Technical Overview of the Development of Modular, Extensible Autonomous Underwater Vehicles WAILORD and LANTURN

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1. ABSTRACT

Information and experience from previous years' competition robots is collected and analyzed to reveal faults in design strategies, which has been used to guide the development of RoboSubLA's new vehicle WAILORD, and re-development of our vehicle LANTURN. (1) First, system modularity is identified as the primary goal of vehicle development, intending to avoid standing issues of robot reuse between years. Weight reduction is also prioritized to allow for maximum mission payload capacity. (2) Second, revisions are made to the power distribution system in both robots, with improvements in both total available power and overall system reliability. (3) Third, our previous control systems are redesigned to be vehicle-agnostic, utilizing a physically based thruster allocation system to enable code reuse between vehicles. (4) Fourth, an enhanced sensor package consisting of improved IMUs, DVLs, and robust computer vision is deployed to both vehicles. (5) Finally, our state machine autonomous subsystem is replaced by a more capable behavior tree implementation, allowing for fallback and repeated states, improving task performance.

2. COMPETITION GOALS

Our competition strategy for WAILORD focuses on modularity and ease of access for all components. One way we have accomplished this is by the use of standardized, 3D printed clamp pieces used to hold various mounts and brackets to the carbon fiber rods in WAILORD's frame, allowing for many components to be installed, relocated, and removed when needed.

For LANTURN, the strategy focused on building a hull completely of aluminum to act as a full body heat sink to solve the common problem of overheating. To complement the aluminum hull, we designed a wrap-around cage that provided the versatility needed to attach all components.

3. DESIGN STRATEGY

A. MECHANICAL

I. FRAME

The key design feature of WAILORD is a modular frame with removable hulls. The central hull also features a removable electronics rack. WAILORD's primary structure is formed by four 6061-T6 aluminum plates, six carbon fiber rods, and customized 3D printed clamps and brackets. WAILORD's 3D printed locking mechanism on each pair of plates allows us to open the frame, providing direct and easy access to the hulls. All vertical and angled thruster mounts are 3D printed, allowing us to relocate thrusters along the length of the carbon fibers rods if desired. The electronics rack has been designed to open like a book, allowing us to reach electronic components on the interior of the electronics rack. The design also includes more workable surface area than a flat plate, and has allowed us to rearrange components to optimal configuration.

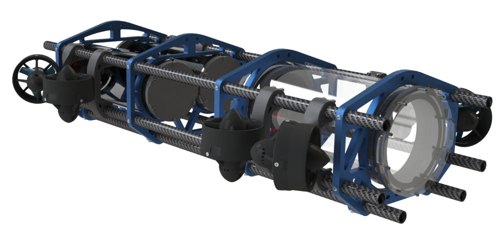

Figure 1. *WAILORD Render*

LANTURN's new 2023 design features an exterior cage design that prioritized manufacturability and weight reduction. The design is made up of sheet metal aluminum for its lightweight and strength, and it has several waterjet cutouts to further reduce the weight. The cage is made from sheets of 1/8” and 1/4” thickness that is mounted along the edge perimeters of the hull using stainless steel screws. This avoids any obligation to drill into the hull for any needed mounting. The external cage protects and supports all the crucial elements of the vehicle. It provides rugged legs, thruster mounting locations, universal mounting locations for sensors and actuators, designated rigging locations, fully devoted handle placement, and it serves to evenly distribute the loads on the hull.

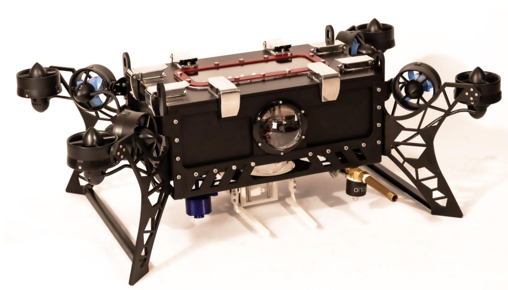

Figure 2*. LANTURN Photo*

The hull of LANTURN is made of 6061-T6 aluminum to help with cooling of electronics. It features several material cutouts throughout that have the purpose of weight reduction. Pressure vessel FEA reports were conducted to examine how the cutouts would affect the integrity of the hull. Most of the machining of the hull and lid were done on a 3-axis CNC and a horizontal mill. The watertight enclosure of the hull was designed using face type O-rings and gland cavities. A vacuum test was conducted to check for leaks in the watertight enclosure.

The design of the electronics carriage revolved around accessibility and functionality. The design criteria were that it needed to have enough space for all the internal electronics including a large battery, to be removable from the hull, user friendly for diagnosing electronics, and the battery must be rapidly exchangeable. The structure needed to be strong enough to support the heavy 3.89 lb battery. Thus, a combination of carbon fiber rods, laser cut acrylic, and 3D printed parts were used for the assembly.

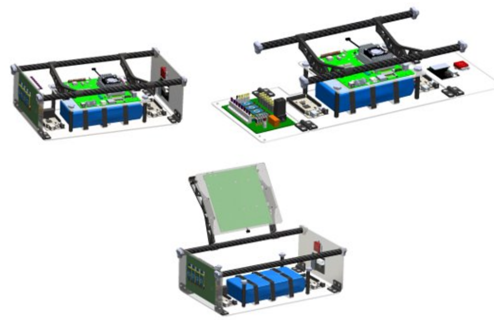

Figure 3*. The electronics carriage features 3 modes to meet the design criteria. Mode I, is for transport. Mode II, is for troubleshooting electronics. Mode III, is for quickly swapping the battery.*

II. ACTUATORS

The actuated systems required designing and building a robotic claw, a ball dropper, and a torpedo launcher. These systems are designed to successfully complete tasks that are needed during competition. The claw and dropper both utilize 3D printed components with servo motors, while the torpedo utilizes pneumatics. FEA’s and CFD’s were produced to certify the proper performance of the systems. The actuated systems team worked together with the computer vision and autonomy teams to ensure the actuators are designed for maximum ease in usage.

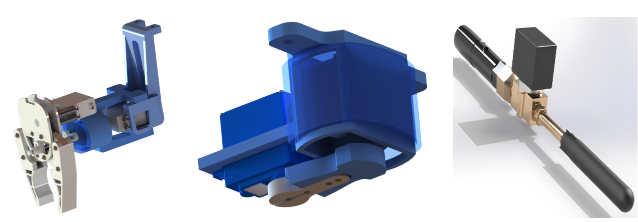

Figure 4*. Claw, Dropper, and Torpedo Systems*

B. ELECTRICAL

I. POWER

The electrical system on both robots consists of a thruster signal routing board, power distribution board, microcontroller, and sensor suite which are powered by a 14.8V 20Ah LiPo battery.

The sensor suite includes:

- VectorNav VN-100 IMU
- Blue Robotics Bar30 Barometer
- Aquarian AS-1 Hydrophones
- Blue Robotics Ping Sonar
- Blue Robotics USB Camera
- Teledyne Wayfinder DVL

This year, both robots include a Jetson TX2 on a Quasar Carrier Board. We've also designed a new, custom power regulator board, with LEDs, surface mount devices (SMD), and multiple output lines. These changes were made as improvements to last year's regulator board that only had one output and fuse line, with no indicator LED linked, which caused a lot of problems with shortage. With multiple outputs, we are able to have separate voltages and currents for each line, such as 9A for 5V and 3A for 9V.

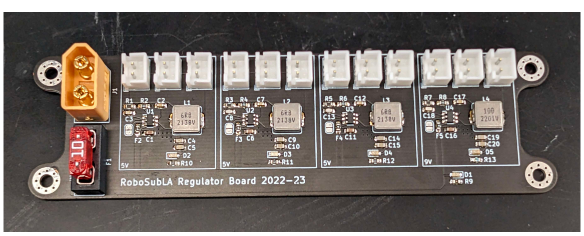

***Figure 5**. Custom Power Regulator Board*

In order to solve the overheating problem of our robots from previous years, LANTURN was mechanically designed to have the frame as a heat sink, and WAILORD incorporates an active heat pipe cooling system around the electronics components.

II. INTERVEHICLE COMMUNICATION

With the construction of two new robots this year, an intervehicle communication system (IVC) was developed. This system consists of three major categories, a transmitter, receiver, and communication method. For our implementation, acoustic waves are used, with LANTURN housing the transmitting electronics, while WAILORD houses the receiving electronics.

On the side of the transmitter, a custom transducer and custom power board were created. The transducer consisted of a 65kHz PZT cylinder potted in electrically insulative epoxy. The mold and spacer used to hold the PZT in place during the potting were machined on the lathe and vertical mill from PTFE. A custom power board was also built to take voltage inputs from the Teensy and create a high voltage sine wave for the transducer.

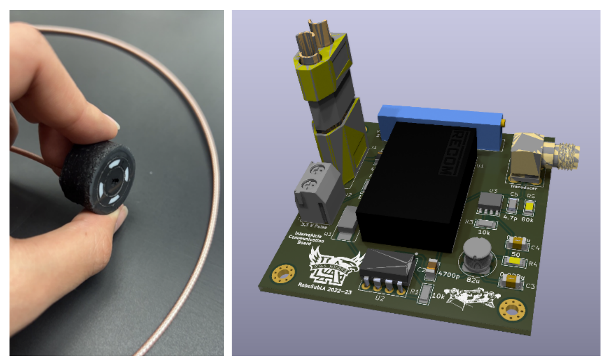

***Figure 6.** IVC Transducer and Power Board*

In order for data to be transmitted between the robots, frequency-shift keying (FSK) is utilized to modulate the signal between 60kHz and 65kHz. For the receiver, a commercial hydrophone is used to collect the sound from the transmitter. This voltage signal is then connected to our custom made hydrophone board which adjusts the voltage between 0V and 3.3V to be read and demodulated by the other robot's Teensy.

C. SOFTWARE

I. CONTROLS

This year, in order to streamline current and future developments, a custom controls carrier board was developed which includes a Teensy 4.0 module with a CORTEX-M7 32-bit ARM microcontroller onboard running at 600 MHz. This allows us a significant headroom for software development, as even somewhat inefficient implementations will run at far greater speeds than needed. The controls carrier also includes locking board to board connectors for multiple communication buses, including I2C, SPI, and UART for communication with sensors and other subsystems.

In order to simplify the development of both vehicles' control software, a significant portion of time this year was dedicated to developing subsystems that allow identical software to be deployed irrespective of the differences between vehicles. To accomplish this, many components of the software are abstracted by one or multiple layers, and configuration parameters per frame are stored in each vehicle's control board EEPROM.

The most obvious component of this vehicle androgyny is the thruster solver, a clever implementation of matrix multiplication that allows a six-component control vector (comprised of 3 axes each force and torque) to be converted into an output vector with components corresponding to individual thruster force requirements, dynamically allocated based on vehicle thruster positioning. Each thruster's individual force is then converted to an output signal compensated for battery voltage and forward/reverse thrust differences, and sent to the PWM generator onboard each vehicle's thruster board.

II. AUTONOMY

This year, we have transitioned from using State Machines to Behavior Trees for implementing the high-level behavior on both WAILORD and LANTURN. This transition improves the modularity, execution flow, flexibility, error handling, readability and overlap of our two autonomous systems.

Drawing from the success of last year's state machine implementation, we have deconstructed and redesigned last year's system to adapt them into the Behavior Tree Framework. By reusing nodes that have proven to be successful, we have been able to refine the behavior of our systems while simultaneously improving the development of additional software through the advantages provided by the new behavior tree implementation.

For our behavior tree implementation, we used the *Behavior Tree V3* library which provides execution control nodes, such as sequence, parallel, and decorator nodes [1]. These execution control nodes allow for greater control over the execution of the structure of the tree, enabling our system to be more flexible and allowing for better design of execution nodes for specific tasks required from WAILORD and LANTURN. Furthermore, this library provides tools that allow for rapid creation of reusable behavior subtree structures. This capability enables us to break down tasks into smaller behavior nodes that allow for reusability of smaller behavior nodes and more detailed construction of behavior trees. Overall, the new framework allows for faster debugging and development during testing and competition runs.

This year, the strategy is to give different tasks to each of the robots to increase the efficiency of the competition runs. LANTURN will do the task requiring a claw, mainly the *octagon* task, and

WAILORD will do tasks requiring torpedoes and the dropper, that is, the *torpedo* and *bin* tasks.

Testing the autonomous system has been a huge obstacle because of the requirement for other systems to be completed and the nature of the environment we need to test on. An effort has been made this year to overcome that obstacle by developing a simulation based off of *Project DAVE [2]*. This software is in the early stages of development and could not be used for progressing the autonomous system this year. However, our robot has been inserted into the platform and documentation has been created to serve as a base for future years to continue the development.

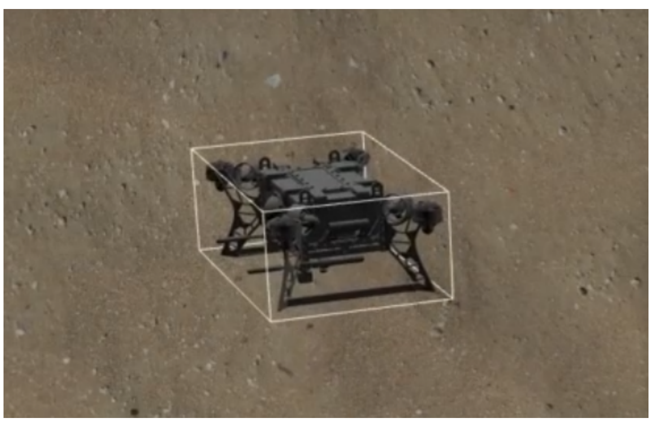

Figure 7. *LANTURN in Project DAVE Simulation*

III. COMPUTER VISION

The implementation of computer vision for WAILORD relied on the You Only Look Once (YOLO) Version 7 Convolutional Neural Network (CNN) in addition to the Python library OpenCV. YOLOv7 was decided with considerations to the Nvidia Jetson TX2 device within the submarines. YOLOv7 is the most recent official release which is substantial since it derives its architecture from its preceding instances, such as YOLOv4 which we used last year, and optimizes for the prioritization outperforming "... DETR, Deformable DETR, DINO-5scale-R50, ViT-Adapter-B and many other object detectors in speed and accuracy" [3]. In determining which CNN to use, we revisited YOLOv4 with the same annotated dataset of 1000 images. In the training process, we learned that the mean average precision of the object detection model trained with v4 was marginally better than v7 (96.423 vs. 96.318), but much slower in training and inference. Additionally, Version 7 is defined in Pytorch which is lightweight and efficient for the computational constraints. For OpenCV, we leveraged various algorithms for applying augmentations to the images in our dataset including, but not limited to Gaussian blur, cropping, shifting, adding static and grayscale. Electing to keep augmentations more cosmetic and not changing orientation was intentional to enable us to create orientation (90°, 180°, 270°) classes for each object.

Figure 8. *Example of Additional Class to Determine Object Orientation*

Doing so enables us to pass positioning information to determine navigation and adjustments of the submarine as needed, which we lacked last year. Moreover, we used OpenCV to extract and save frames from WAILORD's cameras. In preparation and training purposes, we reconstruct the provided obstacle objects, take underwater videos to best simulate competition conditions, extract at least 1000 frames before augmentations, annotate and then train to build our custom models.

4. ACKNOWLEDGEMENTS

Our team would like to thank our faculty advisors, Dr. He Shen, Dr. Mike Thorburn, Dr. Mark Tufenkjian, and Richard Cross for their invaluable inputs to our project during review sessions and team meetings. We would also like to thank Cal State LA and the ECST department for their continuous support of our RoboSub team. Our team is extremely grateful to our sponsors who supported this project through hardware donations and generous discounts. These include the Office of Naval Research, VectorNav, Blue Trail Engineering, Blue Robotics, MathWorks, and Dassault Systemes. Thank you for making the development of our 2023 RoboSub vehicles possible!

5. REFERENCES

[1] M. Colledanchise and P. Ögren, Behavior Trees in Robotics and AI: An Introduction. Boca Raton: CRC Press, 2020.

[2] Project DAVE, https://field-robotics-lab.github.io/dave.doc/ (accessed Jun. 16, 2023).

[3] C.-Y. Wang, A. Bochkovskiy, and H.-Y. M. Liao, “Yolov7: Trainable bag-of-freebies sets new state-of-the-art for real-time object detectors,” arXiv.org, https://arxiv.org/abs/2207.02696 (accessed Jun. 16, 2023).