Hammerhead Technical Design Report

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***Abstract*—The documents the design goals for the RoboSub 2024 Competition. With the goals of reliable movement in six-degrees of freedom, and basic object localization while submerged. These goals were achieved in the previous revision of the AUV. Replicating the results from the previous revision in the new frame will provide the foundation for additional systems in future revisions.**

I. COMPETITION GOALS

A. *Starting Place*

The starting place of this design iterations process, the Autonomous Underwater Vehicle (AUV), had reliable a functional Mechancial Design. A complete overhaul was performed between the 2023 and 2024 competition years. The mechanical aspects of the AUV were enlarged to allow for more systems and improve reliability. The power regulation and distribution was over hauled for the first time since 2013 to improve efficency and reliablilty. The high level and low level communication protocols were improved to decrease signal loss, increasing reliability.

B. *Primary Goal: Construct new AUV*

1) Build new AUV

The team has endeavored to build a new mechanical frame and housing for the AUV. The new frame and enclosure should provide more internal space for future systems, as well as improved protection for thrusters.

C. *Auxiliary Goal: Replicate Reliable Movement Control in new AUV*

1) Motor Control

The motor control design objective was to establish an effective method of controlling the revolutions per minute (rpm) of each of our eight vectored T200 thrusters.

2) Control Movement in the Rotational Axes

The second design milestone was to establish reliable movement across all rotational axes on the surface of the water. This was required prior to other movement profiles because the tuning of the other PIDs will be dependent on the angle of the thrust vectors. Therefore, the pitch, roll, and yaw must be controlled.

3) Control Movement in the 2D Plane

The third milestone was control navigation in a 2D plane on the surface. While it is a competition requirement to submerge, these tests were conducted on the surface for easier observation and testing. For all practical purposes, navigation on the surface is identical to navigation when submerged.

4) Control Submerging and Surfacing

Finally, the AUV is required to conduct the operations for competition while submerged. This as simply accomplished by adding a control effort to apply a force against the force of buoyancy with the thrusters.

II. COMPETITION & DESIGN STRATEGY

A. Gate

The first objective to overcome is to solve the gate task. This is a prerequisite to solving other tasks. The current strategy is to use our scanning sonar to find where the gate is relative to the AUV.

B. Coinflip & Style

The Coinflip and Style tasks complement our updated controls software. The task will serve to demonstrate our heading navigation and sensing capabilities.

C. Buoys

The buoys tasks are near the limit of our current capabilities. While the identification part of the task is beyond our current capabilities, the localization portion of the challenge will utilize both our updated control system and sonar capabilities.

D. Octagon

In conjunction with estimated position of the octagon, the doppler velocty logger (DVL) is able to accruately track the 3d position of the AUV and match that the to position of the octagon before surfacing.

III. TECHNICAL SYSTEMS

A. High Level System

The last generation communications framework reached End of Life (EOL), in Spring of 2023 a transition to the ROS2 platform began to ensure long-term stability of our system. To implement the novel framework, refactoring all systems designed for the ROS interface for the next generation ROS2.

The code based was divided into two primary domains: Data Management and Algorithms & Auxiliary Logic. The Data Management domain dealt with messages, services, actions, publisher, and subscriber interfaces. Additional device interface packages developed in-house were written such that communications with the device and device native behavior were taken care of in one device class. This device class is completely independent from any of our middleware. Therefore, a simple wrapper for the communication middleware would be the only integration effort necessary.

The Algorithms & Auxiliary Logic scripts function as system controllers. In previous revisions this would send commands to the motor’s Pulse Width Modulation (PWM) based control board, and the on-board scanning sonar. In the current revision, mission planning and other high-level algorithms will be used to control these functional commands. In previous revisions, the completion of competition objectives was directed by python scripts implementing a timing-based method of execution.

Hammerhead will be the first AUV to utilize a mission planner. Hammerhead utilized a behavior tree (BT) based mission planner. The planner possesses a BT for each task. These task-behavior-trees (TBT) are implemented into a unified-behavior-tree (UBT), which controls the AUV and directs craft maneuvering and ensures compliance with required safety metrics defined by the designers and any other supervising bodies.

B. Low Level Communication System

The low-level communication system handles the transmission of movement commands from the high level UBT to the individual motor controllers. In previous revisions, a pulse width modulation (PWM) signal was used to communicate to the motor controllers. In this revision, a controller area network (CAN) based network was chosen to increase reliability. Previous revisions of the low-level communication system have been the most frequent point of failure, and CAN is known for its reliability, decreased use of wire harnesses designed to maximize space efficiency in the small internal volume of the AUV.

This adoption and integration process took significant manhours and resulted in the implementation of a CAN standard known as OpenCyphal. CAN, like ethernet, is a differential signal. This method allows noise to be removed when being received by subtracting the voltage of the high line from the inverse of the low line. This method effectively filters noise from the signal data. This provides a signal resilient against the electromagnetic field (EMF) induced by the ESC and the three phases alternating current (AC) leads running the length of the electrical compartment in Hammerhead.

CAN transmissions are based on the CAN frame. CAN relies on a main trunk/pair running from start to finish on the network accompanied by a 120ohm termination resistor on each end of the backbone to prevent signal reflections. The backbone has small branches to connect each device in the network, as of now only the motor controllers are on the CAN network.

C. Computer Vision with Feature Point Detection

Hammerhead utilizes computer vision to classify objects detected in its area of operations (AO). The first algorithm option that has been developed and implemented is based based on feature point detection as implemented in OpenCV.

Feature point detection is a crucial aspect of computer vision that can enhance the reliability and robustness of object tracking, especially in scenarios where object detection models like YOLO exhibit low confidence. The ability to track feature points continuously, regardless of the detection confidence level, is essential for maintaining a consistent monitoring system.

Feature point detection offers several advantages:

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Reliable Tracking: When YOLO or any object detection model has low confidence, feature point detection can still provide reliable tracking by focusing on specific points of interest on the object. This ensures that even if object detection fails, the tracking system remains functional.

Adaptability: Feature point detection can be adapted to any object detection model. This versatility allows the integration of feature point tracking with various detection frameworks, enhancing the overall tracking capability.

Continuous Monitoring: Unlike object detection, which predicts the presence and location of objects in each frame, feature point detection works continuously. This means that once feature points are identified, their tracking persists across frames, providing a more stable and continuous tracking experience.

Object Matching: This implementation allows us to match descriptors taken from feature points of specific interest and matches them to feature points in the environment. This returns all matching points, allowing us to find the object of interest.

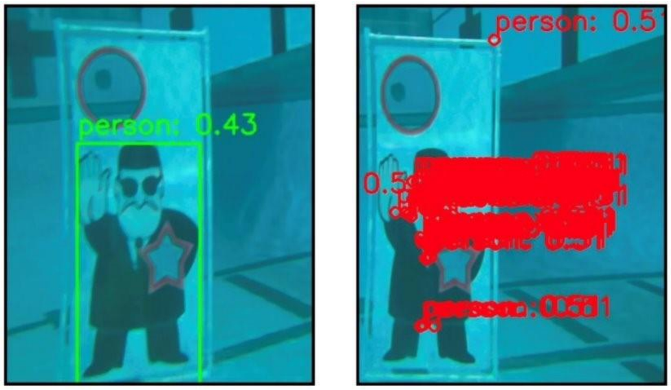

Figure 1: Feature Point Tracking on Frame of Footage Capture at 2022 RoboSub Competition

D. YOLO Object Detection

YOLO (You Only Look Once) is a state-of-the-art object detection model that provides real-time detection capabilities. The software has been expanded to include the following:

Group Normalization: Integrating group normalization into YOLO to handle datasets with long-tailed distributions more effectively. Group normalization helps in stabilizing the training process and improving the model's performance on imbalanced datasets.

E. Norfair Realtime Object Tracking

Norfair is proposed as an expansion for computer vision tasks, especially in object tracking. Its implementation offers several benefits:

Enhanced Object Tracking: Norfair provides significantly better tracking capabilities compared to traditional methods. It uses advanced algorithms to maintain the continuity and accuracy of tracked objects.

3D Bounding Boxes: Implementing 3D bounding boxes on objects helps in depth estimation and retrieval tasks. This is particularly useful in underwater environments where understanding the spatial arrangement of objects is crucial.

F. Combining Norfair and Kalman Filter with Feature Points

To further enhance the tracking system, the integration of Norfair with a Kalman Filter and feature points is proposed. This combined approach leverages the strengths of each component to create a more robust and accurate tracking solution.

Norfair for Object Tracking: Norfair provides the foundation for object tracking by using sophisticated algorithms to maintain the position and trajectory of objects. It excels in scenarios with multiple objects and varying conditions.

Kalman Filter: The Kalman Filter is a powerful tool for predicting the future state of an object based on its past states. When integrated with Norfair, it helps in smoothing the trajectory of tracked objects and predicting their future locations, which is particularly useful in dynamic environments.

Feature Points: By incorporating feature point detection, the system can maintain continuous tracking even when the primary object detection confidence is low. Feature points provide additional data points that can be tracked independently, enhancing the overall robustness of the system.

The combined approach works as follows:

Initial Detection: YOLO detects objects in each frame, and Norfair initializes the tracking process using these detections.

Feature Point Detection: Concurrently, feature points on the detected objects are identified and tracked continuously across frames.

Kalman Filter Integration: The Kalman Filter uses the trajectory data from both Norfair and the feature points to predict future locations of objects. This prediction helps in maintaining accurate tracking even when objects undergo rapid movements or temporary occlusions.

Continuous Update: The system continuously updates the tracked positions using the latest data from Norfair, the Kalman Filter, and feature point tracking. This approach ensures that the tracking remains stable and reliable.

G. *Summary of AI Algorithms*

The proposed AI algorithms and techniques for RoboSub encompass a comprehensive approach to underwater object detection and tracking. By leveraging advanced methods such as feature point detection, sonar detection with RNNs, and integrating Norfair for enhanced tracking, the system aims to achieve robust and reliable performance. The incorporation of YOLO with group normalization further ensures that the detection model can handle diverse datasets effectively. These implementations are designed to enhance the AUV's ability to navigate and interact with its underwater environment with precision and reliability.

H. *PID based Control System*

The control system is based on simple but robust PID controllers. One controller mapped to each degree of freedom. The six degrees are:

Rotational

- Roll
- Pitch
- Yaw

Translational

- Heave
- Surge
- Sway

A separate controller must be initialized and tuned to control each of these axes.

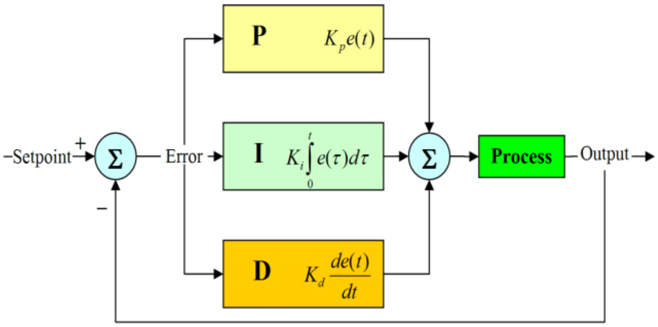

Figure 2 [3]

The PID controller works through a traditional control loop, where an error is calculated through the difference between a setpoint and a plant.

$$S - P = e \ (1)$$

Where S is the setpoint, P is the plant, and e is the calculated error.

For each of our axis, the control effort is an increase of decrease to the control signal that drives our T200 Thrusters. The tuning constant, K_p, K_i, and K_d, influence how the AUV will respond to induced error. The proper tuning parameters can be found through simulation or hardware experimentation. For this year, hardware experimentation was used to find functional parameters.

Once tuned, these control efforts were summed for each motor individually. This was done to ensure competition control efforts would reach equilibrium. For example, the thrusters that controlled pitch also controlled depth, therefore, to maintain pitch and depth, the from motors would have to apply more force than the rear thrusters.

$$\sum E = E_R + E_P + E_Y + E_H + E_{Su} + E_{Sw} \ (2)$$

Where E_R is the control effort for Roll, E_P is the control effort for pitch, E_Y is the control effort for yaw, E_H is the control effort for heave, E_{Su} is the control effort for surge, E_{Sw} is the control effort for sway. These are all summed for the control effort for each of our eight thrusters.

I. *Sonar System*

Our sonar system comprises of one sensor from Blue Robotics, the Ping360 Sonar. The Sonar driver relies on the IEEE standard 802.3u, 100Base-T. This allows for enough bandwidth and room for growth should our scanning capture and/or processing algorithm be required. The driver takes in a value of a max scan distance, start and end angles, and a few other parameters. The proper transducer transmission duration and sample period are then calculated using the speed of sound through water and a few other variables. The sonar then sweeps the degrees specified and broadcasts all resultant scan data onto a ROS2 Topic. Currently the scan data reception and publishing are done on a single thread. Our hope is to make this driver multi-threaded to dedicate one thread to data capture then the other to data publication and processing.

J. *Sonar Detection Algorithms*

Sonar detection leverages sonar data to understand the underwater environment, providing an alternative to traditional image-based detection methods.

IMPLEMENTATION

Recurrent Neural Network (RNN) and Autoencoder: Utilizing an RNN and an Autoencoder to process raw sonar data. RNNs are well-suited for sequence data, making them ideal for interpreting sonar signals over time. Autoencoders help in denoising the sonar data and identifying anomalies.

Gaussian Splatting for 3D Scene Reconstruction: Implementing Gaussian splatting to reconstruct the 3D scene from sonar data. This technique helps in creating a more accurate representation of the underwater environment, which is crucial for navigation and obstacle avoidance.

BENEFITS

Skip Image Processing: Directly using sonar data eliminates the need for complex image processing steps, reducing computational overhead.

Noise Removal: The RNN and Autoencoder can effectively remove noise from the sonar data, improving the clarity and reliability of the detected signals.

Environmental Prediction: Using the RNN to predict locations and movements within the environment enhances the AUV's ability to navigate and avoid obstacles.

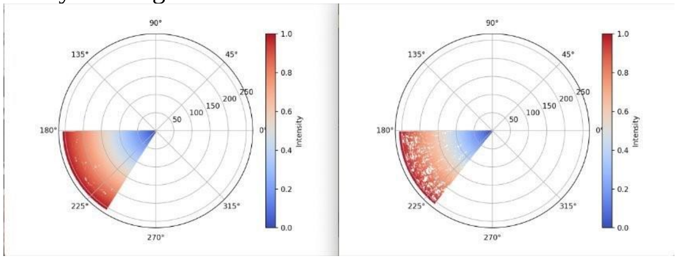

Figure 3: Sonar Data Before and After Preprocessing

K. *Improved Electrical System*

DESIGN OF POWERBOARD

To regulate the distribution of power throughout the AUV, a new power distribution board (powerboard) was created to route and regulate power from the batteries to the components. The current design of Hammerhead has every electrical component, besides the thrusters, being supplied power through the powerboard).

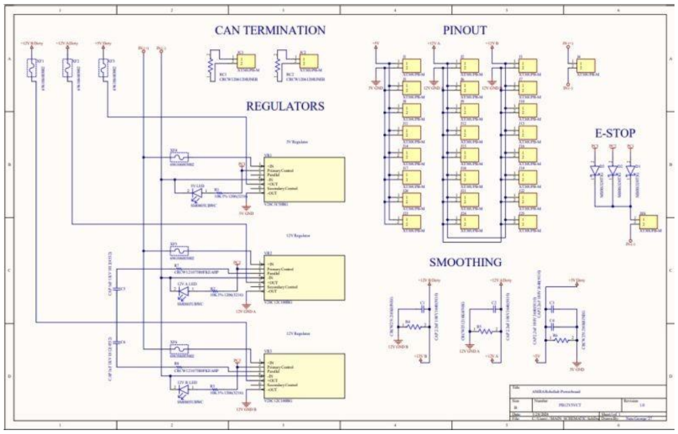

Figure 4: Improved Powerboard Schematic

The electrical system is driven by two 4-cell lithium polymer (LiPo) batteries. Each battery operates at a nominal voltage of 14.8V. These batteries are in parallel and fed into the powerboard. The powerboard features three Vicor DC-DC converters which use rapid switching to reduce the overall output voltage through a process known as pulse width modulation (PWM). Two of these converters output 100W at 12V while the third outputs 50W at 5V. These regulators models are V28C5C50BG and V28C12C100BG. Additionally, they operate at the two voltage levels required by the onboard computers and sensors. The regulators are the most expensive components on the powerboard, so they are protected on both sides by commercially available cartridge fuses. The input end is protected against a potential power surge from the LiPo batteries while the output is protected against potential overdrawing from the components, particularly on startup.

MANUFACTURING OF POWERBOARD

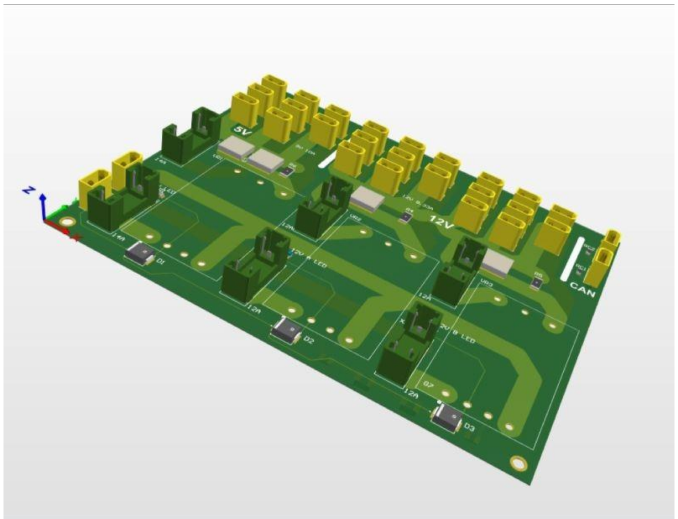

Figure 5: 3D CAD Render of Powerboard Proposal

The output also features smoothing capacitors and resistors to reduce the noise created by the PWM process which would impact the performance of the computers and potentially cause brownouts. After the smoothing circuits, the output is connected to eight XT30 connectors per regulator. These are the connection points for all the components to plug into. The powerboard includes some additional features to aid in troubleshooting electrical problems with the AUV. Each regulator has its own dedicated indicator LED confirming the normal operation of the regulator. Additionally, the regulators are all connected to a single XT30 connector located next to the input connector which serves as a disabling feature. Connecting the two pins in the connector via a relay or switch will deactivate all three regulators without needing to cut off power from the LiPo batteries. Lastly, the powerboard features two CAN termination connectors on the upper right corner of the board. Some of the components and computers on the AUV communicate via the CAN protocol, so termination connectors were implemented on the powerboard for proper termination of the signal wires.

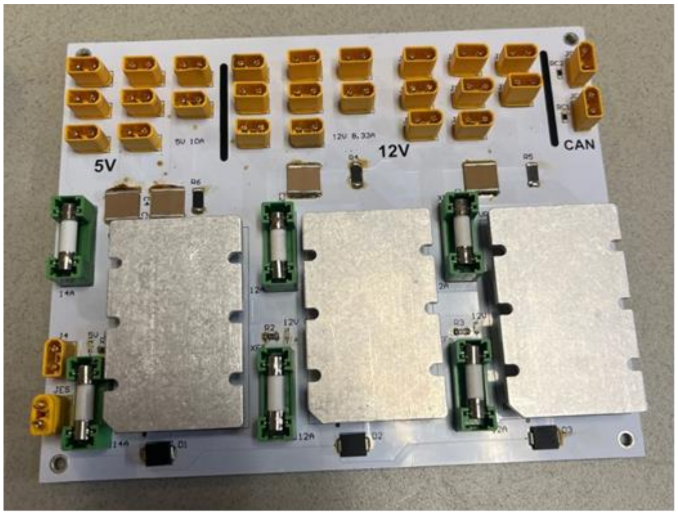

Figure 6: Photo of Completed Powerboard v1

IV. TESTING STRATEGY

A. Testing Difficulties

Testing was unable to be conducted to the latest revision of Hammerhead. Many of the mechanical systems were delayed in the machine shop for several months, leading to having no time for integration testing before competition.

ACKNOWLEDGMENT

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