowledge we have acquired throughout the years continues to be passed down to the newer members. The team designed Polaris to be capable of completing every task, which is a rich learning experience and an endeavor that poses numerous challenges.

Following Robosub 2022, the team reflected on the task division between Leviathan and the soon-to-be-built Polaris. Since CUAUV will have 2 AUVs in competition, the tasks will be divided in the interest of time. Polaris will focus on *Location*, *Goa'uld Attack*, *Engaging Chevrons*, and *DHD* because it is equipped with a more sophisticated sensing suite featuring a DVL and a new ZED depth-sensing camera. These tools allow Polaris to execute actions more precisely and extract more information from its environment, allowing for more informed decision-making. On the other hand, Leviathan is light and agile. Leviathan will attempt *Oh for crying out loud* and *Destination* with style points. The above strategy leaves Polaris with more time to complete complicated tasks and distributes risks. If the team decides to restart one AUV's run, the other AUV's score will not be affected.

III. Design Strategy

A. Mechanical Systems

1) Downward Capabilities: From Robosub 2021, the team noticed that it was difficult to gauge distance with the downward camera. To tackle *Location* with increased precision, we decided to use a camera with binocular vision to improve the depth perception of our sensing system. Adding this larger camera, though, pushed us to think outside of the box. The new camera is considerably larger than previous ones and has a rectangular shape, meaning we would have to make a very different kind of camera enclosure *(fig 2.)* The camera enclosure also needed to be connected to our main hull not to have any data loss in the electrical connections. To achieve these objectives, the camera hull is larger and wider and has a stem that attaches it to the main pressure vessel. It required us to hone our manufacturing skills with a CNC milling machine and to think critically about our frame design.

In conjunction with using a more effective camera, this year, we are also adding LED lights so that there is more constant lighting. In the same vein of increasing the reliability of our camera system, we added a color palette that can be fit onto a previous camera enclosure to act as a color reference.

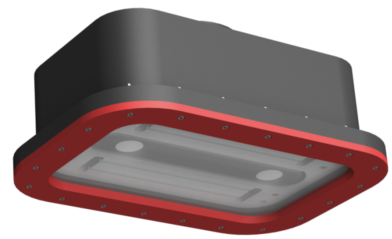

Fig. 2. Camera enclosure containing the binocular vision camera

2) Hydraulic Actuation: Another big change this year was changing from a pneumatically-powered actuation system to a hydraulic-powered system. The pneumatic system used many paintball parts since they were a good size and fit for our components. However, these parts were becoming unreliable and harder to source. Therefore, we decided to move to hydraulic lines *(fig 3)*. By using this new system, we no longer rely on buying or accessing pressured air tanks, making testing much more efficient.

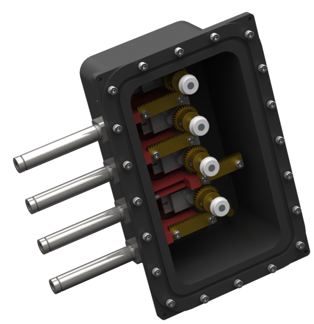

Fig. 3. Servos create the hydraulic pressure for actuation

The new hydraulic system pushed our innovation and design process. We needed to provide a reliable and quantifiable displacement to the hydraulic lines to have the greatest amount of control over them. Our solution was to use pistons that would be connected to a rack and pinion. We could use servo motors to power the rack and pinion, thus having an exact control over the displacement.

3) Kill Switch: To increase the reliability of our kill switch *(fig 4.)*, we have moved to use off-the-shelf parts from Blue Robotics. In the past, we have had issues with our kill switch being over-engineered and having many components; this meant that it could be unreliable. Using an off-the-shelf part for the kill switch meant we only had to machine an enclosure to mount the switch, which meant that we had to make fewer parts.

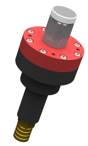

Fig. 4. Kill Switch

B. Electrical Systems

Polaris and Leviathan feature nearly identical electrical systems with interchangeable PCBs. Each custom PCB was designed, populated, and tested by CUAUV's electrical subteam, with the custom circuitry on each board going through numerous design cycles and reviews. This process has not only allowed us to identify hardware or firmware bugs with our boards but has also helped establish CUAUV's environment of fostering knowledge and experience for our members in order to develop a full electrical system. Both submarines' electrical systems have been redesigned to be as similar as possible, which has helped us streamline and simplify our vehicles' design, testing, and maintenance. With nearly identical electrical systems between Polaris and Leviathan, boards can be swapped between vehicles, thus providing our team with more flexibility when electrical issues arise.

1) Backplane System: CUAUV's backplane system uses multiple backplane PCBs to facilitate integration of our custom PCB boards. Both Polaris and Leviathan have two backplanes each: one for connecting and powering the PCBs, and another SEACON backplane for linking the PCBs to the onboard Jetson TX2 computer, external sensors, and mechanical subsystems such as thrusters. These dual backplanes enable plug-and-play capabilities and streamline testing for proper connections between the PCB boards and external devices. The traces and power planes on the backplanes were modified this year to be larger, thus allowing electrical components to draw more current without the risk of the backplane burning due to overcurrent. See *(fig 5.)*

2) Onboard Power Delivery: Polaris and Leviathan each use two 10000 mAh lithium-polymer batteries, providing 16V to the merge board. The merge board balances voltages and distributes 16V to other boards, like the thrusters or actuators board, which power external mechanical systems. The DCDC board converts this 16V to

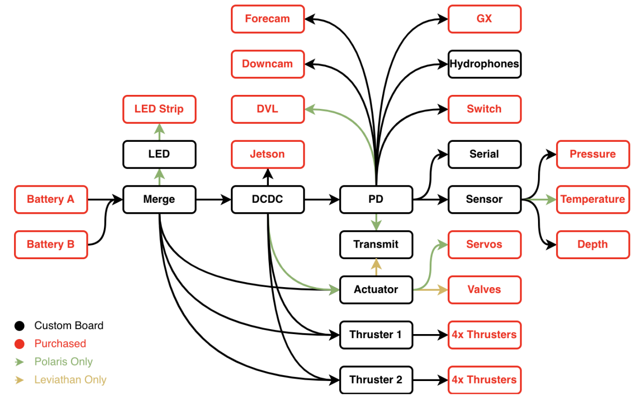

Fig. 5. Flow of power through Polaris and Leviathan

12V and 6V for other boards, such as the power distribution board (PD). PD controls the vehicle's subsystems by enabling or disabling its onboard channels.

The electrical subteam redesigned the merge power board to address previous power management issues this year. The new merge board includes enhanced current protection to prevent overcurrent during complex vehicle movements. It features power MOSFETs capable of handling up to 60A of continuous current, a larger connector for increased current draw from the batteries, and additional fuses for surge protection. An added hall-effect current sensor provides accurate readings from the battery. The updated merge board also includes LEDs for clearer kill logic indication during mission runs, reducing power issues and improving testing efficiency *(fig 6.)*.

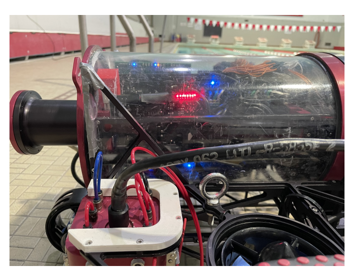

Fig. 6. Merge board LED status in Leviathan

3) Acoustics Communication System: Polaris and Leviathan each have their own hydrophone systems to detect submerged pingers and determine their heading. The updated hydrophones board now includes four transducers instead of three, and the firmware has been modified to enhance the speed of

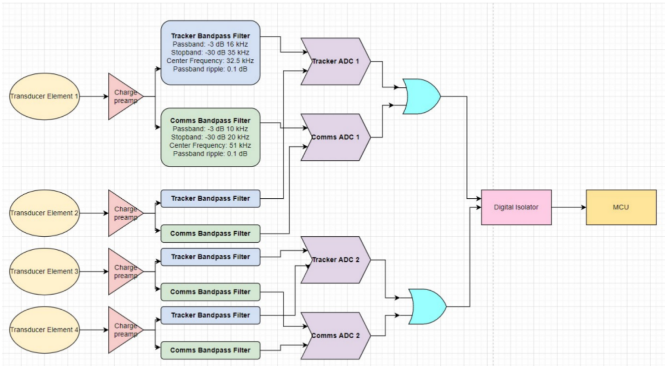

Fig. 7. Acoustics signal processing flowchart

digital signal processing for pinger localization *(fig 7.)*. The addition of hardware filters helps eliminate environmental noise. Both submarines also feature onboard transmit systems using piezoelectric transducers for intersub communication.

C. Software Systems

1) Vision Pipeline Framework: The vision system is responsible for collecting and routing sensory data (video frames) from the cameras through a pipeline and into the system for vision modules to use. The vision module results are then fed into the SHared Memory framework (SHM), which is responsible for passing messages on the AUVs. Since hardware limitations only allow a single process at a time to access a camera, the software stack maintains a shared buffer employing a one-writer multiple readers system. This framework underwent significant changes this year to improve reliability and performance. More efficient locking of shared resources between threads avoids race conditions and deadlocks. An additional/new socket communication protocol between our WebGui and vision modules decreases CPU usage. The result is higher frame throughput and smoother videos.

2) Consistency: Even while using YOLOv5, our subs are unable to recognize mission elements in every frame. And lighting inconsistencies and small sub movements can introduce noise into our estimations of the positions of objects. This can cause the sub to become confused and mess up its mission plan. To address this common challenge, we built a new framework this year for consistently tracking object positions over time. Using Lloyd's algorithm, this framework reduces the noise in our detection positions and also helps the sub remember the position of objects even when recognition temporarily fails.

3) Machine Learning: CUAUV has traditionally used OpenCV techniques for computer vision. Although these work well in practice, the team discovered that minor lighting changes led the algorithms not to recognize the elements reliably. Over the past year, the team developed a machine learning pipeline, including a hosted tagging server to generate data to train YOLOv5, the image recognition algorithm.

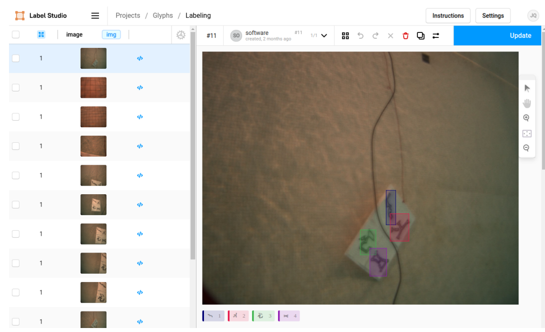

Fig. 8. Label Studio hosted on our server

IV. Testing Strategy

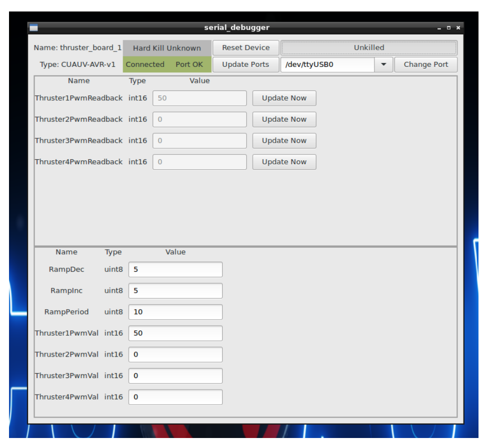

Fig. 9. Serial debugger.

Polaris and Leviathan's custom PCB boards undergo in-house testing using our developed serial debugger. *(fig 9.)* This debugger connects the board to our laptops via UART communication protocol. With the serial debugger, we can set variable values in the board's firmware and verify the expected behavior through status LEDs or oscilloscope readings. To ensure proper integration of connectors linking the board to the submarine, we employ a digital multimeter to check for continuity.

For sensor validation, the electrical subteam connects the board to the submarine. Using the software subteam's control helm *(fig 10.)*, we read measurements from sensors like the inertial measurement unit (IMU) and Doppler velocity log (DVL). Scripts are utilized to read data from sensors such as the pressure sensor. The electrical team compares these readings with the submarine's actual position in the water, adjusting the sensor board's firmware until the values align with the vehicle's real-time motion.

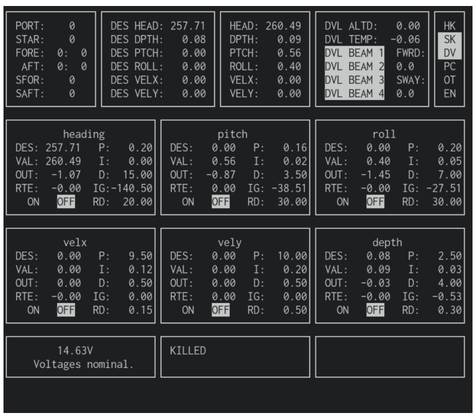

Fig. 10. Software control helm telemetry.

Mechanically, every design is tested both in simulations and in an intensive leak test. Enclosures and parts are simulated under pressure in SolidWorks CAD Simulations. Simulations include both normal operating pressures at 20 ft, but also at 50 ft. This higher pressure simulation is to model extreme conditions or emergencies, like if the AUV sinks while being tested *(fig 11.)*.

We also run drop tests and ramming tests. We model the forces that would be applied to the part if it were being carried and dropped by mistake or if it accidentally ran into a wall of the pool. These tests are unique to the enclosure because it depends on their location in the frame to understand how forces will be applied to them.

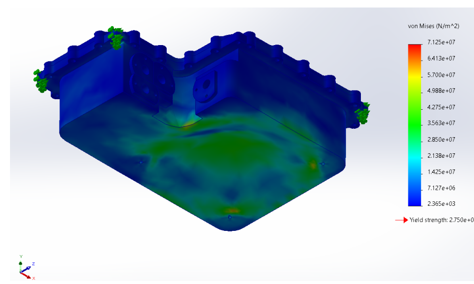

Fig. 11. Simulation of the hydrophone enclosure at a depth of 50 ft.

Appendix A.

Component	Vendor	Model/Type	Specs	Source	Cost	Year
Buoyancy Control	Home Depot	Owens Corning Foamular 250	Pink insulating foam	Purchased	N/A	2018
Frame	Datron	Custom aluminum waterjet	Custom	Custom	$600	2023
Waterproof Housing	In-house	CNC	Custom	Custom	N/A	2023
Waterproof Connectors	SEACON	HUMMER/WET-CON	Dry/Wet connectors	Custom	$1,675	2018
Thrusters + Propellors	Blue Robotics	T200	Brushless Thruster	Purchased	$2,311.92	2018
Motor Control	Blue Robotics	Basic ESC	Speed Control	Purchased	$400	2018

High Level Control	In-house	6-DOF Dual Quaternion and YPR	Linear Least Square PID	Custom	N/A	2015
Actuators	Pololu	HD-1900A	180 degree servo	Purchased	$32	2023
Battery	HobbyKing	Multistar High Capacity 4S	LiPo Battery	Purchased	$165.90	2018
Converter	CUlinc	PDQ30-D	Iso 5V DCDC	Purchased	$34.94	2018
Regulator	Texas Instruments	LM3940	3.3V 1A SOT-223-4 LDO	Custom	$1.65	2018
CPU/GPU	NVIDIA	Jetson TX2	Six 2GHz Arm8 Cores	Purchased	Sponsored	2018
Compass and IMU	LORD Microstrain	3DM-GX3 / 3DM-GX5	AHRS	Sponsored	Sponsored	2018
Doppler Velocity Logger	Teledyne Marine	Pathfinder DVL	DVL	Purchased	$11,995	2018
cameras	IDS	UI-6230SE UI-5140CP	cameras	Sponsored	Sponsored	2018
ZED camera	StereoLabs	Zed 2i	cameras	Purchased	$499.99	2018
hydrophones	Teledyne Marine	RESON	Acoustic transducers	Purchased	N/A	2018
vision algorithm	OpenCV	OpenCV4	Transparent GPU Support	Open Source	Free	2023
Acoustics	CUAUV	Custom DSP	—	Custom	Free	2023
Localization and Mapping	Mur-Artal	ORB-SLAM2	—	Modified	Free	2023
Autonomy	CUAUV	Mission planning system	—	Custom	Free	2023
Software	CUAUV/ FSF	GNU	—	Custom	Free	2023