Technical Design Report of Deuterium

MANIPAL INSTITUTE OF TECHNOLOGY, BENGALURU

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***Abstract*—AUV MIT-B is entering RoboSub 2026 with Deuterium, a first-generation, modular 5-DoF autonomous underwater vehicle developed from the ground up. The vehicle uses a laser-welded aluminum hull with a transparent acrylic access lid, redundant O-ring sealing, Blue Robotics T200 thrusters, and 3D-printed mechanisms for task interaction, including a torpedo launcher and marker dropper. The electrical system integrates a Li-ion battery pack, battery management system, custom power-distribution hardware, RP2350-based control electronics and an NVIDIA Jetson Orin Nano Super for onboard autonomy. Perception is built around forward- and downward-facing ZED 2i stereo cameras, YOLOv8-based object detection, visual servoing and a BehaviorTree.CPP mission planner running within a ROS 2 Humble software stack. Stabilization uses PID and LQR-based control loops for vehicle orientation and depth regulation, while Gazebo-based simulation supports mission-logic testing and subsystem integration. The team also developed an in-house hydrophone acquisition approach for acoustic sensing. Deuterium prioritizes reliable execution of high-confidence RoboSub tasks, maintainable subsystem integration and a scalable platform for future underwater robotics development.**

I. Competition Strategy

As a first-time RoboSub team, AUV MIT-B prioritized reliability, integration and repeatable task execution over feature breadth. Deuterium was developed over approximately one year as a modular 5-DoF AUV intended to complete a focused set of high-confidence tasks using vision-based navigation, depth and orientation stabilization, acoustic sensing and Behavior Tree mission execution. The competition strategy is to build scoring consistency through a mechanically simple platform, a maintainable internal layout and a software architecture that allows individual subsystems to be tested, replaced and expanded as pool-test data increases. Stereo cameras are used for visual perception and object localization, while the onboard IMU and hydrophones assist in orientation estimation and acoustic sensing.

A significant part of the development process involved research and testing to evaluate different subsystem designs and support design decisions. The design process balanced manufacturing complexity, compute requirements, maintainability and subsystem reliability. The development process included iterative changes based on simulation results, subsystem failures and feedback from pool testing. The team was divided into Mechanical, Electrical and Software subsystems while ensuring effective coordination among all members. Through Deuterium, AUV MIT-B aims not only to perform well in the competition but also establish a strong platform for future underwater robotics projects.

Fig. 1: Deuterium

II. Design Strategy

A. *MECHANICAL SUBSYSTEM*

The mechanical subsystem includes the hull, sealing, thruster setup and internal electronics layout.

These design choices were made to keep the system waterproof, maintain stable underwater performance and allow quick changes during development and testing.

*1) **Hull**:* The vehicle uses laser cut sheets of aluminium HE30 which are laser welded together, forming a single unified structure. Sealing is achieved through a transparent acrylic lid with a double O-ring arrangement, providing redundant sealing at the lid interface. The lid is fastened using toggle clamps placed along the perimeter for uniform compression and quick access during maintenance.

*2) **Penetrators**:* Cable pass-throughs are handled using 6.5 mm Blue Robotics WetLink Penetrators, primarily for routing the T200 thruster cables into the hull. Using off-the-shelf penetrators over custom solutions also reduces the risk of sealing inconsistencies, since waterproofing failures are among the more common and disruptive issues in underwater systems.

*3) **Thrusters Placement**:* The vehicle uses five Blue Robotics T200 thrusters (two horizontal, three vertical) providing control over surge, heave, yaw, roll and pitch. The T200 was selected for availability, prior use in AUV applications, and compatibility with the vehicle's thrust requirements. Horizontal thrusters are arranged symmetrically about the centerline and handle forward motion and yaw through differential thrust, while the vertical thrusters are placed in a triangular configuration around the hull to regulate depth and hover stability.

*4) **Placement of Electronics**:* Internal layout was driven by three priorities: keeping the center of gravity stable, managing heat and making maintenance easy. Batteries sit low and near the center of the hull, which passively balances the AUV. Compute boards are mounted on elevated plates, keeping them away from potential water leak areas. Each component has a 3D printed mounting so that they stay stable inside while the vehicle is moving.

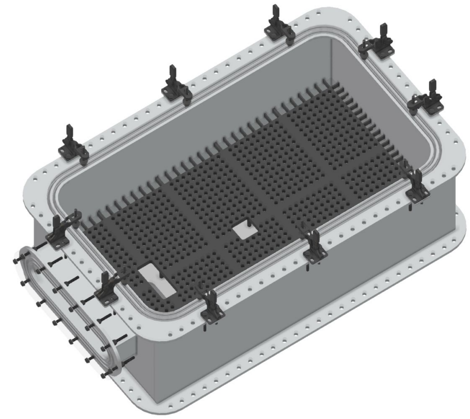

Fig. 2: Bottom Mesh for Placement of Components

*5) **Torpedo Launcher**:* The launcher is a spring-based mechanism and the spring compression can be adjusted to increase the launch speed when needed. A servo-controlled release unlocks the mechanism during firing, enabling smooth and controlled deployment through guided slots. Epoxy sealing was used at critical joints to maintain waterproofing.

Fig. 3: Torpedo, Torpedo Launcher and Dropper

*6) **Dropper**:* A servo-driven circular disc blocker with a hole slightly larger than the markers, rotates across two barrels, letting markers fall under gravity, one by one. The marker is a marble ball (Diameter = 20 mm). Considering the minimal torque requirements, we chose a simple SG90 servo. The SG90 servo was oil-filled and epoxy-sealed to improve water resistance.

B. <u>ELECTRICAL SUBSYSTEM</u>

The electrical subsystem serves as the link between the mechanical and the software subsystem, it handles power distribution and transfer of data between sensors/actuators and the microcontroller. The overall electrical architecture of the AUV is illustrated in Appendix-C (Fig. 12).

1) ***Single Board Computer(SBC)***: The vehicle uses an NVIDIA Jetson Orin Nano Super single-board computer that handles perception, mission planning and high-level autonomy workloads.

2) ***Power Management***: The vehicle uses a dual-bus power architecture powered by a 4S Li-ion battery pack (16.8 V maximum, 12 V minimum) with 18 Ah capacity and a 4C discharge rating. High-current actuator loads are electrically and physically isolated from sensitive logic systems using a custom Power Supply Distribution Circuit (PSDC) to minimize thruster-induced noise.

a) ***Battery Management***: A dedicated Battery Management System (BMS) performs active cell balancing and monitors cell voltage, current draw, State of Charge (SoC) and temperature through an RS-485 interface. Total current is obtained from the BMS, while an ACS712 Hall-effect sensor independently measures PSDC current consumption, allowing thrust-related current estimation:

$$I_{Thrusters} = I_{BMS} - I_{PSDC}$$

The ESC bus is controlled using three independent relays. ESC firmware limits maximum thrust to 3.038 kgf, restricting normalized peak burst current to 13.8 A per thruster.

b) ***Power Supply Distribution Circuit (PSDC)***: The PSDC utilizes XL6009 and LM2596 switching regulators to provide dedicated 20 V, 5 V, and 3.3 V rails for compute and telemetry systems. To ensure stable operation, the design incorporates an isolation matrix using decoupling capacitors and blocking diodes, providing back-feed protection, reduced DC-DC noise, and suppression of EMI and inter-rail crosstalk. Hardware isolation is implemented through system-wide degradation logic and a multipoint water-leak detection system with an isolated microcontroller maintaining redundant safety functionality.

3) ***Sensors***: Multiple sensors were placed on the AUV to get feedback for control and underwater navigation.

a) ***Pressure Sensor***: The pressure sensor measures the depth of the vehicle. MS5837-02BA01 pressure sensor from TE connectivity is mounted on the back wall of the AUV.

b) ***IMU***: The 7Semi BNO055 IMU is used to determine the absolute orientation of the AUV. It has a triaxial 14-bit accelerometer, a triaxial 16-bit gyroscope and a triaxial magnetometer. The IMU is kept at the centre of the hull and connected to the MCU via I2C connection.

c) ***Hydrophones***: The Hydrophones are constructed in-house using piezoelectric transducers and a charge amplifier circuit [1]. Each hydrophone circuit has its own RP2350 MCU to sample and send ping timestamps to a main MCU which performs a TDoA (Time Difference of Arrival) algorithm.

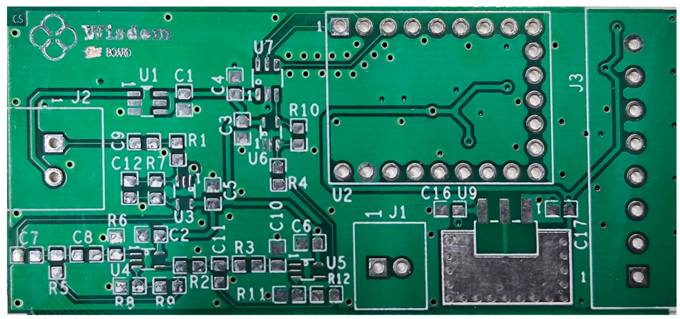

Fig. 4: DAQ Board for hydrophones

d) ***Camera***: Two ZED 2i stereo cameras are used to capture images, one camera is placed at the front of the AUV while the other camera is placed at the bottom. It has up to a 120° wide-angle FOV. It operates at a frame rate of 15–60 fps with a resolution of 720p–2K.

e) ***Water Leak Sensor***: The water leak sensor is positioned along the lower perimeter of the hull and operates using a voltage-divider based copper-electrode sensing circuit. Multiple sensing zones continuously monitor water seepage inside the enclosure by detecting changes in conductivity. The onboard controller generates an interrupt and activates the kill-switch mechanism.

4) ***Thrusters and ESCs***: A set of five Blue Robotics T200 thrusters operated at 12-16 V are used for movement of the vehicle. The maximum forward and reverse thrust it provides at 16 V is 5.25 kgf and 4.1 kgf respectively. A basic bidirectional ESC from Blue Robotics is used to drive the T200 thrusters. The ESC runs on **BLHeli_S** firmware and receives DSHOT signals from the microcontroller for precise motor control.

*5) **Kill Switch**:* The kill switch can be activated in three cases: when a water leak is detected, when the Hall effect sensor stops detecting the magnet, or when the Jetson becomes unresponsive for a specified duration. Once activated, power to the thrusters, RP2350 boards and the Jetson module is cut off immediately to avoid possible damage and maintain safe operation of the vehicle. The Hall effect sensor is connected to the power board and can also be used to manually turn the system on or off whenever needed.

*6) **Communication and Telemetry**:* An RP2350 Main MCU and ESC Communication is implemented using the DSHOT protocol [2], which is a digital communication protocol that provides more reliable and deterministic motor control compared to conventional PWM-based methods. DSHOT implementation requires bit-banging, the RP2350 was selected for its Programmable I/O (PIO) subsystem, which supports deterministic signal generation. An RP2350 Main MCU and Jetson Orin Nano communication is implemented using USB CDC, providing a reliable connection while also powering the MCU. The firmware on the MCU was designed using a non-blocking communication architecture to ensure that communication tasks do not interfere with timing critical control operations. Battery Management System (BMS) and the Jetson Orin Nano use RS-485 communication protocol.

C. SOFTWARE SUBSYSTEM

The software subsystem enables autonomous perception, planning, and control. It consists of a comprehensive framework that helps Deuterium perceive, interpret and act upon its environment. The software stack has access to all visual, inertial and pressure-based sensors, which are calibrated for underwater conditions.

Our main SBC, the **NVIDIA Jetson Orin Nano**, runs **Ubuntu 22.04**. Our source code is primarily written in **Python** and **C++**, handling packages required for vision, navigation, mapping, controls and mission planning. We use **ROS 2 Humble** as our base framework for sensor data handling and efficient communication between all software packages. The software architecture follows a modular design approach where independent subsystems communicate through ROS 2 topics and services, allowing for easier debugging, parallel development and future scalability.

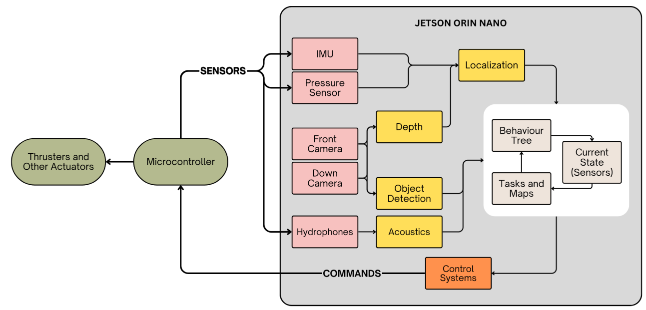

Fig. 5: Software architecture of Deuterium showing sensor integration, localization, perception, Behavior Tree execution and control pipeline.

*1) **Vision Pipeline**:* Our perception system uses two **StereoLabs ZED2i** [3] stereo cameras — one front-facing and one downward-facing — providing stereo RGB imaging, neural depth estimation and inertial sensing. Task-specific YOLOv8 [4] models trained on CVAT.ai annotated datasets with underwater augmentations perform object detection across all tasks.

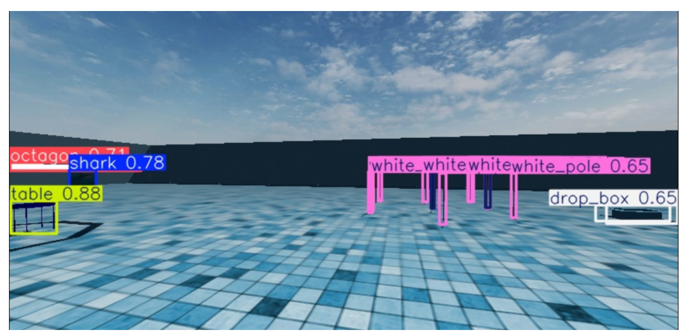

Fig. 6: YOLOv8 Object Detection

For navigation tasks such as gate traversal and buoy circumnavigation, we use **Visual Servoing**. The difference between the detected object's current position and desired position in the image frame is computed as pixel-space error. This error is then used to generate proportional surge, heave and yaw commands while ZED2i depth estimation provides distance information. For precision tasks such as the torpedo challenge, we employ a multi-stage pose estimation pipeline:

- **XFeat** [5] matches the YOLO-cropped detection against a stored reference template, extracting robust feature correspondences under underwater lighting conditions.

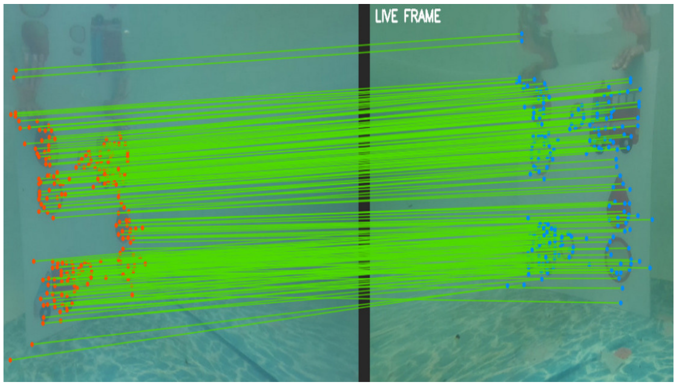

Fig. 7: XFeat based feature matching

- **RANSAC** filters geometrically inconsistent feature matches while retaining reliable point correspondences [6].
- **HDBSCAN** clusters verified correspondences to isolate matches belonging to the target hole [7].
- **Perspective-n-Point (PnP)** maps 2D pixel correspondences to real-world 3D coordinates, recovering the board position and orientation relative to the camera [8].

The recovered pose is passed to the Mission Planner for alignment and task execution.

*2) **Simulation**:* Due to limited access to pool facilities and testing environments, a significant portion of our testing and validation was carried out in simulation. Our simulation environment is built using **Gazebo Fortress** and is designed to closely replicate competition conditions. To achieve realistic underwater behavior, buoyancy and hydrodynamic models based on **Fossen's marine vehicle equations** were integrated into the simulation. Sensor noise models were also incorporated to imitate real-world operating conditions more accurately. Additionally, vehicle parameters including mass, inertia and dynamic properties were carefully tuned and validated to ensure that simulated vehicle behavior closely matches that of the actual AUV.

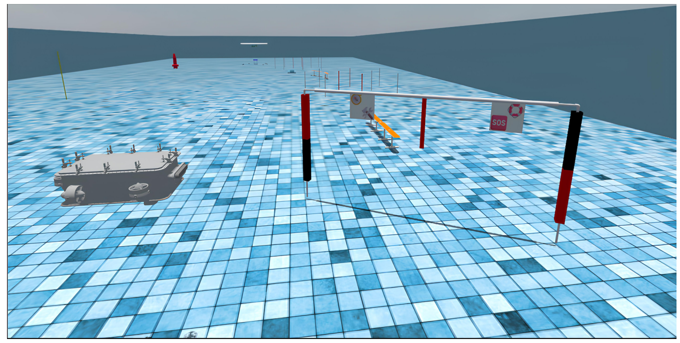

Fig. 8: Gazebo underwater simulation environment

*3) **Mission Planner**:* The mission planning framework of Deuterium uses Behavior Trees (BTs) instead of Finite State Machines (FSMs). While FSMs become difficult to scale with increasing states and transitions, Behavior Trees provide a modular and hierarchical structure that improves flexibility and enables reactive decision making. For implementation, **BehaviorTree.CPP** [9] was selected over Python-based alternatives such as PyTrees due to its lower computational overhead, seamless ROS 2 integration, real-time performance and visualization support through **Groot2**, making it better suited for deployment on the Jetson Orin Nano.

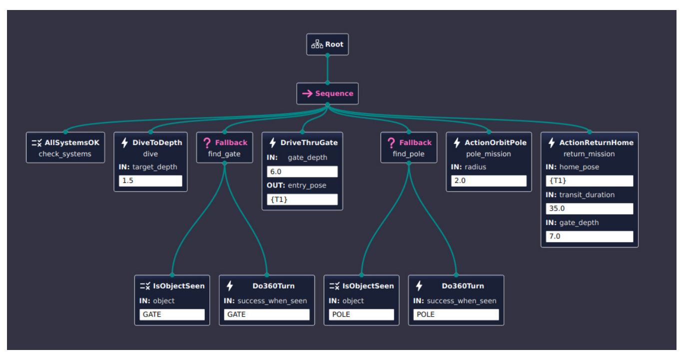

Fig. 9: Pre-Qualification Behavior Tree

*4) **Testing Interface**:* We developed a dedicated GUI interface to monitor the AUV's status in real time. It serves as a centralized dashboard and greatly assists during testing and debugging by providing quick insight into the vehicle's behavior and system health.

D. CONTROLS

The AUV employs a cascaded control architecture to achieve stable underwater motion, as shown in Appendix-C (Fig. 13). It consists of an outer loop PID controller to monitor the roll and pitch angles obtained from the BNO055 IMU. The PID loop generates the angular velocity references(w_x,w_y) which are then fed into the inner LQR loop. Error values are computed by the Jetson and transmitted to the MCU, where a PID controller is implemented to achieve the desired yaw, surge velocity and depth.The yaw error is estimated using feedback from the camera IMU, depth error is estimated using feedback from the pressure sensor and surge error is calculated from camera-based visual feedback by estimating the distance to the target. The frequency of the control loop is 50 Hz.

III. Testing Strategy

To ensure reliability and robustness of the AUV, both simulation-based and real-world tests were conducted throughout the development process. The experiments were conducted in an apartment swimming pool and an indoor pool provided by the college, allowing controlled underwater evaluation. Pre-autonomy tests were performed by connecting Deuterium to a laptop through Ethernet for SSH communication. Testing was conducted in the following stages:

A. Waterproof Testing

To verify hull waterproofing, the hull was submerged in a pool overnight with tissue paper placed along the edges and joints to detect potential leakages. Minor leakage points were identified around welded edges and joints. Therefore, all vulnerable regions were sealed using silicone sealant. After allowing the sealant to cure, the hull was submerged again for 24 hours, after which no further leakages were observed, validating the effectiveness of the sealing process.

B. Controls Tuning

The control tuning process was performed to achieve stable underwater motion. State–space matrices required for the LQR controller were derived and analyzed using MATLAB for roll and pitch stabilization. The tuning process was carried out sequentially, starting with PID tuning for pitch and roll, followed by depth and finally yaw, this sequence improved orientation and depth stabilization during pool testing.

C. Simulation Tests

Our simulation strategy utilized a Gazebo Software-in-the-Loop (SIL) pipeline to validate mission logic before deployment. We tested Behavior Trees for gate navigation and path-following under simulated mass and buoyancy conditions. This allowed us to identify mission-logic errors before pool deployment, minimizing pool-side troubleshooting and safeguarding the physical hardware.

D. Camera Calibration and Imaging Strategy

To ensure accurate underwater perception, a dual-camera calibration pipeline was implemented for both the forward and downward-facing stereo systems. Initial calibrations were performed using Stereolabs' native Zed-OpenCV [10] tool with a standard checkerboard pattern. The remaining uncalibrated data was refined via MATLAB to minimize geometric distortion error. The finalized calibration profiles were converted to OpenCV format and integrated directly as configuration parameters to dynamically rectify all live and recorded data streams.

E. Final Autonomy Testing

Final autonomy tests were conducted after mechanical, electrical, software and controls integration. The complete autonomous pipeline including perception, navigation, stabilization and mission execution was evaluated in controlled underwater environments.

Acknowledgment

We would like to express our sincere gratitude to Manipal Institute of Technology Bengaluru, for the support provided throughout the year-long development process. We thank our faculty advisors Manasa Kongot, Adithya GSS and Ujjwal Verma for their guidance, support and encouragement. We also thank our mentor Pritha Jaipal for her valuable insights throughout the project. We would like to acknowledge our sponsors:

- Vicharak for FPGA support
- Wisdom Technologies for hull manufacturing support and hydrophone materials

Their contributions played a vital role in the successful development and completion of Deuterium.

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APPENDIX-A

COMPONENT SPECIFICATION

Component	Vendor	Model/Type	Specs	Custom/Purchased	Cost in USD
Buoyancy Control	LBS Automation	Steel Blocks	12 kg	Custom	$100
Hull	Wisdom Technologies	Aluminium HE30 5 mm sheets, Laser Cut & Laser Weld	-	Custom	Sponsored
Acrylic Lid	Manipal Institute of Technology, Bengaluru	-	10 mm Thickness	Custom	Sponsored
Clamps	Misumi	-	-	Purchased	10 units - $54.36
Waterproof Penetrators	Blue Robotics	WetLink Penetrators	M10-6.5 mm-LC	Purchased	8 units - $104
Hull Stand	LBS Automation System	Stainless Steel	-	Custom	1 unit - $78
O-Rings	MD Traders	Nitrile Rubber	3 mm Diameter	Purchased	6 meters - $3
Silicone Sealant	Loctite	General Purpose	-	Purchased	2 units - $4.65
Thrusters	Blue Robotics	T200	5.25 kgf Forward Thrust and 4.1 kgf Reverse Thrust at 16 V	Purchased	5 units - $1,150
Motor Control	Blue Robotics	Basic ESC	30 A brushless motor speed controller	Purchased	5 units - $200
High Level Control	NVIDIA	Jetson Orin Nano Super	8 GB RAM	Purchased	1 unit - $302.20
Micro Controller	Robu	RP2350	-	Purchased	3 units - $17.32
Actuators	Mifra Electronics	SG90 Servo Motor	Torque 1.8 kg-cm, 180 degrees range	Purchased	3 units - $3.72
Battery	Blue Robotics	Li-ion 4S6P Battery Pack	Nominal Voltage: 14.8 V, 266.4 Wh	Purchased	2 units - $850
BMS	Daly BMS	Daly Smart Active Balance BMS	-	Purchased	1 unit - $60
Converter 1	Robu	LM2596	Buck Converter	Purchased	2 units - $1

Converter 2	Robu	XL6009	Boost Converter	Purchased	1 unit - $1.5
Regulator	Robu	HW-131	Output voltage of 3.3 V or 5 V	Purchased	1 unit - $3
CPU	NVIDIA	Arm® Cortex®-A78AE CPU	6-core v8.2 64-bit	Purchased	-
Internal Comm Network	-	USB	-	-	-
External Comm Interface	ANT Esports	Ethernet	10 Gb/s	Purchased	1 unit - $2.62
IMU	RoboCraze	Bosch - 7Semi BNO055	9 DOF Absolute Orientation Sensor	Purchased	1 unit - $11.55
Pressure Sensor	DigiKey	TE Connectivity MS583702BA01-50	-	Purchased	1 unit - $7
Cameras	ZED	ZED 2i	Stereo Vision	Purchased	2 units - $1,138
Hydrophones	Wisdom Technologies	CUSA-TR50-150-2500-W68	Resonant Frequency 25 kHz	Custom	Sponsored
Torpdeo System	Designed-In House	3D printed	PLA+	Custom	Sponsored
Dropper	Designed-In House	3D printed	PLA+	Custom	Sponsored
Springs	Carbon Springs	Stainless Steel	-	Purchased	2 units - $4.17
3D Print Filament	Robu	PLA+	1.75 mm Diameter	Purchased	6 units - $66
Algorithms: Vision	-	-	OpenCV, YOLOv8, XFeat	-	-
Algorithms: Acoustics	-	-	Time Difference of Arrival (TDoA)	-	-
Algorithms: Localization and Mapping	-	-	ZED SDK (Neural Depth Estimation)	-	-
Algorithms: Autonomy	-	-	BehaviorTree.CPP	-	-
Open Source Software	-	-	ROS 2 Humble, Gazebo Fortress	-	-

APPENDIX-B
LOCALIZATION

SLAM Exploration Using RTAB-Map

The team explored vision-based localization and mapping approaches to improve autonomous navigation capabilities in future iterations of Deuterium. As part of this effort, Simultaneous Localization and Mapping (SLAM) techniques were investigated using **RTAB-Map**.

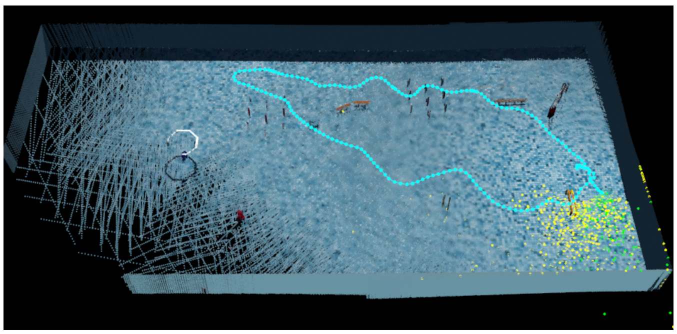

Fig. 10: RTAB-Map Simultaneous Localization and Mapping output

RTAB-Map was evaluated because it provides a complete framework for real-time visual mapping and localization. The system generates 3D point clouds of the environment and identifies overlapping voxel regions between successive observations to estimate vehicle motion.

Additionally, it provides:

- Loop closure detection for reducing accumulated drift
- Occupancy and cost-map generation
- Least-cost path generation
- Real-time environment representation
- Long-term map persistence and localization

These capabilities make RTAB-Map a promising framework for future autonomous underwater navigation and exploration tasks.

However, reliable SLAM performance requires sufficiently accurate and consistent odometry estimates. Since the current vehicle configuration does not include a DVL, localization relied mainly on visual and inertial information, resulting in inconsistent odometry during underwater operation.

Due to these limitations, the SLAM framework was not integrated into the current competition pipeline. Nevertheless, the initial experiments produced encouraging results and remain a potential direction for future vehicle iterations.

Autonomous Path Planning

Another area explored during development was autonomous path planning within the simulation environment. For this purpose, **A* (A-Star)** path planning was integrated and evaluated in Gazebo.

Given a target 3D pose, the planner dynamically generated an optimal trajectory by minimizing traversal cost while avoiding obstacles in the environment.

The implemented framework supported:

- Dynamic path generation toward a target pose
- Collision avoidance with environmental obstacles
- Cost-based trajectory optimization
- Real-time trajectory updates within simulation

Fig. 11: Obstacles Detected Using Point cloud Filtering

Although the path planning framework was not integrated into the current competition pipeline, the experiments demonstrated its potential for future autonomous navigation tasks involving obstacle avoidance and complex mission planning.

APPENDIX-C

ELECTRICAL AND CONTROL ARCHITECTURE

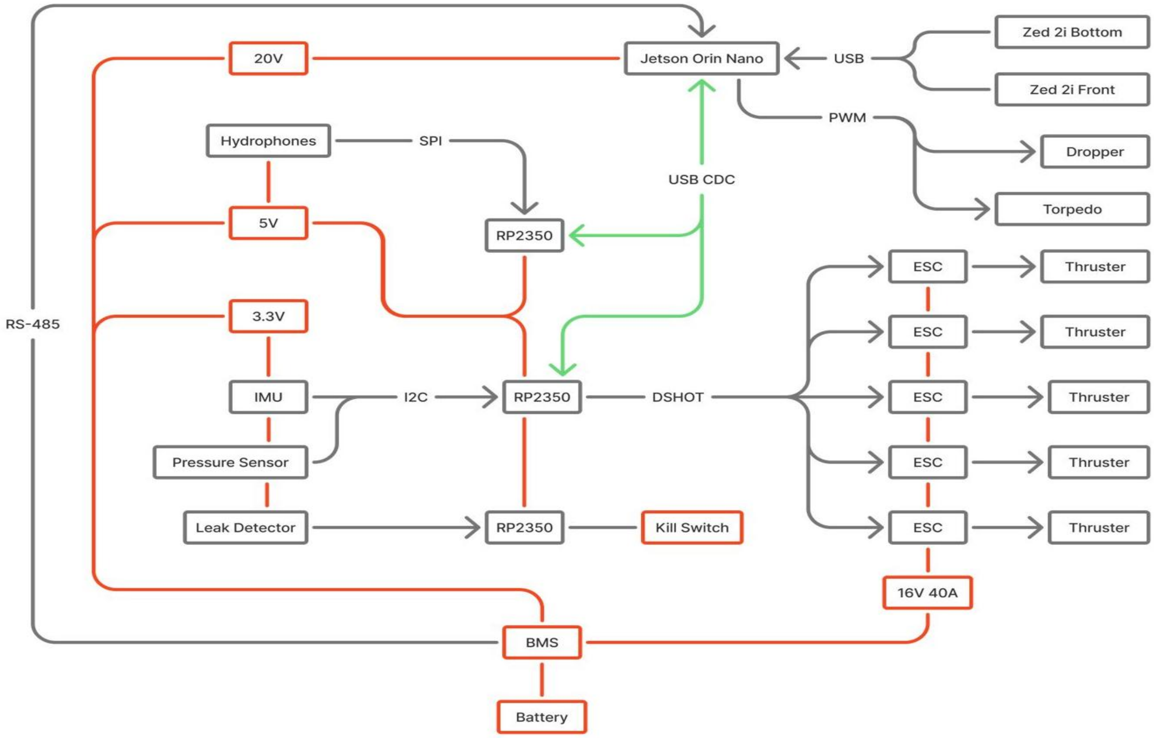

Fig. 12: Electrical Architecture of Deuterium

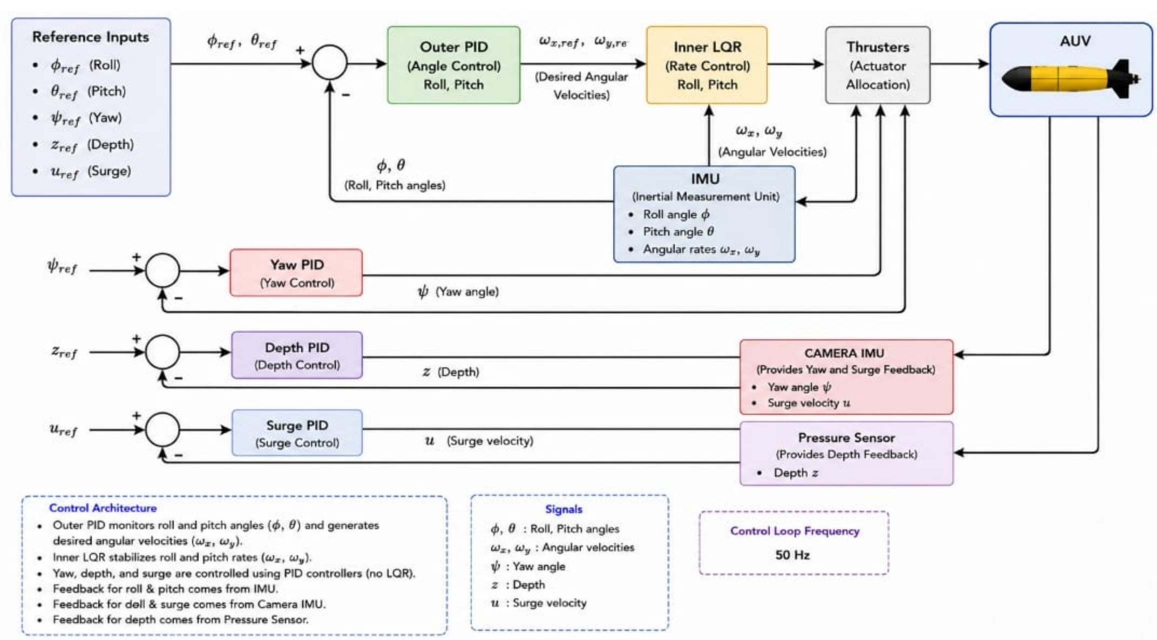

Fig. 13: Control System Block Diagram

APPENDIX-D

OUTREACH ACTIVITIES

AUV MIT-B actively participated in multiple outreach activities and technical interactions to promote awareness about underwater robotics and autonomous systems. Through presentations, competitions and collaborative discussions, the team aimed to engage with the student community, industry professionals and fellow engineering teams while sharing the development journey of the project.

IEEE RAS Competition – Vidyashilp University

The team participated in the IEEE Robotics and Automation Society (RAS) competition conducted at Vidyashilp University. The project was evaluated based on innovation, technical implementation and system integration. AUV MIT-B secured first place in the competition, which served as an important achievement and recognition of the team's engineering efforts and collaborative development process.

Technical Interaction at ARTPARK, IISc Bengaluru

As part of the team's outreach and collaborative learning activities, members of AUV MIT-B visited ARTPARK at the Indian Institute of Science (IISc) Bengaluru. The visit involved discussions with researchers and other technical teams regarding the project, underwater robotics and autonomous systems development. These interactions provided valuable exposure to ongoing research activities and encouraged exchange of technical knowledge and ideas.

Industry Presentation for Alstom

The team was also given the opportunity to present the project to engineers and representatives from Alstom. The presentation focused on the system architecture, subsystem integration and development methodology followed during the project. This interaction enabled the team to receive professional feedback from industry experts while gaining exposure to engineering practices followed in industrial environments.