RoboSub 2026 Technical Design Report

Konya Technical University (RACLAB), Konya, TURKIYE

Beyza Nur Yağcı, Hatice Kübra İlhan, Abdurrahman İnce,

Abdulsamet Han, Ahmet Selim İlhan, Mustafa Bedir Sarıtosun, Mevlüt Burak Dağlı

Abstract—

This study presents the design, implementation, and validation processes of BLASTOISE, a fully autonomous underwater vehicle developed by the RACLAB team as part of the RoboSub 2026 competition. As a newly participating team, our strategy focuses on achieving high reliability while keeping system complexity limited and ensuring successful performance in selected tasks. This approach has directly influenced the modular and hierarchical design of the system architecture.

BLASTOISE combines NVIDIA Jetson Orin Nano for high-level sensing and Arduino Mega for low-latency control, all built on a ROS 2 Humble-based software infrastructure. To reduce underwater image distortions, the object detection process was supported by contrast enhancement and color normalization techniques. Position estimation is achieved by combining DVL, IMU, and pressure sensor data with an Extended Kalman Filter. The task execution process is managed by Finite State Machines that incorporate fallback strategies providing resilience to uncertainties.

A three-stage validation process, encompassing simulation, controlled pool tests, and realistic environments, demonstrates the system's reliability and adaptability. This study provides a balanced approach between system complexity and operational robustness, laying a scalable foundation for future autonomous underwater systems.

Keywords— Autonomous Underwater Vehicle (AUV), RoboSub, ROS 2, Sensor Fusion, Extended Kalman Filter (EKF), Task-Based Autonomy

I. COMPETITION STRATEGY

A. Strategic Vision

Participating in the RoboSub competition for the first time, the RACLAB team adopted a strategy focused on controlled system complexity and high operational reliability, taking into account their limited development time and resources. The primary goal here is to develop a system that can complete selected tasks consistently and with high accuracy, rather than trying every possible task.

In this context, a comprehensive benchmarking study was conducted by examining previous RoboSub technical design reports and competition performance videos. The tasks were evaluated in terms of technical requirements, system integration costs, and expected success rates. As a result of the analyses, the Octagon mission, which requires acoustic signal processing and advanced positioning, has been excluded from this season's schedule due to its high system complexity and integration burden. Instead, the strategy has been defined to focus on doorway control, image-based target detection, and basic interaction tasks.

This task selection directly influenced the system design decisions. Accordingly, the development of a robust and noise-tolerant image processing infrastructure, the creation of precise and stable control systems, and the establishment of a modular software architecture that enables seamless switching between tasks have been identified as priority engineering objectives.

The adopted approach aims to strike a conscious balance between system complexity and reliability. This reduces risks that may arise during the integration process and ensures consistent system performance in a real-world environment.

The BLASTOISE platform is designed not only to meet current competition requirements but also as a scalable infrastructure capable of adapting to more complex tasks and multi-vehicle operations in the future.

The overall architecture of the BLASTOISE platform is illustrated in Fig. 1, while the strategic alignment of system capabilities with competition tasks is detailed in Table I.

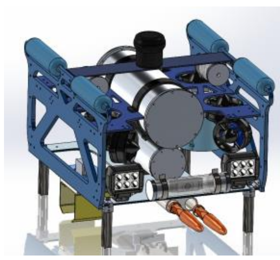

Fig. 1: Overview of the BLASTOISE Autonomous Underwater Vehicle (AUV) platform.

TABLE I. TASK-CAPABILITY ALIGNMENT MATRIX

Task	Vision (YOLO)	Navigation (DVL)	Actuation	Priority
Gate	Required	Required	Scenario I: Entry	Critical
Slalom	Required	Required	Scenario II: Search	High
Bin	Required	Required	Servos	Medium
Torpedoes	Required	Required	Pneumatic Contro	Medium
Return	Required	Required	Acoustic Homing	High

B. Trade-offs Between Complexity and Reliability

1) Systematic Risk Management and Design Philosophy: The BLASTOISE system architecture is designed according to the principles of low coupling and high cohesion in order to limit fault propagation. The system consists of sensing, state estimation, control, and task management layers They are decoupled, with each layer communicating via clearly defined data interfaces.

This layered structure prevents individual component failures from spreading throughout the system and enables fault isolation. Specifically, during task execution, a failure in the sensing layer does not directly affect the control layer; instead, the system is redirected to alternative data streams.

This approach facilitates the deterministic analysis of the system and ensures that it exhibits predictable behavior under field conditions.

2) Distinction Between Hardware Hierarchy and Deterministic Control: The system architecture is designed in two layers to isolate real-time control loops from high-level calculations:

- ***High-level processing:*** Image processing, task planning, and decision-making processes (Jetson Orin Nano)

- ***Low-level control:*** Motor driving, PWM generation and closed-loop speed/thrust control (Arduino Mega – ATmega2560)

The control loops operating at the low-level layer are run at a constant frequency (deterministic loop timing) to minimize jitter. In the event of delays or process failures at the high-level layer, the low-level control unit can continue to operate independently, and the system can be restored to a safe state.

Furthermore, communication between the two layers is monitored using timeout and watchdog mechanisms; the system automatically switches to fail-safe mode when the data flow is interrupted.

*3) Electronic Architecture, Signal Integrity and EMI Control:*To maintain signal integrity and minimize electromagnetic interference (EMI), BLASTOISE's electronic architecture is built on physically and logically separated data buses; accordingly, high-speed data lines (Ethernet, USB), low-speed communication protocols (UART, I2C), and power distribution lines are strategically isolated from each other to prevent cross-talk during the design phase.

Grounding and line routing strategies have been optimized, reducing the impact of noise, especially on analog sensor data. This has improved the signal-to-noise ratio (SNR) of the data obtained from the IMU and pressure sensors.

Thanks to its modular connector structure, module-based isolation can be achieved in case of malfunctions without disassembling the system.

4) Software, State Prediction, and Fault Tolerance: The software infrastructure, structured in distributed nodes using a ROS 2-based publish-subscribe architecture, provides process isolation through loosely coupled data flow; while in the state estimation layer, it combines DVL, IMU, and pressure sensor data within an Extended Kalman Filter (EKF) to suppress IMU drift errors, stabilize DVL velocity measurements, and maximize depth data and z-axis accuracy.

In the event of data loss at the sensing layer, the system switches to dead-reckoning-based position estimation using the EKF output.

The behavior-based decision architecture used in the task execution layer ensures that tasks are executed in a recoverable and fault-tolerant manner. This allows the system to continue performing its task in a degraded mode instead of completely shutting down in the event of sensor failure or detection errors.

C. Task-Specific Implementation Strategies

This section summarizes the sensing, control, and decision-making mechanisms that BLASTOISE uses to complete its competition tasks.

1) Gate: At the start of the competition, the vehicle performs a controlled rotational scan around its own axis to localize the door. Our custom model based on YOLOv8n calculates the 3D orientation vectors by defining the geometric keypoints of the door. While the vehicle navigates the passage by following a route perpendicular to the door plane, it captures visual data of "sea creature" via side cameras and stores this information in a temporary data buffer on the Jetson Orin Nano for future missions.

2) Slalom (Navigation): In this task, BLASTOISE progresses by processing "path tracking" data from the bottom-view camera. Upon reaching the task area, the wide-angle front camera identifies PVC pipes. With the red tube on the right and the white tube on the left, the vehicle combines DVL (A50) and IMU (BNO086) data at the EKF layer to follow a stable route independent of currents. The maneuver is dynamically updated to include a total of three passes around the pipes.

3) Bin (Marker Drop): The tool uses a probabilistic search algorithm to detect the box. When the box is located, the PID-based precise positioning system is activated. In the Gate mission, the "sea creature" information stored in memory is used to select the correct area to place the markers. If visual contact is lost, the Dead Reckoning algorithm recovers the task (fallback) by returning the toolbox to its last known coordinates.

4) Torpedoes: In this task requiring precise alignment, circular apertures on the target are separated using image processing algorithms.. The Jetson Orin Nano calculates the target's position in 3D space (Pose Estimation) and transmits this data to the Arduino Mega via UART. When the vehicle enters the designated firing line, it triggers the pneumatic system, firing the torpedoes.

5) Return Home: Once all tasks are completed, the vehicle uses its navigation history based on DVL data to navigate to the starting area. After the exit gate is visually verified, it passes through safely, and the vehicle emerges onto the surface, completing the operation. The correlation between the sensor suite and specific mission milestones is summarized in Table II.

TABLE II. SENSOR AND TASK MATCHING MATRIX

TASK	*YOLOv8n (Vision)*	*DVL (A50)*	*Ping360 (Sonar)*	*Arduino (Control)*
Gate	✓	✓	-	✓
Slalom	✓	✓	✓	✓
Bin	✓	✓	-	✓
Torpedoes	✓	✓	-	✓
Return	✓	✓	✓	✓

D. Success History & Engineering Evolution

1) TEKNOFEST 2025 Success and Autonomy Without DVL: The RACLAB team won first place in Turkey and the Best Team Spirit award in the Advanced Category at the TEKNOFEST Unmanned Underwater Systems Competition held in 2025. The most critical technical aspect of this achievement is the high autonomy performance demonstrated despite the absence of a DVL (Doppler Velocity Log) in the system at that time. Our team developed a unique velocity estimation and odometry algorithm using Hall-effect-based water flow velocity sensors, given the limited accessibility to costly navigation sensors available at that stage.

2) Innovative Solutions Under Limited Resources: The sensor used measures the flow rate of the water passing through it. **Equation 1**(Q) It generates proportional digital signals. Our team converted these signals into physical data using the following mathematical model:

Flow Rate Calculation:

$$Q = \frac{\text{Pulse Count}}{\text{Calibration Factor}} \qquad (1)$$

Speed Calculation: Sensor cross-sectional area (A)
Using the flow rate as a constant parameter, In **Equation 2** the relative speed of the vehicle is calculated.

$$V = \frac{Q}{A} \qquad (2)$$

Distance Calculation: The instantaneous speed data obtained, time (t) by integrating with this, the total displacement of the vehicle is calculated: **Equation 3**

$$Dis\tan c\,e = V \cdot t \qquad (3)$$

2) Mission Algorithm and Navigation Fusion: Since this odometry data alone would not be sufficient, it was fused with heading data from the BNO055 IMU and depth data from the pressure sensor on the Jetson Orin Nano. Thanks to this hybrid structure, the vehicle was able to descend to the target depth, orient itself towards the target angle, and steadily progress to the target coordinates using distance data from the flow sensor, after obtaining the initial reference point. The custom-developed flow measurement unit, which serves as a velocity-over-ground alternative, is illustrated in Fig. 2.

Fig. 2: Flow measurement-based DVL alternative navigation sensor unit.

3) BLASTOISE: Where Experience Meets Technology: BLASTOISE, which we developed for RoboSub 2026, combines the algorithmic expertise gained from our TEKNOFEST championship with professional-grade Water Linked A50 DVL hardware. Our past experience with flow sensors has significantly accelerated the integration of complex data (velocity-over-ground) from the new sensor into our software architecture and its processing at the Extended Kalman Filter (EKF) layer. BLASTOISE was developed under limited resources. It is the embodiment of autonomy, elevated to industrial standards with professional equipment.

E. Risk Assessment

Our team follows an "Experience-Based Reliability" strategy to minimize hardware-related risks. Although our primary navigation source is the DVL A50, our past successes with the water flow sensor have enabled us to develop a software architecture flexible enough to quickly adapt to all types of data sources (visual odometry, IMU integration, etc.). This modular structure forms the basis of the "Hardware Abstraction Layer" (HAL), which is necessary for the vehicle to continue its mission in the event of sensor loss.

II. DESIGN STRATEGY

A. Mechanical Design

1) Design Strategy and Methodology: BLASTOISE's mechanical architecture is built on the parameters of reliability, modularity, and ease of maintenance. Analytical calculations (CoG/CoB) and numerical analyses (FEA/CFD) were used as primary validation tools in the design process; a chassis was designed within the competition requirements (600x600x300 mm) aiming for a functional structure free from complexity.

2) Material Analysis and Body Architecture: To increase structural rigidity, the HDPE material used in previous prototypes was replaced with Aluminum 6061-T6 alloy. This choice increased the modulus of elasticity from 0.8 GPa to 69 GPa, resulting in an 85-fold increase in rigidity and a tenfold increase in yield strength from 25 MPa to 240 MPa. The density disadvantage of the material was compensated for through topology optimization; a 50µm thick anodized coating was applied to all surfaces to provide corrosion resistance and insulation.

3) Sealing and Pressure Vessel Technology: After analyzing the hydrostatic pressure of 9 bar at the maximum operating depth and the risk of buckling, a safety factor of 3 was selected, and an acrylic tube design with a wall thickness of 5 mm was implemented. To guarantee sealing performance, O-ring compression ratios in the range of 13–15% were preferred, and the flange and gasket seat geometries were manufactured with high tolerances using machining methods.

4) Propulsion System and Performance Analysis: Of the 8 Blue Robotics T200 thrusters used in the vehicle, 4 horizontal units positioned at a 45° angle provide a total forward thrust of 145 N it offers a significant capacity. This value exceeds the hydrodynamic drag force (range of 30–50 N) calculated at a speed of 1 m/s, providing high maneuverability and acceleration reserve. The total thrust capacity of 206 N on the vertical axis offers precise depth control.

5) Static Stability and Hydrostatic Stability: The passive stability of the vehicle has been achieved by maximizing the metacentric height (GM) parameter. The concentration of mass at the base provided by the aluminum chassis lowers the center of gravity (G), while the PE foam with a density of 30 kg/m³ integrated into the upper section raises the center of buoyancy (B). The 5%–8% positive buoyancy achieved through strategic foam placement increases the restoring moment, providing a high self-righting capability along the roll and pitch axes.

6) Mission-Specific Actuators (Torpedo and Marker Systems): The BLASTOISE platform incorporates specialized mechanisms for complex mission tasks, including a dual-shot torpedo system and a sequential shutter-type marker dropper. The mechanical architectures of these systems are illustrated in Fig. 3. As shown in Fig. 3, the torpedo system is optimized for ballistic stability, while the marker dropper utilizes a single-servo shutter design for phased release. These actuators are modularly integrated into the chassis to ensure high operational reliability during task execution.

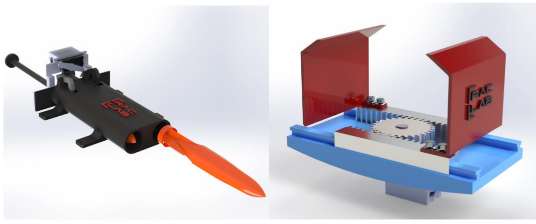

Fig. 3: 3D CAD models of mission-specific mechanisms: (Left) Dual-shot torpedo launching system for precision aperture targeting and (Right) Sequential shutter-type dropper for controlled marker release.

B. Electrical and Electronics Architecture

The electronic architecture of the BLASTOISE platform is designed as a "Pixhawkless" (private control hierarchy) structure in accordance with the principles of high current management, low impedance transmission, and hierarchical control.

1) Hierarchical Control and Pipeline: The system is divided into two main layers to optimize processing load; the NVIDIA Jetson Orin Nano unit, located at the top of the hierarchy, handles computationally intensive autonomous tasks such as YOLOv8n object detection and EKF-based navigation. The Arduino Mega 2560, acting as a low-level control unit, converts commands from the higher-level unit into PWM signals for the motors and packages sensor data, transmitting it to the higher-level unit in real time

2) Copper Busbar Based Power Distribution Structure: Instead of traditional PCB solutions for high current distribution, RACLAB's uniquely designed solid copper busbar architecture (Fig. 4) provides low impedance, minimizing voltage drop and Joule heating while ensuring high voltage stability. Offering 60A capacity via XT60 connector, this structure acts as a natural heat sink, maximizing thermal stability, while screw connections guarantee mechanical reliability.

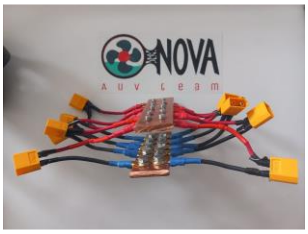

Fig. 4: Solid copper busbar power distribution unit manufactured specifically for the BLASTOISE platform.

C. Software Architecture & Sensor Fusion

BLASTOISE's autonomous capabilities are built upon a deterministic and distributed software hierarchy based on ROS 2 Humble. The architecture processes data at the low-level collection and high-level perceptual fusion layers.

1) Multi-Protocol Data Collection: The vehicle's environmental awareness is ensured by synchronizing data flowing over different communication protocols. In this context, high-precision depth data is read from the pressure sensor via the I2C protocol and transmitted to the Jetson unit via the Arduino Mega, ensuring high positional accuracy along the Z-axis. Simultaneously, the vehicle's dynamic orientation and angular velocity are monitored. Data is transmitted via the UART interface through the BNO086 IMU unit at a frequency of 100 Hz+. This architecture utilizes UART to prevent potential address conflicts on I2C lines, thereby increasing overall data transmission reliability.

2) EKF-Based Sensor Fusion: Sensor data with different frequencies and noise characteristics (DVL, IMU, Pressure) are combined in the Extended Kalman Filter (EKF) layer within the Robot Localization package. In this process, DVL (A50) velocity data and IMU acceleration data are integrated to perform 6-DOF underwater position estimation of the vehicle; the EKF algorithm filters out sudden deviations (outliers) in the sensors, providing noise rejection and guaranteeing that the navigation system remains on a stable course even in environments with strong currents.

3) Dynamic Mapping with Ping360: In low visibility conditions, the Ping360 scanning sonar unit is activated. Acoustic data is processed at ROS 2 nodes to detect obstacles in the polar coordinate system. The Occupancy Grid Map generated from this data feeds the SLAM and reliable obstacle avoidance algorithms.

4) Decision Support and Task Management: All fused data is processed at the Behavior Tree (BT) layer. The BT architecture performs "Loop Closure" by comparing the DVL odometry with the sonar map and verifies the absolute position. This modular structure minimizes the risk of "Single Point of Failure" and guarantees task continuity.

III. TEST STRATEGY

To verify the operational reliability of the BLASTOISE platform, a three-stage test hierarchy was applied, extending from a simulation environment to real pool conditions. This process aims to determine the performance of software algorithms in edge cases while minimizing hardware risks.

A. Simulation-Based Verification

The software architecture was tested on the Gazebo/Ignition simulator, which works in full integration with ROS 2 Humble, during the physical prototype production phase. By transferring the vehicle's mass distribution, thruster configuration, and water lift/drag forces into the simulation, a digital twin of BLASTOISE was created. On this digital structure, YOLOv8n-based object detection and EKF navigation algorithms were run in a virtual world under different lighting and current conditions. In this way, pre-tuning of the PID parameters is completed before pool testing, preventing hardware failure risks and verifying algorithmic consistency.

B. Component & Waterproofing Tests

To maintain the structural integrity of the vehicle underwater, critical subsystems were individually tested in a laboratory environment. The designed acrylic tubes and aluminum covers were subjected to 24-hour vacuum at -0.8 bar after assembly to confirm their leak-proof reliability; O-ring compression ratios in the range of 13–15% were preferred to maximize sealing performance. In parallel power system load tests, the unique copper busbar unit was monitored with a thermal camera in scenarios where all thrusters drew maximum current (60A+); it was determined that the Joule heating remained below the critical threshold and the system maintained its thermal stability.

C. In-Water & Autonomy Testing

The final stage of the validation process is system integration testing conducted in a controlled underwater test facility that simulates the real operating environment. During this process, the vehicle's hydrostatic buoyancy equilibrium and ballast configuration are experimentally validated; and thanks to the 5% - 8% positive buoyancy achieved through strategic weight placement, the metacentric height is also validated. (GM) it has been determined to be sufficient for passive stability and self-righting capability.

Using Water Linked A50 DVL and BNO086 IMU data, the PID coefficients for the vehicle's 6-DOF motion dynamics were optimized via live tuning. The tests technically confirmed that the vehicle reached the target coordinates with minimum overshoot and settlement time. In the final stage, the Gate, Slalom, and Bin tasks were tested with end-to-end autonomous scenarios; the "Fallback" decision-making mechanisms of the Behavior Tree architecture under environmental uncertainties and the dynamic obstacle detection performance of the Ping360 sonar were successfully validated.

IV. CONCLUSION

This study details the design and testing processes of the BLASTOISE AUV platform, which offers innovative and modular solutions to underwater autonomy challenges. The unique copper busbar power architecture and ROS 2 Humble-based software ecosystem developed ensure that the system operates stably and autonomously even under high current conditions.

The greatest added value offered by this project is its modular structure, which allows it to easily adapt to different underwater missions BLASTOISE is not only a competition platform but also provides a strong foundation for industrial applications such as "Autonomous Pool Cleaning Robots." This infrastructure, developed for pool cleaning operations, environmental mapping, and autonomous sweeping algorithms, will form the focus of future commercial projects and academic research.

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VI. REFERENCES

[1] Z. Zhang, “Trajectory tracking control for autonomous underwater vehicles based on improved PID and fuzzy control,” *Machines*, vol. 11, no. 2, p. 300, 2023. doi: 10.3390/machines11020300.

[2] X. Sun, L. Liu, and G. Wang, “Underwater image enhancement based on deep learning and physical models,” *Complexity*, vol. 2020, Art. no. 6707328, 2020. doi: 10.1155/2020/6707328.

[3] “Underwater image processing and perception for autonomous vehicles,” *Comput. Electr. Eng.*, vol. 102, Art. no. 108215, 2022. doi: 10.1016/j.compeleceng.2022.108215.

[4] Blue Robotics, “Understanding and using scanning sonars,” 2019. [Online]. Available: https://bluerobotics.com/learn/understanding-and-using-scanning-sonars/

[5] A. Koçak, “Aktif sonarın ROV ve AUV’lerde kullanımı,” Prezi, Nov. 23, 2024. [Online]. Available: https://prezi.com/p/ziboxe-cyxpg/aktif-sonarn-rov-ve-auvlerde-kullanm/

[6] G. A. Canlı, İ. Kurtoğlu, M. O. Canlı, and Ö. S. Tuna, “Dünyada ve ülkemizde insansız sualtı araçları İSAA-AUV & ROV tasarım ve uygulamaları,” *Gemi İnşası ve Deniz Bilimleri Dergisi*, no. 4, pp. 16–25, 2014. [Online]. Available: https://dergipark.org.tr/tr/pub/gidb/article/717533

[7] A. E. Yılmaz, “Maviliklerdeki neferler: İnsansız su altı araçları,” *Bilim ve Teknik*, no. 638, pp. 60–63, Jan. 2021. [Online]. Available: https://bilimteknik.tubitak.gov.tr/e-arsiv/sayi638/maviliklerdeki-neferler-insansiz-su-alti-araclari/

[8] X. Xu and L. Wang, “An IMM-aided ZUPT methodology for an INS/DVL integrated underwater navigation system,” *Sensors*, vol. 17, no. 9, p. 2030, 2017. doi: 10.3390/s17092030.

[9] A. Tal, “Inertial navigation system/Doppler velocity log (INS/DVL) integration with partial DVL measurements,” *Sensors*, vol. 17, no. 2, p. 415, 2017. doi: 10.3390/s17020415.

[10] Z. Huang, J. Chen, and S. Yan, “Obstacle avoidance, path planning, and control for autonomous vehicles,” in *Proc. 2019 IEEE Intelligent Transportation Systems Conf. (ITSC)*, 2019, pp. 2004–2009. doi: 10.1109/ITSC.2019.8917178.

[11] S. Yılmaz and S. B. Kılcı, “Otonom sualtı araçlarında genel tasarım ilkeleri,” *Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, vol. 11, no. 1, pp. 119–131, 2021. doi: 10.21597/jist.715459.

[12] H. Terzioğlu and F. Cengiz, “Otonom sualtı aracının (AUV) tasarımı, modellemesi ve hesaplamalı akışkanlar dinamiği (CFD) analizi,” *Doğu Bilim Dergisi*, vol. 8, no. 1, pp. 53–68, 2025. doi: 10.57244/dfbd.170836.

APPENDIX A: SIMULATION-BASED VALIDATION (GAZEBO)

This section presents test scenarios performed in the Gazebo/Ignition simulation environment, fully integrated with ROS 2 Humble, to validate the autonomous capabilities of the BLASTOISE platform. The tests focused on verifying the synchronization of computer vision, state machine hierarchy, and PID control algorithms.

A. Qualifying Task: Autonomous Gate Approach

In the preliminary task, the vehicle's ability to detect and pass through the gate was tested. Image processing nodes successfully masked the geometric boundaries of the gate under varying lighting conditions and provided centering data to the vehicle.

- Scenario: The vehicle detects its target, centers its course, and transitions to the "APPROACH_GATE" state.

- Result: As shown in Fig. A1, the object detection algorithm successfully identified the door, and the controller initiated autonomous passage by minimizing the offset from the center.

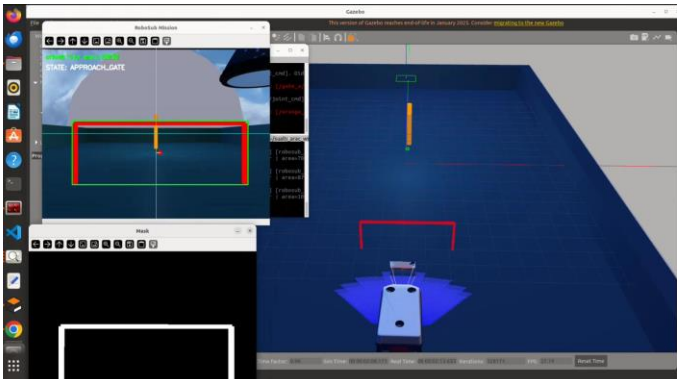

Fig. A1: Visual tracking and state-switching during the APPROACH_GATE phase.

B. Maneuvering Tasks: Pole Alignment and Orbit

At this stage, the interaction of the vehicle with vertical obstacles (poles) encountered after passing through the gate was tested. The stability of the transitions between the "ALIGN_POLE" and "ORBIT_POLE" states was measured.

- Scenario: Alignment with visual data after mast detection, followed by 360-degree autonomous orbital tracking around the mast (Orbit).

- Result: Figs A2 and A3 demonstrate that the vehicle maintained its orbital trajectory while keeping its mast centered; Fig. A4 shows that it retained its ability to search for and align with the next target (Gate 2) after completing a mission.

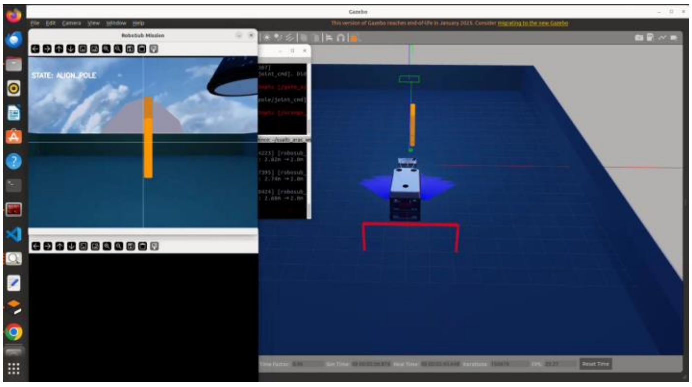

Fig. A2: Real-time obstacle detection and automated path planning logic.

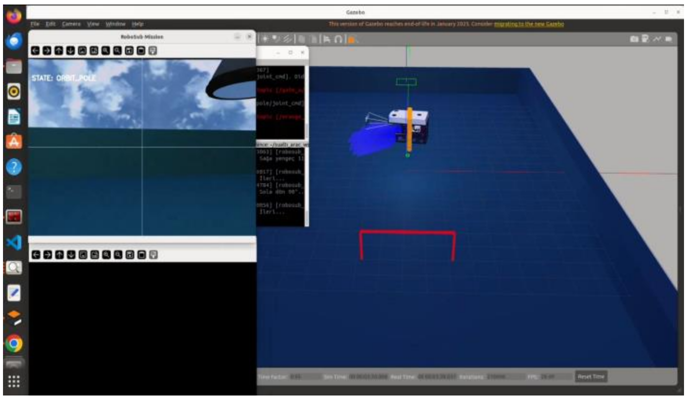

Fig. A3: ORBIT_POLE state.

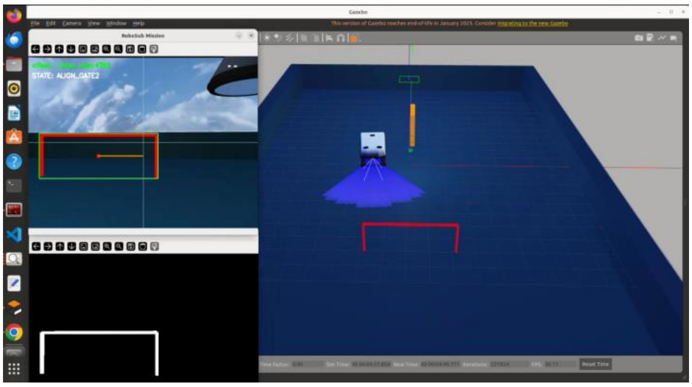

Fig. A4: ALIGN_GATE2 state.

C. Navigation Field Simulation and Sensor Validation

At this stage, the vehicle's overall navigation capability and sensor-based environmental sensing performance within its mission area were evaluated.. Created in a gazebo setting in this scenario, the generalization ability of the algorithms was tested using static obstacles and target objects placed at different locations. The vehicle generates environmental awareness using data provided by the forward vision sensor and dynamically updates route planning by transferring this data to the navigation layer.

Scenario: The vehicle uses environmental data to avoid collisions and maintain stable progress towards its target while navigating through a multi-obstacle environment.

Result: As shown in Fig. A5, objects located within the detection cone created from sensor data were successfully detected; the vehicle exhibited safe and stable navigation behavior based on this data. These results confirm that the data flow between the sensing and control layers is consistent and operates in real-time.

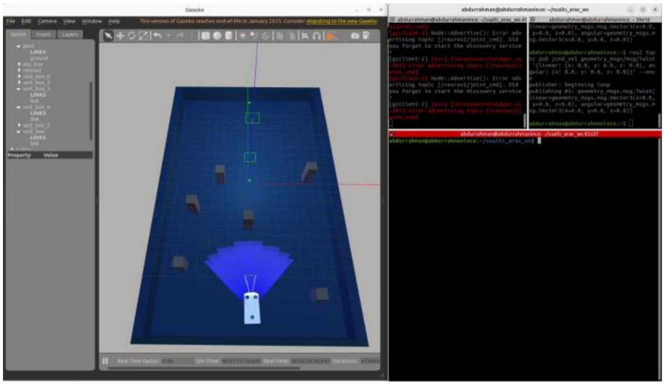

Fig. A5: Sensor field of view and environment interaction in Gazebo simulation.

D. Real-Time Acoustic Mapping with Ping360 Sonar

To enhance environmental sensing capabilities in underwater conditions with low visibility and high turbidity, the Ping360 mechanically scanned sonar sensor is directly integrated into a ROS 2-based real-time mapping infrastructure. The system is designed to operate using entirely real sensor outputs instead of simulation data.

Raw acoustic scan data obtained from Ping360 is converted to the vehicle body coordinate system using TF transformations defined by considering the sensor's mounting configuration. Instantaneous position information is calculated via an odometry node developed during vehicle movement, and sonar measurements are spatially aligned according to this reference frame. In this way, the scan data accumulated over time creates a consistent environmental representation.

The obtained 2D sonar data is converted into a 3D point cloud format via the developed ROS 2-based transducer node and transferred to the OctoMap mapping infrastructure. In this process, the environment is voxel-based it is represented by an occupancy model; occupied and vacant areas are calculated probabilistically.

Simultaneous visualizations performed in the RViz2 environment validated both acoustic measurements and the generated map; consistent transformations between the sensor, body, and global coordinate systems were observed. The results demonstrate that the Ping360 sonar sensor can be used effectively and reliably in real-time environmental mapping and obstacle detection tasks.

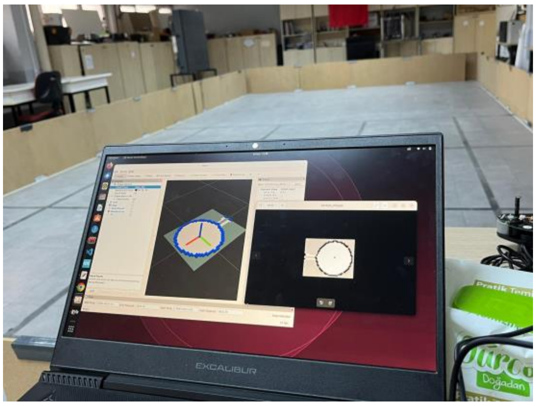

Fig. A6: Visualization of Ping360 sonar data processed within a ROS 2-based pipeline, showing 2D/3D mapping outputs in RViz2.

Fig .A7 :Experimental setup for real-time acoustic data acquisition using the Ping360 sonar sensor in a controlled water environment

The autonomous door detection, alignment, and passage strategy developed for the vehicle is modeled using a flowchart. This structure defines the detection, approach, alignment, and passage phases with a deterministic state transition logic.

The system operates in continuous scanning mode at the start of the task, localizing the door using YOLO-based object detection. Once the gate is detected, the vehicle approaches the target using visual feedback, and when it reaches the designated distance, it references the center of the gates it performs PID-based alignment. Once the alignment is complete, the vehicle moves forward for a specified time interval to complete the transition. If visual contact is lost, the system returns to scanning mode to maintain mission continuity (Fig. A8).

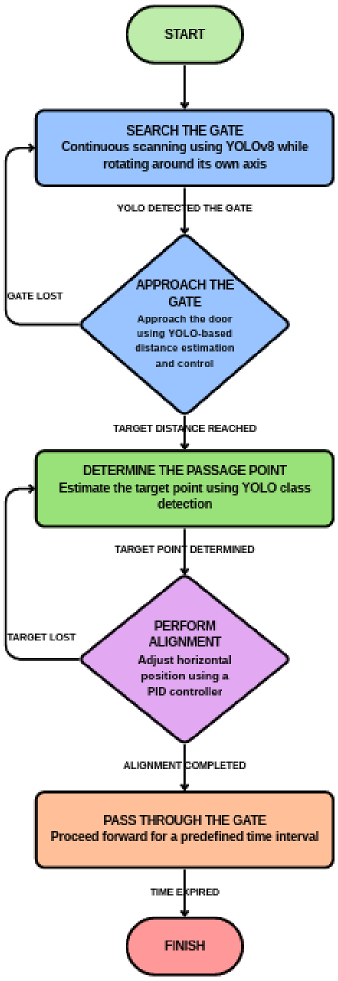

Fig. A8: Flowchart of the autonomous gate detection, alignment, and traversal strategy.

E. ADVANCED MISSION TASK: TORPEDO TARGETING AND LAUNCH VALIDATION

The autonomous torpedo task represents one of the most complex challenges for the BLASTOISE platform, requiring the seamless fusion of high-level classification and precise spatial alignment. This phase of the simulation validates the vehicle's capability to distinguish between target symbols and maintain a stable hover for successful mission execution.

- Perception and Icon Identification: Utilizing YOLOv8, the perception system identifies mission-specific targets, such as the "fire truck" or "ambulance" icons, in real-time. This ensures that the AUV targets the correct aperture before initiating the firing sequence.

- 6-Region Decision Architecture: To achieve high-precision centering, the visual field is virtually partitioned into six distinct regions. Depending on the target's centroid coordinates within these regions, the AUV autonomously executes specific maneuvers—such as "Crab Mode" for lateral corrections or "Turning Mode" for angular alignment—minimizing the offset from the center of the frame.

- Simulation and Control Loop Integration: As demonstrated in Fig. A11, the Gazebo environment is used to verify the synchronization between the NVIDIA Jetson Orin Nano's perception nodes and the low-level PID controllers. The simulation confirms that the vehicle can maintain its target lock even under simulated underwater disturbances, ensuring a reliable transition to the firing state once the optimal distance is reached.

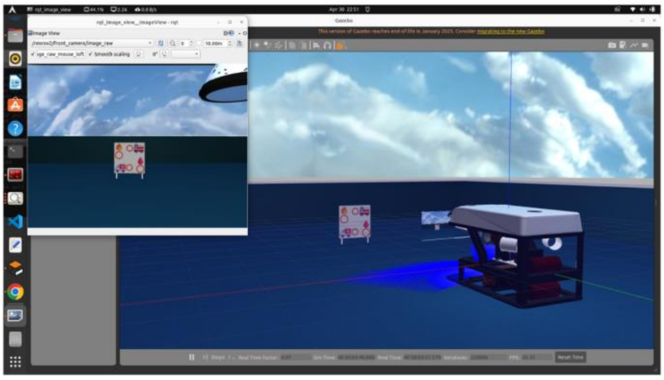

FIG. A11: GAZEBO SIMULATION FOR TORPEDO TASK TARGETING AND VISUAL FEEDBACK.

F. PROPRIETARY 6-REGION DECISION MECHANISM AND COLOR ROBUSTNESS ANALYSIS

The spatial awareness and decision-making hierarchy of the BLASTOISE platform are governed by a specialized image partitioning algorithm. This architecture serves as the primary bridge between the high-level perception layer and the physical maneuvers required for precision navigation.

- AI-Enhanced Perception and Geometry-Based Logic: To identify underwater targets such as gates and obstacles, the system utilizes a hybrid approach, combining traditional image processing with YOLO-based object detection models. While standard competition path markers are orange, the algorithm has been rigorously validated using alternative colors, such as black, to ensure that the system relies on geometric features and spatial coordinates rather than simple chromatic thresholding.

- 6-Region Spatial Decision Architecture: As illustrated in Fig. A10, the visual field is virtually partitioned into six distinct regions. Depending on the target's centroid coordinates within these regions, the AUV autonomously executes specific maneuvers—such as "Crab Mode" (Yengeç Modu) for lateral adjustments or "Turning Mode" (Viraj

Modu) for angular alignment—to center the target within the frame.

- Environmental Adaptability and Continuity: This multi-scenario validation confirms that the navigation stack can maintain mission continuity even if the perceived color of the path shifts due to underwater light refraction, turbidity, or varying pool backgrounds. By prioritizing spatial positioning over color-specific data, the vehicle achieves a higher level of operational robustness, ensuring stable performance across all mission states.

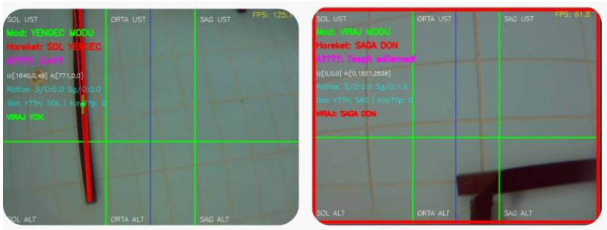

FIG. A10: VISUAL PERCEPTION LOGIC AND 6-REGION DECISION-MAKING ARCHITECTURE.

EPPENDIX B: HARDWARE INTEGRATION AND ELECTRICAL INTERFACES

The physical architecture of the BLASTOISE AUV is engineered for high reliability, modularity, and rapid diagnostic capability. The hardware ecosystem is divided into three functional domains: high-level perception, low-level real-time control, and a multi-stage power distribution network.

A. Master Compute and Sensor Fusion

As illustrated in Fig. B1, the NVIDIA Jetson Orin Nano serves as the central processing unit, managing high-bandwidth data streams from the primary sensor suite:

- Acoustic and Visual Sensing: The Ping 360 Sonar and high-resolution USB Cameras provide redundant perception layers for environmental mapping and target classification.

- Navigation Suite: Real-time localization is achieved through the fusion of DVL (UART), IMU (I2C), and Barometer (I2C) data, ensuring stable 6-DoF operation.

B. Embedded Control and Propulsion

The transition from high-level decision-making to physical movement is managed by a dedicated Control Card: Signal Processing: The control card receives high-level commands from the Jetson module via a dedicated UART link and translates them into eight independent PWM signals.

- Actuation: Eight ESCs drive the thruster array, providing the necessary thrust for precision maneuvers and stable hovering during task execution.

C. Power Management and Safety Systems

A robust power delivery network ensures system integrity during high-load operations:

- Safety Interlocks: Power from the LiPo Battery passes through a physical Emergency Stop Button and an insurance module before reaching the Power Distribution Card.

- Regulation: The distribution card provides regulated voltage levels to the compute modules and sensors while managing the high-current demands of the propulsion system.

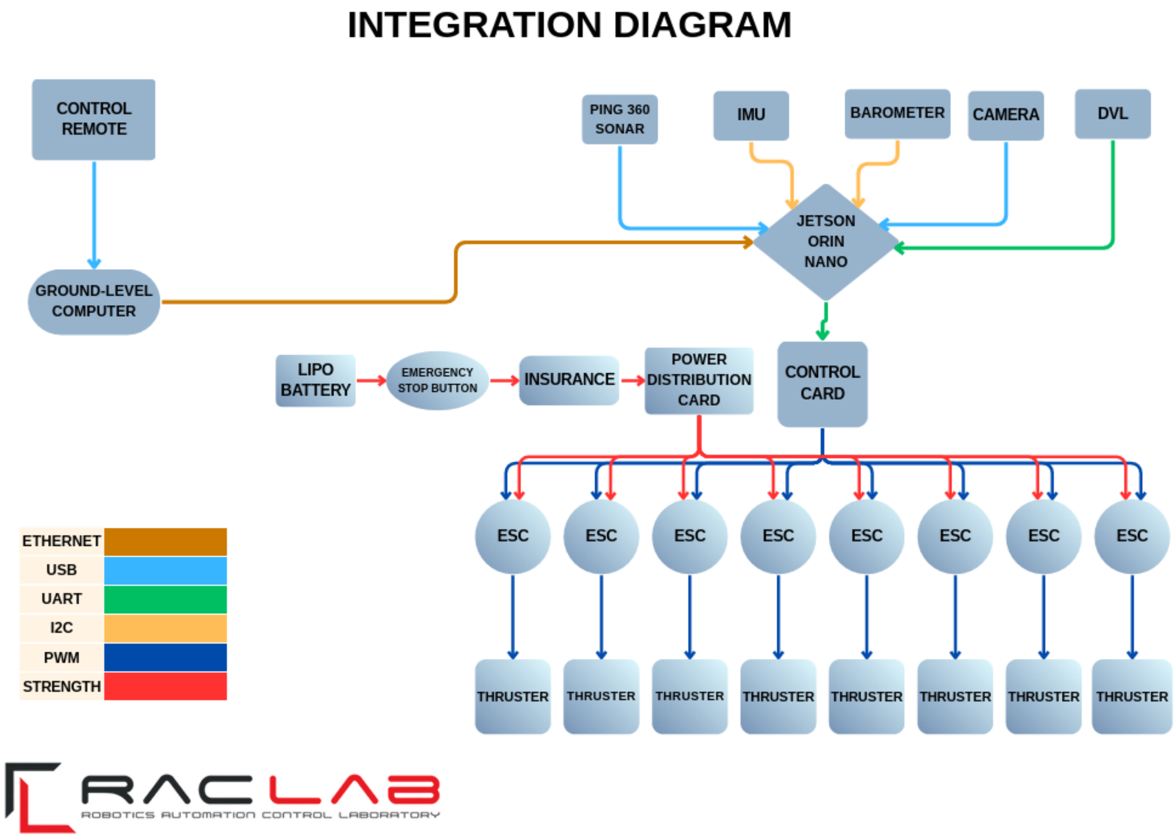

Fig. B1: Detailed Hardware Integration Diagram. This diagram highlights the communication protocols (Ethernet, USB, UART, I2C, PWM) and the structured power flow between the BLASTOISE onboard systems and the ground-level station.

APPENDIX C: COMPONENT SPECIFICATIONS AND FISCAL ANALYSIS

The complete technical and financial breakdown of the BLASTOISE AUV is documented in Table III. This comprehensive inventory details the platform's subsystems, including vendor sourcing, specific models, and technical specifications. The audit distinguishes between high-performance commercial-off-the-shelf (COTS) components and custom-engineered solutions developed by the RACLAB team.

Table III. COMPONENT SPECIFICATIONS AND FISCAL ANALYSIS

Component / Subsystem	***Vendor***	***Model/Type***	***Specs***	***Custom/Purchased***	***Cost***
Buoyancy Control	established industry	Polystyrene Foam	Low-density, water-resistant material for buoyancy	Purchased	$6
Frame	RACLAB NOVA	6061-T6 Aluminum	Anodized aluminum & frame design	Custom	$580
Waterproof Housing	In-house / Local	Acrylic Cylinder	High-transparency, optical-grade acrylic housing	Custom	$150

Waterproof Connectors	RACLAB NOVA	Nova M10	High-pressure resistant connectors	Custom	$5
Thrusters	Blue Robotics	T200	Brushless DC, 5.1 kgf thrust thruster	Purchased	$3,350
Motor Control	Degz Robotics	Blu 30A ESC	BLDC speed and directional control	Purchased	$660
High Level Control	RACLAB NOVA	Version 1	Custom board for sensor interfacing	Custom	Inventory
Actuators	Blue Robotics	T200	High-performance underwater actuators	Purchased	Inventory
Propellers	Blue Robotics	T200 Prop Set	Glass fiber reinforced propellers	Purchased	Inventory
Battery	Leopard Power	4S Lipo	13000 mAh, 14.8V, 25C Lipo battery	Purchased	$365
Converter	RACLAB NOVA	Voltage Regulator	14.8V to 5V step-down converter	Custom	Inventory
Regulator	RACLAB NOVA	Power Module	Stable voltage regulation for electronics	Custom	Inventory
CPU	NVIDIA	Jetson Orin Nano	40 TOPS AI, autonomous processing unit	Purchased	$1,060
Internal Comm Network	Open Robotics	ROS2 Humble	DDS-based reliable data communication	Custom	$0
External Comm Interface	Ethernet / Wi-Fi	Tether System	Real-time monitoring and control interface	Custom	$0
Compass	CEVA Tech	BNO086 (Internal)	Integrated magnetometer for heading	Purchased	$43
Inertial Measurement Unit (IMU)	CEVA Tech	BNO086	Fusion algorithms for orientation sensing	Purchased	$43
Doppler Velocity Log (DVL)	Water Linked	A50	Doppler Velocity Log, high precision	Purchased	$5,700
Manipulator	RACLAB	Gripper V1	Object retrieval and manipulation tool	Custom	Inventory
Algorithms	RACLAB NOVA	Version 1	PID Control, sensor fusion, navigation	Custom	$0
Vision	OpenCV	CLAHE / YOLO	Real-time object detection and tracking	Custom	$0

Acoustics	Blue Robotics	Ping360	360° scanning sonar, obstacle avoidance	Purchased	Inventory
Localization & Mapping	RACLAB	EKF Fusion	IMU + DVL + Pressure sensor fusion	Custom	$0
Autonomy	RACLAB	Task Manager	State-machine based autonomous logic	Custom	$0
Open Source Software	Open Robotics	ROS2 / OpenCV	Distributed robotic operating system	Custom	$0
Inter-Vehicle Communication	RACLAB	MiniROV Sync	Coordination with MiniROV system	Custom	$0
Programming Language(s)	Python / C++	ROS2 Nodes	Real-time processing and control logic	Custom	$0

APPENDIX D: PHYSICAL TESTING AND COMPETITION TASK SETUP

To validate the robustness of the BLASTOISE AUV beyond the simulation environment, extensive physical pool tests were conducted at the Konya Technical University aquatic facilities. These tests focused on the physical implementation of the RoboSub mission tasks, ensuring that the visual perception and control algorithms perform reliably under real-world underwater lighting and buoyancy conditions.

A. Task Assemblies and Submerged Environments

The physical testing setup utilized custom-engineered task structures designed to replicate official competition standards.

- Gate Passage Task: As shown in Fig. D1, a submerged gate assembly was used to verify the vehicle's "SEARCH_GATE" and "APPROACH_GATE" state transitions. The markers on the gate provide high-contrast visual cues for the YOLOv8-based detection system.

- Torpedo and Marker Task: The target board illustrated in Fig. D2 features fire and rescue-themed motifs (ambulance, fire truck, etc.). These icons serve as classification targets for the torpedo-launching task, requiring the AUV to perform precise alignment and identification before execution.

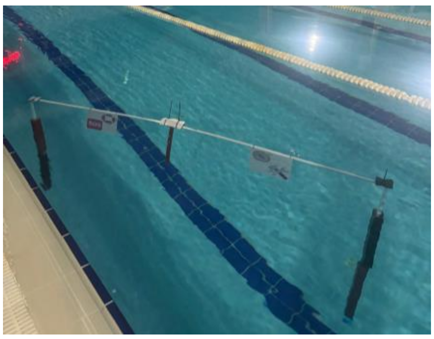

Fig. D1: Submerged gate assembly utilized for autonomous navigation and gate-centering tests in the university testing pool.

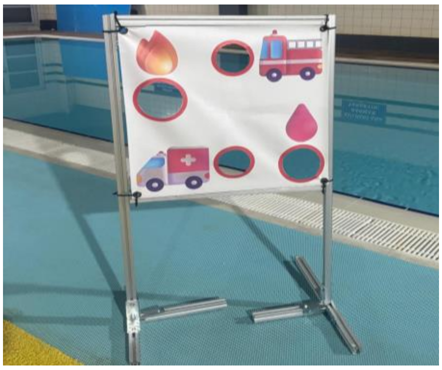

Fig. D2: Custom-designed mission board for torpedo and marker tasks, featuring high-contrast icons for real-time target classification and identification.

APPENDIX E: PROPRIETARY DATASET GENERATION AND AUTO-LABELING TOOLS

To maintain the high accuracy of the perception system (as evidenced by the 98% gate detection rate), the RACLAB NOVA team developed a bespoke software solution titled the "ROV Dataset Generator". This tool is a testament to the team's software engineering maturity, designed to eliminate the bottleneck of manual data annotation for underwater environments.

1) A. Automated Labeling and Efficiency

As illustrated in Fig. E1, the application provides a highly intuitive GUI that integrates automated object detection with manual refinement tools. Unlike conventional labeling platforms, this proprietary tool features:

- Automatic Detection Mode: Leveraging pre-trained weights to automatically suggest bounding boxes for subsequent frames, reducing manual labor by approximately 80%.
- Seamless YOLO Integration: The tool directly exports annotations in the YOLO format, ensuring zero-latency compatibility with the vehicle’s high-level compute module.
- Environmental Tuning: Dedicated sliders for confidence thresholds and scale adjustments allow the team to fine-tune detections based on the specific turbidity and lighting conditions of the testing pool.

2) B. Impact on Model Training

By developing this internal tool, the team has successfully processed thousands of frames from pool tests (e.g., the SOS and marker tasks seen in Fig. E1) into a high-quality training corpus. This end-to-end control over the data pipeline is a core reason for the robustness of the BLASTOISE navigation stack, allowing for rapid iteration and model re-training before competition phases.

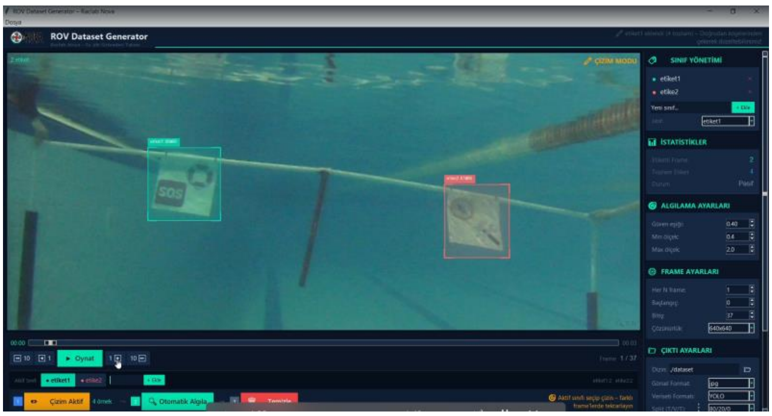

Fig. E1: The "AUV Dataset Generator" developed by RACLAB.

APPENDIX F: PROJECT TIMELINE AND MANAGEMENT STRATEGY

The development lifecycle for the BLASTOISE AUV is organized into five primary functional categories to ensure system reliability and mission success. The following schedule outlines the milestones and activities planned between January and July 2026.

TABLE III: ROBOSUB 2026 DESIGN, SOFTWARE, AND INTEGRATION TIMELINE

Category	***Task / Milestone***	***Jan-Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***
Mechanical	Hull Design and Hydrostatic Analysis	X					
Mechanical	Robotic Arm and Multi-Axis Manipulator Design	X	X				
Mechanical	Thruster Guard and Safety Equipment Fabrication		X	X			
Mechanical	Main Chassis Assembly and Robotic Arm Integration			X	X		
Mechanical	Center of Gravity and Static Buoyancy Balancing				X	X	
Electronics	Power Distribution and Battery Management Unit	X	X				
Electronics	Embedded Control Board and Communication Bus	X	X				
Electronics	Ping360 Sensor Mounting and Integration		X	X			
Electronics	Waterproof Connectors and Cable Management			X	X		
Software	ROS 2 Architecture and Core Node Development	X	X				
Software	Low-Level Control Interface and Serial Comms		X	X			
Software	Ping360-Based Obstacle		X	X	X		

	Avoidance and Navigation						
Software	Computer Vision and Object Recognition Models			X	X	X	
Software	Sensor Fusion and Autonomous Decision Mechanism				X	X	
Autonomy	Gate Passage and Style Point Maneuver Software			X	X		
Autonomy	Slalom and Obstacle Avoidance Algorithm Testing				X	X	
Autonomy	Targeting and Autonomous Torpedo Launch Systems					X	X
Autonomy	Octagon Debris Collection and Distance Tracking					X	X
Admin/Test	Technical Design Report (TDR) Preparation		X	X	X		
Admin/Test	Website and Promotional Video Submission	X	X	X	X		
Admin/Test	Pre-Qualification Application and Pool Testing				X	X	
Admin/Test	General System Audit and Quality Control Testing						X

APPENDIX G: COMPUTER VISION MODEL TRAINING AND PERFORMANCE EVALUATION

This section details the deep learning training pipeline and performance metrics for the BLASTOISE AUV's perception system. The model is specifically optimized to identify mission-critical underwater objects (e.g., *itfaiye, ambulans, halka, alev, kan*) with high precision and recall.

1. Dataset Preparation and Annotation (CVAT)

High-quality training data was generated using the CVAT (Computer Vision Annotation Tool) platform.

- Annotation Strategy: Pixel-level bounding boxes were applied to objects captured in various simulated underwater environments.
- Environmental Robustness: To ensure reliability, images were labeled under different lighting conditions and turbidity levels, accounting for light refraction common in subaquatic environments.
- Labeling Interface: The CVAT interface enabled structured class management, ensuring consistent labeling across the dataset.

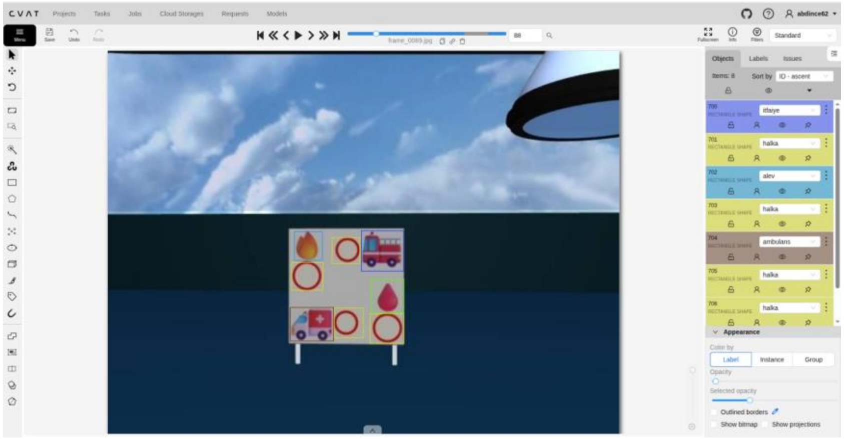

Fig. G1: Multi-class object annotation process within the CVAT environment

2. Training Metrics and Model Convergence

The model was trained over 80 epochs, showing a steady convergence of loss functions and a sharp increase in accuracy metrics.

- F_1 Score: The model achieved an exceptional F_1 score of 0.98, indicating a near-perfect harmonic mean between Precision and Recall. This ensures minimal false triggers during autonomous mission execution.
- mAP Analysis: The mAP_{50} values stabilized above 0.95, while mAP_{50-95} showed consistent growth, confirming the model's ability to localize objects accurately even with partial occlusions.
- Loss Curves: The consistent decline in box_loss and cls_loss demonstrates successful learning without signs of overfitting.

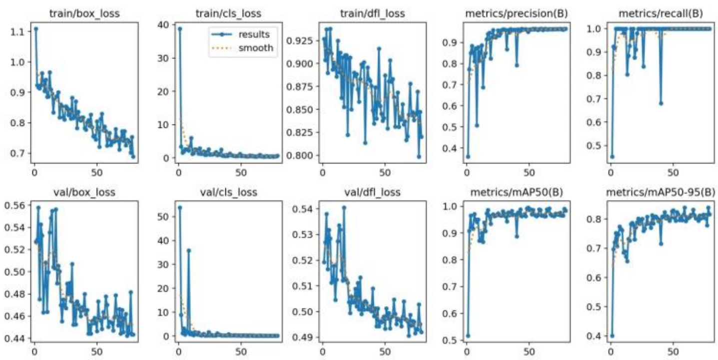

Fig. G2: Training and validation loss curves alongside Precision, Recall, and mAP progression

3. Confusion Matrix and Error Analysis

The discriminative power of the model was validated using a Confusion Matrix, assessing its performance across all defined classes.

- Classification Accuracy: The model achieved 100% accuracy for the itfaiye, alev, and ambulans classes, with zero cross-class confusion.
- Detection Density: The halka class (gate) formed the highest density on the diagonal axis with 76 successful detections, reinforcing its reliability for primary navigation tasks.
- Background Suppression: Only a marginal error rate (3 out of 19 for the kan class) was recorded as false negatives against the background, proving the model's robustness against complex underwater visual noise.

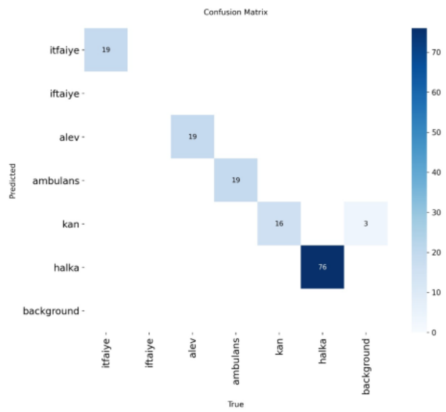

Fig. G3: Confusion Matrix highlighting the high diagonal density and low inter-class confusion

APPENDIX H: REAL-TIME VISION INFERENCE AND LABELING VALIDATION

This section presents the real-time inference performance of the YOLOv8 models developed for the BLASTOISE AUV. The results validate the system's ability to identify and classify mission-critical objects under varying underwater conditions.

1. Gate Detection and Alignment Accuracy

The gate passage is the primary qualifying task, requiring high-confidence bounding boxes for stable navigation.

- High-Confidence Tracking: As illustrated in Fig. H1, the model maintains a consistent lock on the gate ("kapi") with confidence scores reaching 0.97.

- Variable Perspective Inference: Fig. H2 showcases the model's robustness when detecting the target from different distances and tilt angles, ensuring reliable data for the PID controllers.

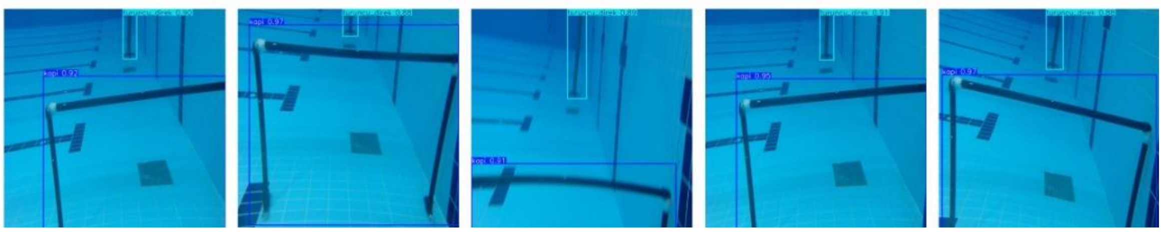

Fig. H1: Stable gate detection with 0.97 confidence score.

Fig. H2: Inference stability under tilted vehicle perspective.

2. Multi-Class Mission Object Identification

The model's ability to distinguish between different labels (icons) is essential for task prioritization within the Behavior Tree.

- Complex Scene Analysis: In Fig. H3, the vision stack successfully performs simultaneous detection of multiple classes.
- Classification Targets: The system identifies "Pusula" (Compass) and "Sos" icons along with structural markers ("Orta-Direk", "Sag-Direk") with high precision, allowing the vehicle to execute specific mission maneuvers based on the detected icon.

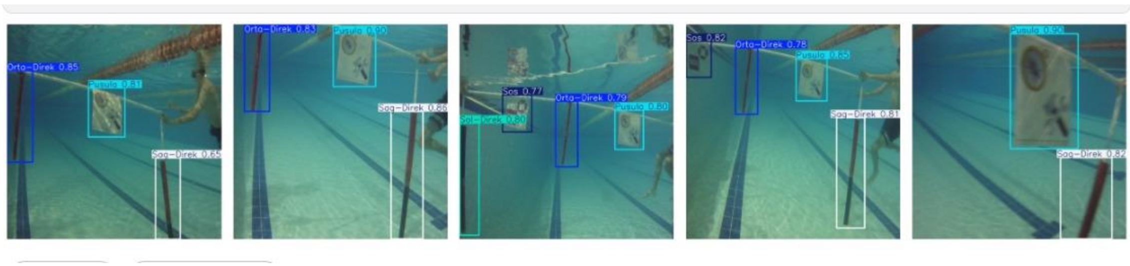

Fig. H3: Simultaneous multi-class inference of mission labels and alignment poles.

APPENDIX I: DUAL-SHOT TORPEDO LAUNCHING SYSTEM

The torpedo system is specifically engineered for the RoboSub mission, designed to navigate through target apertures with high precision. The system focuses on ballistic stability and sequential firing reliability.

1. Torpedo Geometry and Dynamics

Each torpedo is manufactured from PET-G material using additive manufacturing. The dimensions are optimized to ensure a clearance-fit passage through target holes while maintaining a stable flight path.

- Physical Specifications: $L = 200mm$, $\emptyset 40mm$, and $m = 0.185kg$.
- Kinetic Parameters: At a launch velocity of $v = 1.5m/s$, each torpedo possesses an initial kinetic energy of $\approx 0.21J$ and a momentum of $0.278kg\, m/s$.
- Stability: The mass distribution is front-heavy to shift the center of gravity forward, significantly enhancing linear stability during the $2\ m$ effective range.

2. Firing Mechanism and Sealing

The system utilizes a compression spring principle for propulsion, triggered by a high-torque servo motor.

- Actuation: A 30 $kg\, cm(\approx 2.94Nm)$servo rotates in dual directions to independently trigger the left and right torpedoes in sequence.
- Environmental Protection: The 3D-printed housing is treated with an epoxy coating and liquid gaskets to ensure high-pressure sealing.

- Hydrodynamic Verification: The final hull design and torpedo profile were validated via Computational Fluid Dynamics (CFD) to minimize drag.

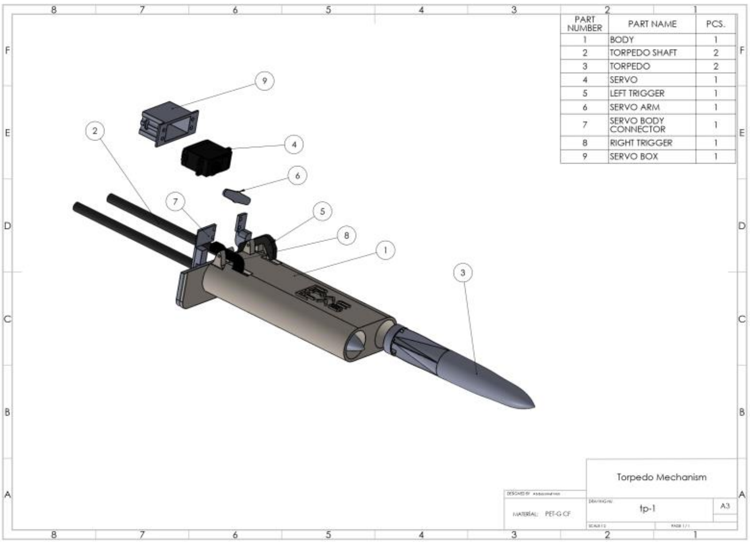

Fig. I1: Technical exploded view of the dual torpedo mechanism.

Fig. I2: High-fidelity render of the torpedo system assembly.

APPENDIX J: SEQUENTIAL SHUTTER-TYPE MARKER DROPPER

For the marker drop task, a high-reliability shutter mechanism was developed to ensure controlled and sequential release. This system ensures that markers are deployed only after a positive target confirmation from the vision stack.

1. Sequential Release Logic

To minimize actuator count and weight, a single-servo shutter design is employed.

- Mechanism: A rack-and-pinion system (as seen in Fig. J1) provides a phased opening. The first phase of the motion releases the first marker, while the continued rotation of the servo releases the second.
- Redundancy: This design prevents the accidental simultaneous release of both markers, ensuring task accuracy.

2. Operational Reliability

- CV Integration: The drop command is only triggered when the YOLO-based detection model confirms the target's centroid is within the designated drop zone.

- Underwater Durability: To prevent mechanical jamming, tolerances were increased for underwater thermal expansion, and a low-friction design was prioritized to maintain consistent performance across multiple mission cycles.

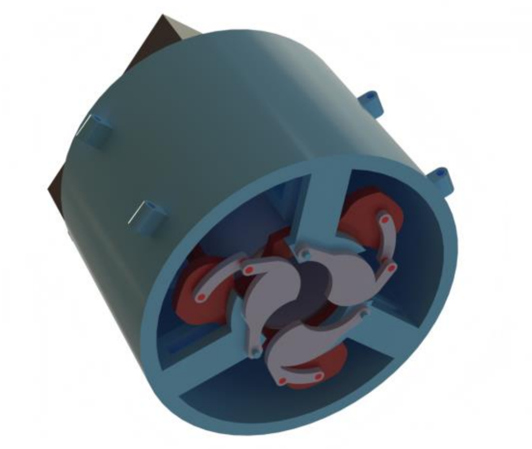

Fig. J1: Internal architecture and detailed technical drawing of the sequential shutter-type marker dropper.

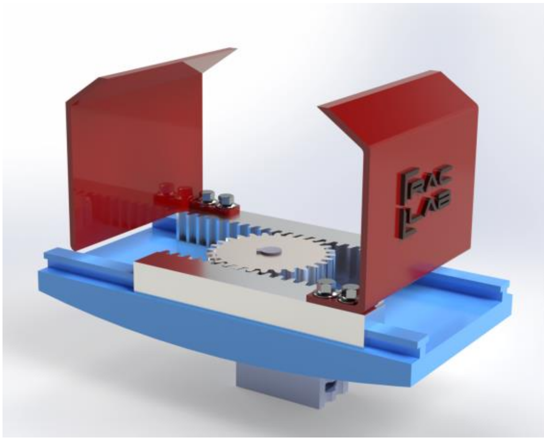

Fig. J2: Final render of the marker dropper assembly demonstrating its modular integration with the BLASTOISE AUV hull.