Design And Development of Remotely Operated Vehicle VARUNA 4.0

SYSTEM OVERVIEW:

Varuna 4.0 is a Remotely Operated Underwater Vehicle (ROV) developed to address the multi-stage challenges of the upcoming competition, with emphasis on precision maneuvering, robust control, and reliable perception in underwater environments. The ROV uses eight-thruster configuration to achieve stable six-degree-of-freedom motion, enabling accurate gate traversal, station keeping and payload manipulation. A pressure sensor provides continuous depth estimation while an onboard IMU supports attitude stabilization and closed-loop PID control for enhanced maneuverability and endurance. Visual perception is achieved using three onboard cameras positioned to support forward navigation, downward inspection and manipulation tasks. The software architecture is built around the Robot Operating System (ROS) ensuring modular integration of sensors, control algorithms, and operator interfaces. Through a robust mechanical design and a sensor-driven control strategy, Varuna 4.0 is engineered to reliably perform all competition tasks, including endurance navigation, low-light color-guided maneuvering, and QR-based pickup and placement operations.

COMPETITION STRATEGY:

To successfully accomplish all AMU-ROVc 4.0 tasks, Varuna 4.0 is designed with primary focus on precise control, reliable depth stabilization, and effective visual feedback.

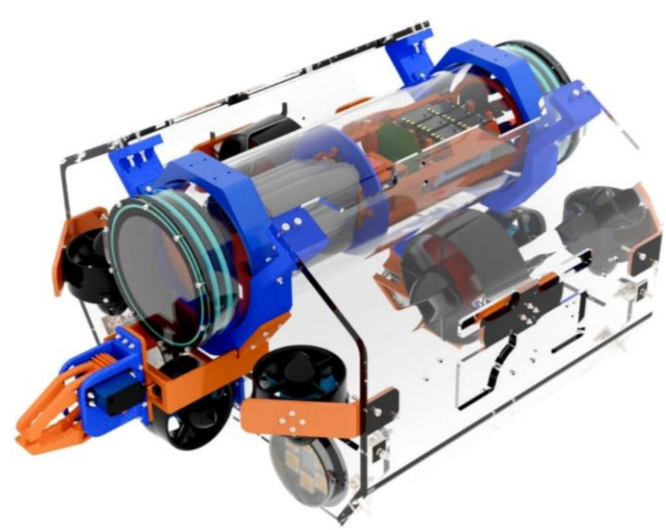
For Task 1 (Gate Navigation & Endurance): the eight-thruster layout combined with IMU-assisted PID control enables rapid gate traversal within the stipulated time while maintaining stable submerged operation for endurance scoring.

In Task 2 (Night Challenge: Color-Guided Zigzag): the forward-facing camera and onboard lighting system provide clear visual identification of assigned colored gates while depth control via the pressure sensor ensures navigation in low-light conditions.

For Task 3 (QR-Guided Pickup & Placement): the downward-facing camera is used to detect and interpret QR codes with ROS-based decision logic assisting navigation toward the correct pickup and drop locations. The vehicle's stable attitude control and precise depth regulation allow accurate weight retrieval and release.

Overall, the integration of sensors, ROS-based control and a highly maneuverable thruster configuration positions Varuna 4.0 for consistent task completion of all competition stages.

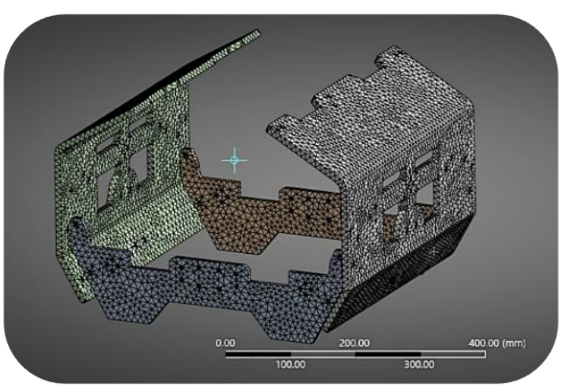
MECHANICAL DEPARTMENT



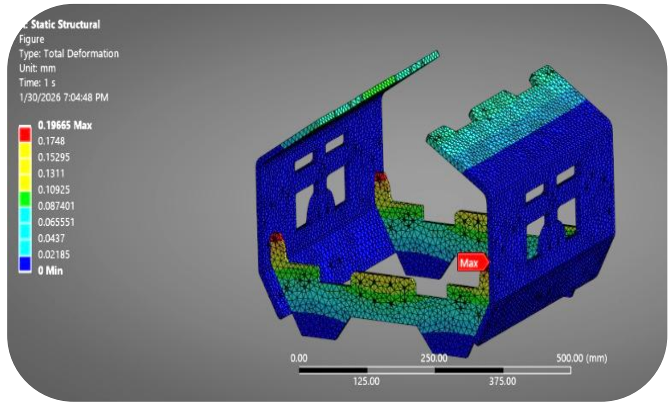
Varuna 4.0

Mechanical Frame

The frame of Varuna 4.0 is uniquely designed with careful consideration of static and dynamic stability, structural integrity, optimized weight distribution, and ease of accessibility and disassembly. Instead of relying on a single material, the frame employs a hybrid construction using clear virgin cast acrylic, PETG and Carbon Fiber Reinforced Plastic Composite allowing an effective balance between strength, stiffness, and manufacturability. The primary load-bearing edge plates are fabricated from 12 mm thick acrylic, ensuring adequate resistance to bending and torsional loads encountered during maneuvering and endurance tasks. To achieve the desired hydrodynamic profile, thermoforming and controlled bending of acrylic sheets were employed, enabling smooth contours and improved flow characteristics while maintaining structural rigidity. The ROV is designed to operate with near-neutral buoyancy to minimize steady-state thrust requirements and improve overall energy efficiency. Buoyancy is achieved through careful volume distribution of the pressure hull and syntactic foam, ensuring that the buoyant force closely balances the vehicle's weight in water. Stability is ensured by maintaining a deliberate vertical separation between the center of buoyancy and the center of gravity, with the center of buoyancy positioned above the center of gravity. The frame geometry was modeled based on parameters such as strength, stiffness, weight, machinability, safety, and aesthetics. Laser cutting was used for precise fabrication of acrylic components, and topology optimization was applied to reduce overall weight while retaining sufficient structural strength. The frame directly supports all critical subsystems including the electronics hull, thrusters, pneumatic system, and camera housings. Structural analysis of the complete frame was carried out in ANSYS to validate performance under expected static and dynamic loading conditions.



Mesh Analysis



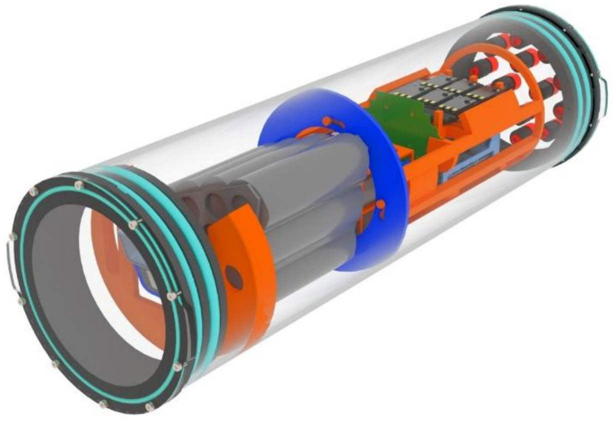
Deformation Analysis

Waterproof Hulls

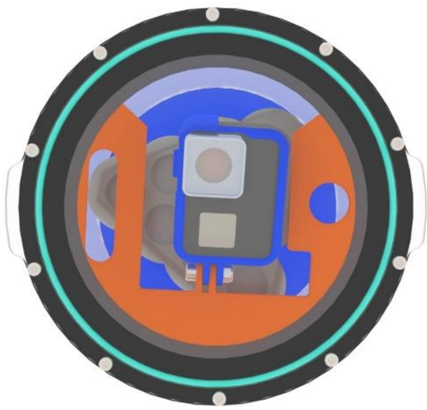
VARUNA 4.0 has 1 cylindrical waterproof hull housing for onboard electronics and 1 external cuboidal hull for vision cameras.

Electronics Hull: A cylindrical hull is used for housing the electronics stack of the ROV. The hull is made of acrylic. The hull has an inner diameter of 151.95 mm and an outer diameter of 164 mm and is 540mm long.

The electronic hull is sealed using two flanges and end caps mounted at either end of the cylindrical enclosure. One end is fitted with a solid blank end cap, while the opposite end incorporates an end cap machined with 10mm diameter ports to accommodate electrical connectors for thrusters and vision cameras. Watertight integrity is ensured through the use of BUNA-N O-ring seals integrated within the flange assembly, providing reliable protection against water ingress. The cylindrical geometry of the hull simplifies sealing and offers superior resistance to leakage under hydrostatic pressure, while also contributing to enhanced structural stability. Additionally, the cylindrical hull design is readily available, cost-effective, and well-suited for underwater applications due to its uniform stress distribution and ease of fabrication.



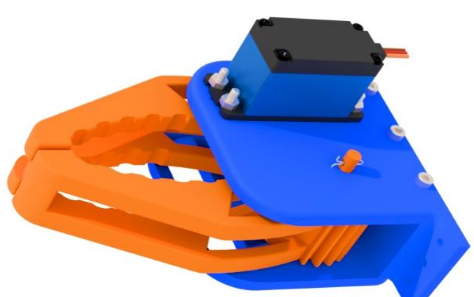
Electronics Hull



Front View

Gripper

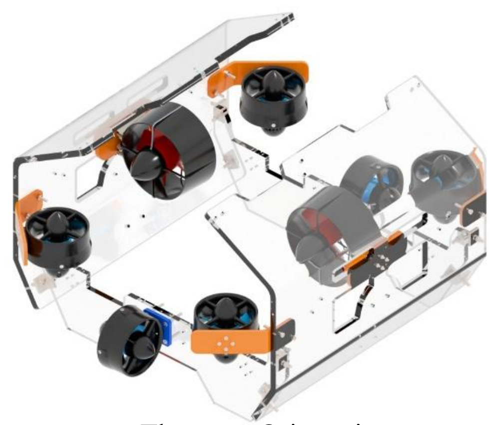
The gripper of Varuna 4.0 is a compact, parallel-jaw mechanism designed for reliable pickup and placement of the competition-specified cylindrical payload. It features contoured jaws for improved contact and secure gripping, with a mechanically synchronized actuation system to ensure symmetric motion. The open-frame structure reduces hydrodynamic drag and provides clear visibility from the downward-facing camera for accurate alignment. The gripper is modular and detachable, allowing easy installation without significantly affecting the vehicle's stability or center of mass.



Gripper

Propulsion System

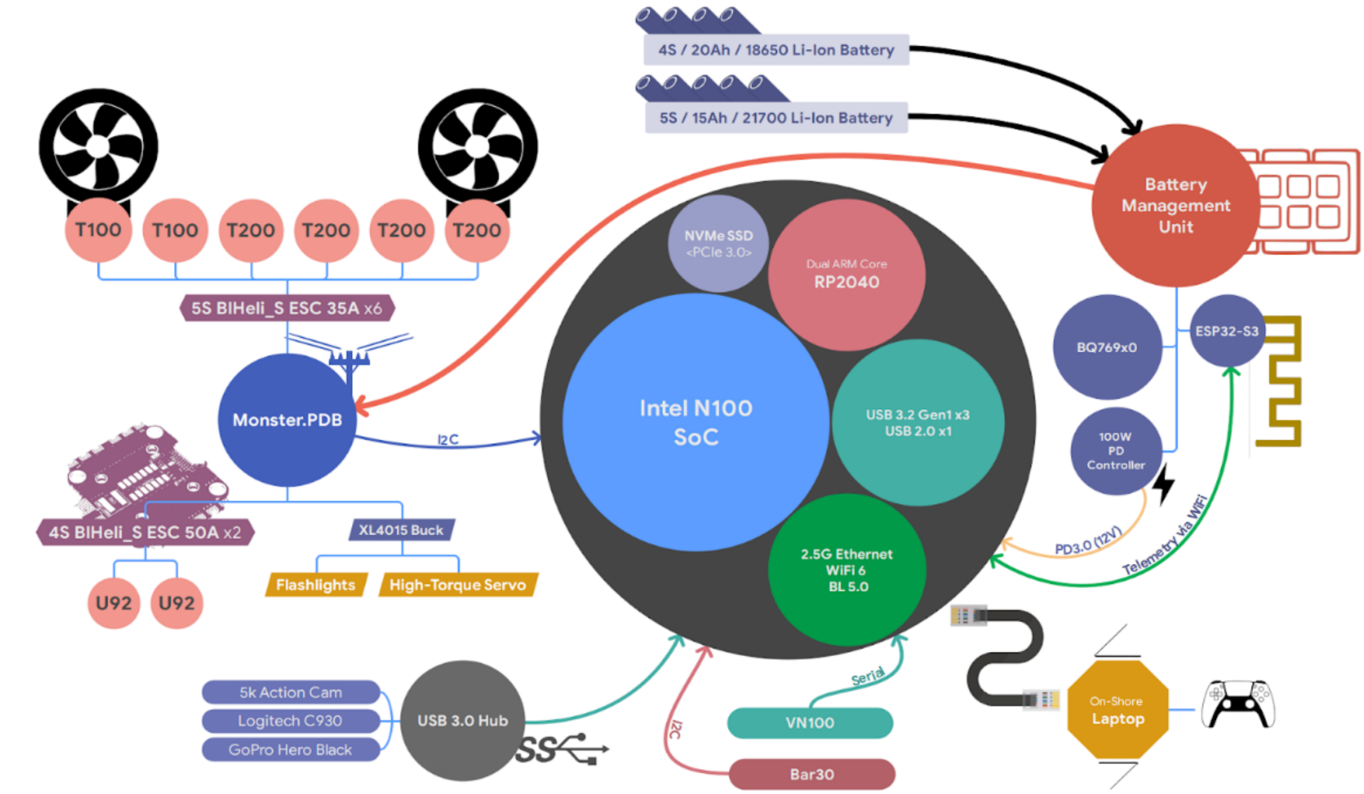
In the previous iteration, the vehicle employed a six-thruster configuration to achieve six degrees of freedom by mechanically coupling multiple axes of motion to individual thrusters. While this arrangement enabled basic maneuverability, it required significant thrust vector mixing, leading to reduced control authority, higher coupling between motion axes and limited stability during precision tasks. In the current design, the propulsion system has been upgraded to an eight-thruster configuration, allowing independent and dedicated control of heave, surge, and sway motions. This increase in thruster count reduces axis coupling, distributes thrust loads more evenly, and improves overall maneuverability and responsiveness. The additional thrusters provide higher redundancy, improved fault tolerance, and finer control during low-speed operations such as gate alignment, station keeping, and manipulation.



Thrusters Orientation

ELECTRICAL DEPARTMENT

The ROV is designed to provide a high-performance and power-efficient control backbone for underwater operation. The design focuses on robust power management, tight integration of computation and control and efficient handling of both high-current propulsion loads and sensitive logic electronics. By adopting a modular and consolidated electronics architecture, the embedded system supports real-time actuation, sensor interfacing, vision processing, and tether-based communication while minimizing wiring complexity and electrical interference. This approach results in a compact, scalable, and dependable electronics stack capable of supporting stable navigation, precise control, and extended underwater missions.

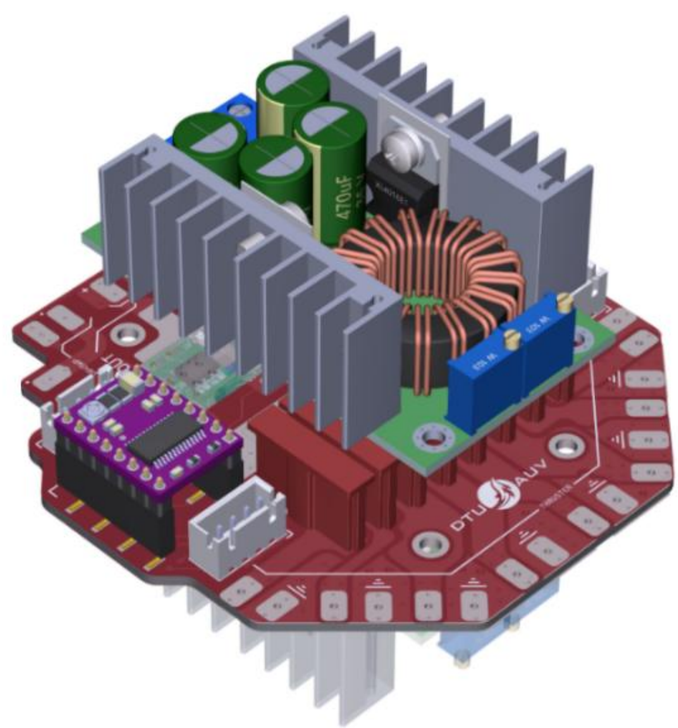


VARUNA 4.0 - ARCHITECHTURE

Power Distribution System

In the current design, the power architecture builds directly upon the experience gained from the previous iteration's Monster Power Distribution Board maximizing its strengths while addressing its limitations through a more integrated approach. The Monster PDB provided critical insight into high-current routing, thermal behavior of power traces, regulator placement, and fault isolation under sustained thruster loads, which directly informed the design of the present Battery Management Unit (BMU). Alongside this, two custom-built battery packs are employed to support high-duty-cycle operation while isolating sensitive logic electronics from propulsion-induced noise.

Two Li-Ion Battery packs, each protected by BMS, are designed to safely handle sustained 70–90% thruster duty cycles. The BMU now acts as the centralized power source for all onboard subsystems, retaining the proven high-current distribution philosophy of the Monster PDB while integrating regulated power delivery for thrusters, logic electronics, and auxiliary loads. By combining validated design principles from the Monster PDB with custom battery packs and integrated regulation, the updated power system achieves improved electrical robustness, reduced wiring complexity, and higher overall reliability compared to the previous iteration.



Power Distribution Board

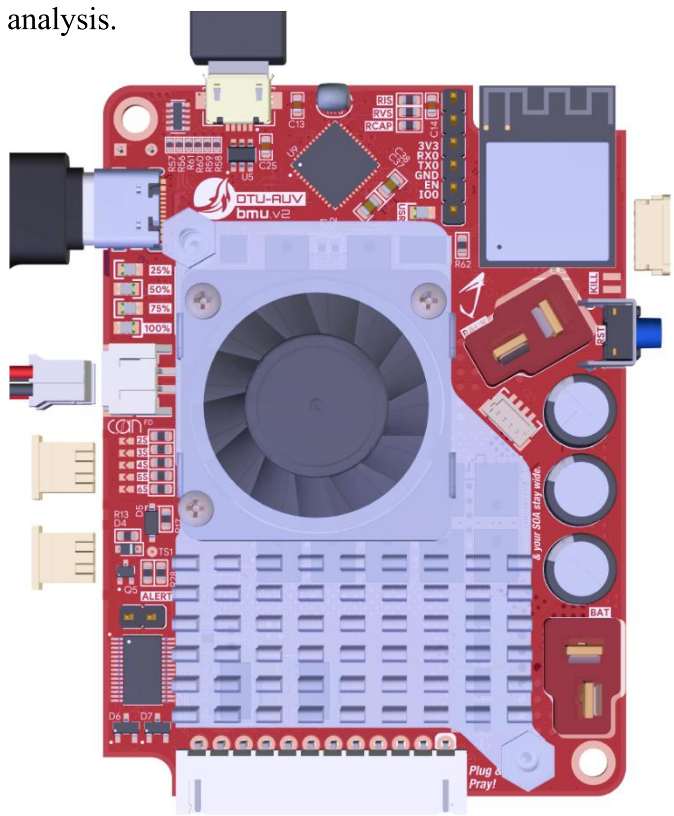
Control System

In the previous design, onboard computation and control were distributed across multiple processing units, including a Raspberry Pi for high-level tasks, an Arduino for real-time control, and an ESP-based module for auxiliary functions, which increased system complexity due to inter-board communication, additional power regulation stages, higher wiring density, and latency between computation and actuation. In the current iteration, these roles are consolidated into a single Radxa X4 platform serving as the sole onboard computing unit for mission logic, vision processing, and tether-based communication. The Radxa X4 is powered by an Intel N100 processor and equipped with 8 GB LPDDR5 RAM, support for M.2 2230 NVMe storage, dual micro-HDMI outputs up to 4K, multiple USB 3.2 and USB 2.0 host ports, and a 2.5 Gb Ethernet interface with PoE support, providing a substantial increase in computational throughput, memory bandwidth, and I/O capability. Integrated wireless connectivity, GPIO expansion, and native Power Delivery input further simplify system integration. Compared to the Raspberry Pi 5 used previously, the Radxa X4 offers superior CPU performance, faster memory, PCIe-based storage expansion, and higher-bandwidth networking, making it better suited for compute-intensive tasks such as multi-camera vision processing and sensor fusion. This unified architecture simplifies power distribution and signal routing, resulting in a more compact, modular, and easily maintainable embedded system with fewer failure points and improved overall reliability.

Radxa-X4 SBC

Battery Management Unit

The Battery Management Unit (BMU) is an in-house designed subsystem that serves as the centralized power and monitoring backbone of the ROV, optimized for high-current operation, flexibility, and system-level integration. It is engineered to handle substantially higher current levels than off-the-shelf solutions through optimized PCB layout and thermal design, ensuring stable operation under sustained high-load conditions. Direct integration with custom battery packs enables enhanced protection, health monitoring, and precise control of operating limits for safer and more efficient energy utilization. The BMU integrates an ESP32-S3 to provide wireless telemetry, debugging, and configuration, enabling real-time monitoring and parameter adjustment without physical access to the vehicle. Its hybrid power topology supports a wide input range from 3S to 10S and incorporates current sensing for accurate load monitoring and fault detection across propulsion and logic subsystems. A 100 W onboard USB Power Delivery controller directly powers high-performance single-board computers, simplifying power routing and eliminating external regulators. Support for CAN-FD communication and SD-card-based data logging further enhances system diagnostics, robustness, and post-mission analysis.



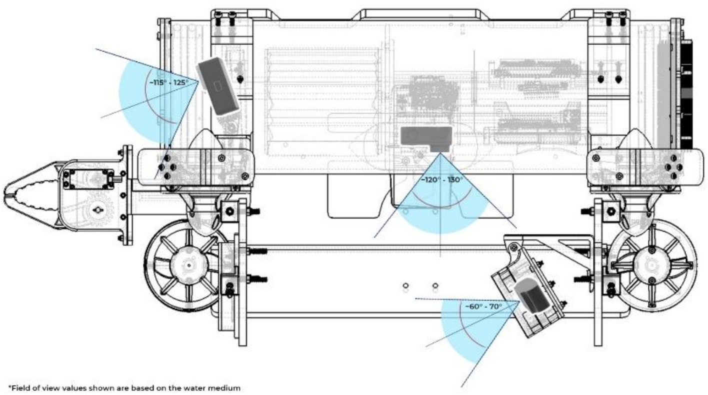
BMU v.2

Sensors and Imaging System

The ROV employs a combination of vision sensors and navigation sensors to provide visual situational awareness, depth estimation, and attitude information required for stable operation and manipulation tasks. This configuration is selected to ensure reliable perception of the underwater environment, precise depth control, and robust orientation feedback while covering all critical viewpoints of the vehicle, including the pool floor and gripper workspace.

Visual sensing is implemented using three cameras: a An Action Camera is mounted on the underside of the ROV within an external hull and angled to provide a clear view of the pool floor, a front-facing GoPro mounted inside the electronics hull at an angle to monitor gripper activity and Logitech camera mounted at the bottom of the electronics hull to provide additional downward visual feedback.

Depth and pressure measurements are obtained using a BAR30 sensor, enabling accurate depth estimation and closed-loop vertical control, while vehicle orientation and inertial data are provided by a VN-100 IMU to support stabilization, navigation and sensor fusion algorithms.



Camera Angles

SOFTWARE DEPARTMENT

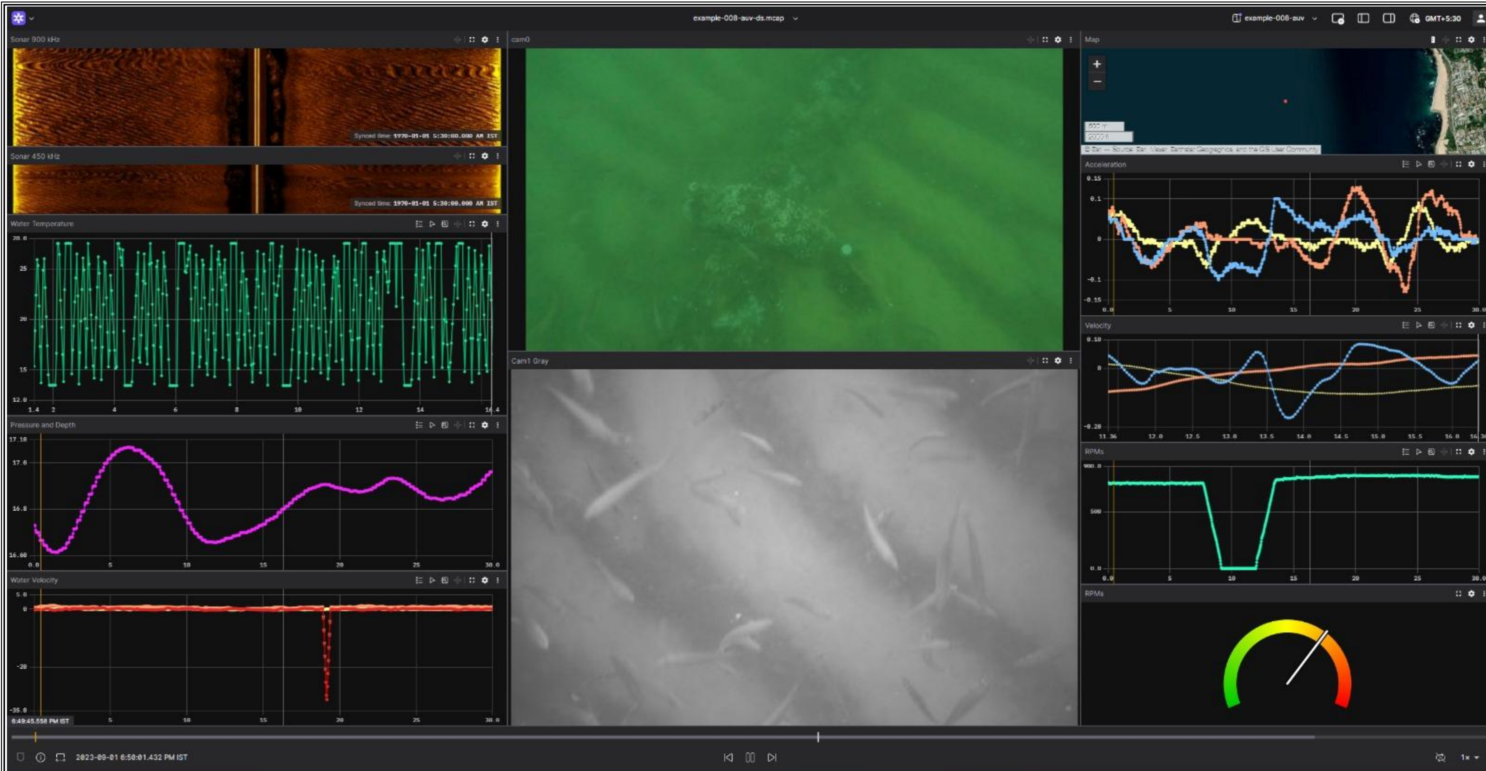
Graphical User Interface (GUI):

The software team developed a custom graphical user interface (GUI) to enable intuitive and efficient monitoring of the vehicle, ensuring ease of use even for operators with minimal experience. The GUI was designed using Foxglove to support real-time visualization of sensor data and processed camera feeds. It provides simultaneous access to three live video streams from the front, rear, and bottom-mounted cameras, along with essential telemetry data.

The chosen software architecture offers a modular and scalable framework that simplifies system expansion, debugging, and future upgrades. Centralized visualization of telemetry and visual data reduces operator cognitive load while enabling real-time performance monitoring and fault detection. This architecture improves operational reliability, supports rapid operator training, and ensures smooth manoeuvrability of the vehicle, making it well-suited for both manual operation and future autonomous or remote mission extensions.

Image Enhancement:

We explored several underwater image enhancement techniques to improve the accuracy for object and colour detection tasks. We have implemented a general Structural Patch Decomposition and Fusion (SDPF) approach. It consists of deconstructing two complementary images (one is contrast-corrected and the other is detail-sharpened) into key components like mean intensity, contrast, and structure, and then fusing the corresponding components to produce a final enhanced image.

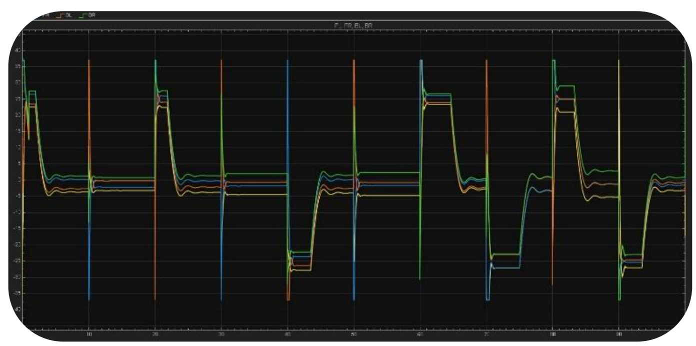


GUI Interface

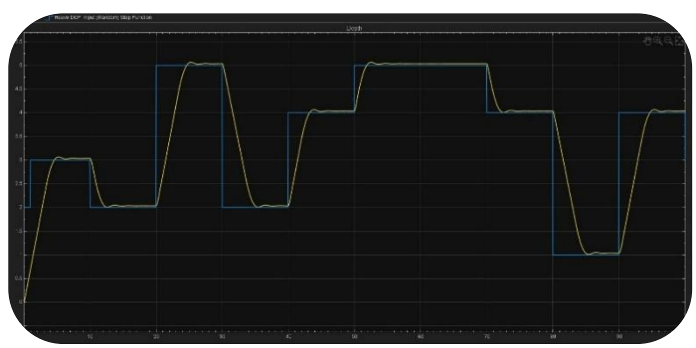
PID:

The control system of the vehicle is structured in a bifurcated PID fashion to maximize control in the different axes with a hybrid thruster configuration. In terms of vertical movement (depth control) and attitude control (orientation control), particularly in heave, pitch, and roll, a quadruple configuration of four Blue Robotics T200 thrusters is used. The PID controller takes in real-time data from the inertial measurement unit (IMU) and depth/pressure sensor to proportionally control the PWM signals sent to the four thrusters; heave is maintained through collective thrust, while pitch and roll are maintained through antagonistic torque pairs, which provide high-precision depth control and horizon leveling.

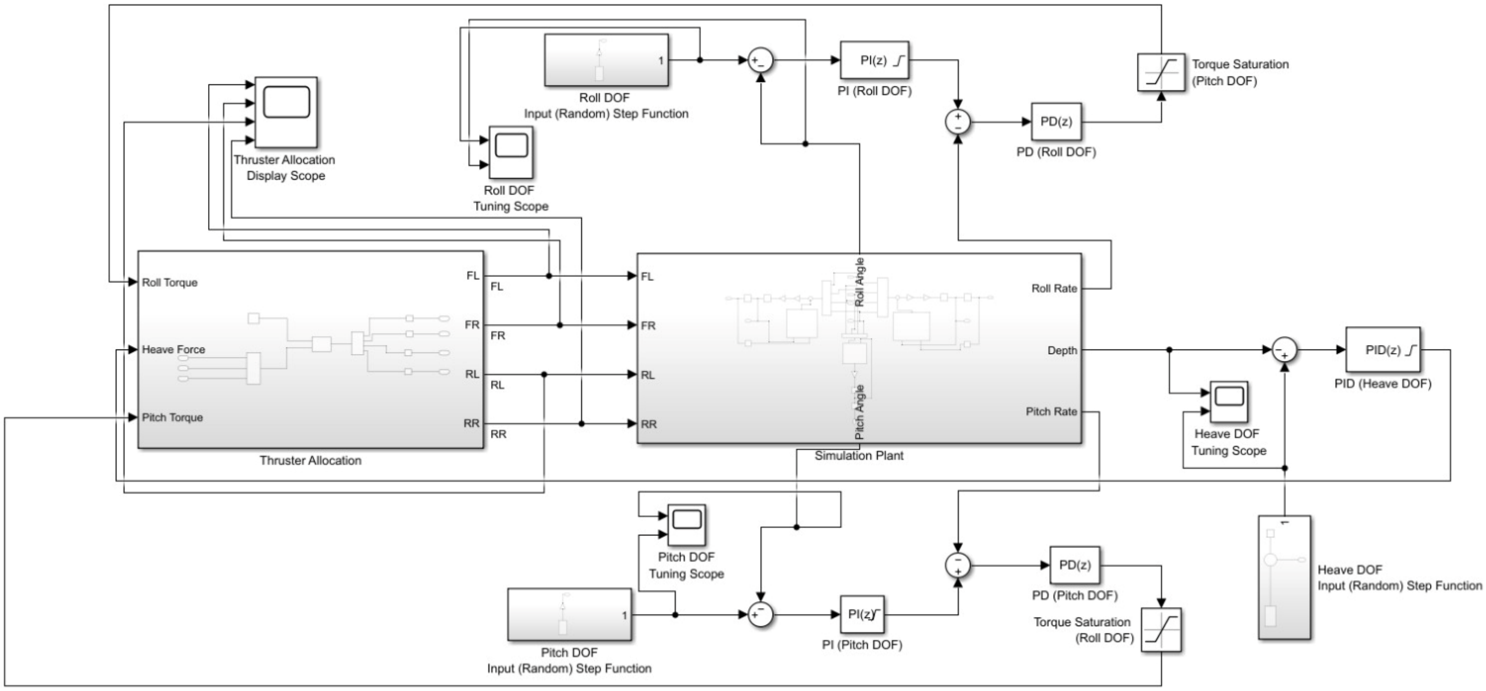
For heading direction and yaw control, however, the system uses two high-torque U92 thrusters. The dual-thruster configuration enables the PID controller to solely control the rotational displacement in the vertical axis. Through differential thrust between the two U92 thrusters, the system is able to provide quick changes in heading direction and precise station-keeping without affecting the other axes controlled by the T200 thrusters, providing a decoupled control system that improves response time and energy consumption during complex underwater operations.



Orientation Control



Depth Control



PID Control Loop

ROS 2 Implementation:

The communication infrastructure of the system is built around the ROS2 framework, which serves as the core middleware enabling reliable and real-time coordination between onboard hardware and the operator station. ROS2 facilitates structured data exchange across distributed nodes, supporting the transmission of critical telemetry parameters, control commands, and PWM values to the Foxglove graphical user interface (GUI). This centralized, node-based architecture allows for modular integration of sensors, actuators, and control algorithms while maintaining deterministic communication behavior. In addition to low-latency control and telemetry exchange, ROS2 is responsible for streaming high-bandwidth camera feeds over dedicated topics, enabling synchronized visual feedback alongside system state information. This architecture ensures minimal communication latency, improved fault isolation, and scalable data handling, allowing the operator to monitor thruster performance, vehicle state, and surrounding environmental conditions through a single, unified interface.

Machine Learning:

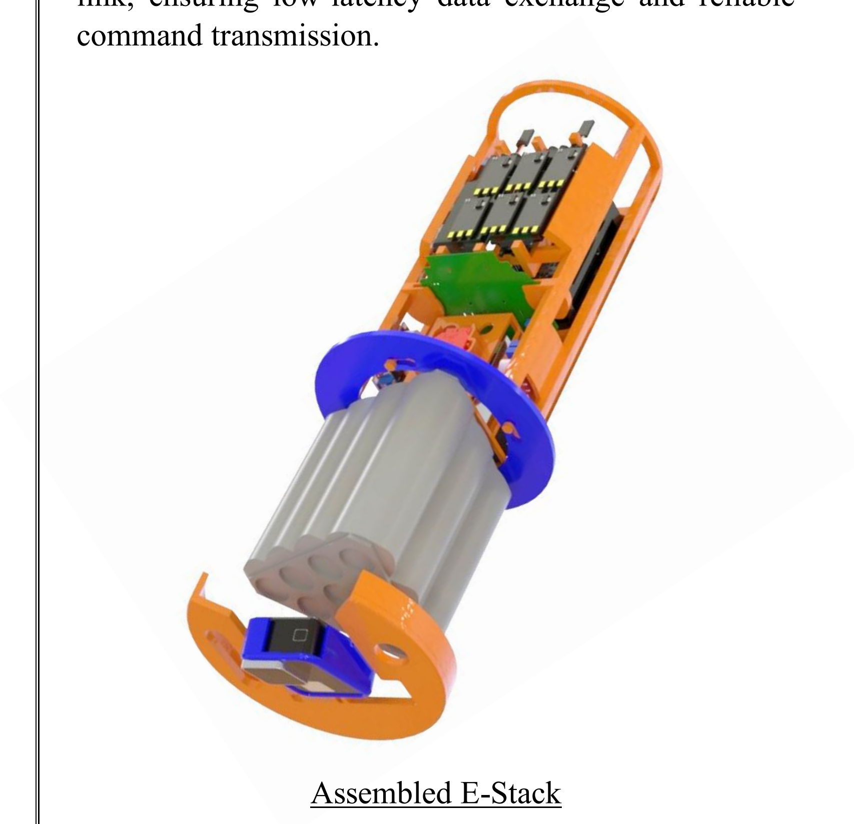
We utilized Unity's Perception package to generate a synthetic dataset consisting of images of underwater gates along with their annotation files. This approach was used to create a diverse dataset with abundant randomizations in underwater lighting, camera angles, noise wtc., to ensure good model prediction accuracy in real scenarios. This dataset was first uploaded on Roboflow to be trained and tested on their server API and on confirmation of accurate results for the gate detection task, was trained locally with YoloV8 using python's ultralytics module. It was further optimized using OpenVINO before final integration in the ROS2 architecture.

Model Trained on Unity Perception

System Integration

The system architecture of Varuna 4.0 is designed to ensure seamless integration and synchronization between all hardware and software subsystems while maintaining reliability and real-time performance. A centralized computing architecture is employed, with the onboard single-board computer acting as the primary node for mission logic, perception, control computation, and operator communication. All sensors, actuators, and power subsystems interface through well-defined electrical and software layers, enabling deterministic behaviour and modular expandability.

Hardware components including thrusters, sensors, cameras, and power systems are interconnected through a centralized electronics stack powered by the Battery Management Unit (BMU). The BMU distributes regulated power to propulsion, computation, and auxiliary subsystems while simultaneously monitoring current, voltage, and system health parameters. Sensors such as the IMU and pressure sensor provide continuous feedback to the control system, while multiple cameras stream visual data for navigation and task execution. Communication between the onboard system and the operator station is established via a tethered Ethernet link, ensuring low-latency data exchange and reliable command transmission.



Assembled E-Stack

Data flow within the system is managed through a structured software pipeline built on the ROS 2 framework. Sensor data is published as ROS topics and consumed by control and perception nodes for real-time processing. Control algorithms compute actuator commands based on sensor feedback and operator inputs, which are then converted into PWM signals for thruster actuation. High-bandwidth camera streams are handled on dedicated ROS topics to maintain synchronization between visual feedback and vehicle state information. This node-based architecture enables clear separation of perception, control, and interface layers while maintaining synchronized system operation.

Safety and fault handling are addressed through both hardware and software mechanisms. The BMU incorporates overcurrent protection, battery management, and real-time power monitoring to prevent electrical faults and unsafe operating conditions. Electrical isolation between propulsion and logic subsystems minimizes noise-induced failures. On the software side, continuous telemetry monitoring enables early detection of abnormal sensor readings, power anomalies, or communication drops. In the event of detected faults, the system allows controlled shutdown of affected subsystems and provides real-time feedback to the operator, ensuring safe operation and recoverability during underwater missions.

Kill Switch

Challenges and Improvements

Propulsion Coupling and Limited Manoeuvrability

Challenge:
The previous vehicle iteration utilized a six-thruster configuration in which multiple degrees of freedom were mechanically coupled to individual thrusters. This resulted in significant thrust vector mixing, reduced control authority, and instability during precision manoeuvres such as gate alignment, station keeping, and manipulation.

Solution:
The propulsion system was upgraded to an eight-thruster configuration with dedicated thrusters for heave, surge, sway, and yaw. This reduced inter-axis coupling, improved thrust distribution, enhanced fault tolerance, and provided finer low-speed manoeuvrability required for competition tasks.

Electrical Power Distribution Reliability

Challenge:
The earlier power architecture relied on a discrete power distribution board with limited integration of regulation and monitoring. Sustained high-current operation introduced thermal stress, increased wiring complexity, and insufficient isolation between propulsion loads and sensitive logic electronics.

Solution:
A centralized, in-house designed Battery Management Unit (BMU) was developed to integrate high-current power distribution, regulated outputs, battery protection, and current monitoring. Dual custom Li-ion battery packs with independent BMS protection were introduced to support high-duty-cycle operation while improving electrical robustness and safety.

Excessive System Complexity in Computing Architecture

Challenge:
Onboard computation and control were previously distributed across multiple processing units, leading to increased inter-board communication latency, complex wiring, additional power regulation stages, and higher system failure points.

Solution:
All computation and control tasks were consolidated onto a single Radxa-X4 single-board computer. This unified architecture reduced system complexity, minimized wiring and power stages, lowered latency between computation and actuation, and improved overall reliability and maintainability.

Depth and Orientation Control Instability

Challenge:
Coupling between yaw, pitch, roll, and depth control axes in earlier designs limited depth-holding accuracy and reduced orientation stability under disturbances during underwater operation.

Solution:
A bifurcated PID control architecture was implemented, separating vertical and attitude control from yaw control. Dedicated thruster groups combined with real-time feedback from the IMU and pressure sensor enabled precise depth regulation, improved orientation stability, and reliable station keeping.

Poor Underwater Visual Perception

Challenge:
Underwater imaging was affected by low-light conditions, colour attenuation, and reduced contrast, leading to unreliable visual detection of gates, markers, and payloads.

Solution:
A multi-camera vision system was integrated to provide forward and downward visual coverage. Image enhancement techniques using Structural Patch Decomposition and Fusion (SDPF) were applied, and machine learning–based gate detection was implemented using synthetically generated datasets to improve robustness under varying environmental conditions.

TEAM INFORMATION

Team Name: DTU-AUV

Delhi Technological University, Delhi-110042, India

Name	Department	Roles
Parag Gole	Embedded	Leads overall project execution, coordinates inter-departmental activities, and ensures timely and cohesive system development.
Nirman Aggarwal	Mechanical	Oversees mechanical subsystem development and manages administrative documentation and compliance.
Suyash Raiswal	Software	Lead ROS2 integration, PID control development, camera systems, and GUI and website implementation.
Aditya Agrawal	Mechanical	Manages mechanical design strategy, budgeting, and material procurement for the vehicle structure.
Raghav Singh Gosain	Embedded	Leads embedded firmware development and SBC interfacing using Embedded C and Python.
Uday Singh Goondli	Embedded	Oversees electronics stack design, system architecture, and technical documentation.
OD Madhav Prakash	Embedded	Designs and assembles power distribution systems and custom battery packs with precision hardware work.
Ansh Wadhera	Embedded	Handles battery pack construction, power distribution, and manual hardware assembly tasks.
Vighnesh R Pai	Embedded	Designs battery management system, battery integration, and final electronics stack assembly.
Smit Bachan	Embedded	Develops SBC networking and PID control code, integrating embedded hardware with software logic.
Azhar Jawed	Embedded	Conducts embedded R&D with focus on advanced motor control and Field Oriented Control implementation.
Arshia Dhar	Software	Directs software architecture upgrades, system tuning, and machine learning integration and simulation.
Sugam Arora	Software	Supports PID algorithm development and simulation-based validation of control strategies.
Marvin Rao	Mechanical	Handles structural design, simulation, and mechanical assembly including thrust and buoyancy analysis
Kushagra Rai	Mechanical	Executes mechanical assembly and component-level CAD modeling using SolidWorks.

Vyom Bhat	Mechanical	Responsible for CAD modeling, mechanical analysis, and maintenance of technical documentation.
Jaiveer Singh	Embedded	Provides financial planning support and R&D guidance based on prior ROV experience.
Dev Verma	Mechanical	Manages financial advisory tasks and contributes legacy system insights for design improvements.
Hriday Bhardwaj	Software	Assists in financial management and technical review using knowledge from previous ROV iterations.
Vatsal Mahajan	Software	Assists in financial management and technical review using knowledge from previous OpenCV iterations.

APPENDIX A: COMPONENT SPECIFICATIONS

Component	Vendor	Model/Type	Specs
Frame	Custom	Clear virgin cast acrylic	10 mm thickness, laser-cut panels with 3D-printed PETG/Carbon Fibre structural holders
Waterproof Housing	Custom	Acrylic	6-inch diameter acrylic tube, rated for shallow-to-mid depth operations
Waterproof Connectors	Blue Robotics	Potted Cable	Epoxy-potted waterproof cable assemblies, pressure-tolerant, corrosion-resistant
Thrusters	Blue Robotics	T100, T200, U92	T200: high-thrust (≈5.1 kgf), T100: medium-thrust (≈2.4 kgf), U92: High Thrust (≈9 kgf)
Motor Control	ROBU	Ready to sky BL-Heli	50A, 35A respectively
Control System	Evalta	Radxa-X4	Intel N100 processor, 8 GB LPDDR5 RAM, M.2 2230 NVMe SSD, dual micro-HDMI (up to 4K), multiple USB 3.2 & USB 2.0 ports, 2.5 Gb Ethernet
Actuators	Custom	3D Printed	Servo-driven 3D-printed manipulators and mechanisms for task execution
Vision	Amazon	Go Pro Hero Black 4K Action Camera Logitech Kreo	Go Pro Hero Black: 4K video recording; Logitech: Full HD 1080p (1920×1080) video up to 60 fps
Pressure Sensor	Blue Robotics	BAR 30	Depth rating up to 300 m, resolution ~2 mm, I2C interface

IMU	Vector Nav	VN 100	9-axis IMU (accelerometer, gyroscope, magnetometer), low-latency orientation estimation
Battery	Custom	Li-ion	Dual-battery system: 4S-8P and 5S-4P configurations for power and endurance balancing
Waterproof Flange	ROV Maker	Aluminum Flange	O-ring sealed end-cap flange, supports cable penetrators and pressure sealing

Declaration of Originality

We hereby declare that the work presented in this Technical Design Report is an original effort carried out by the team members of DTU-AUV for the development of Varuna 4.0. All system designs, analyses, implementations, and results described in this report have been developed by the team unless explicitly stated otherwise. Any external resources, references, tools, datasets, or prior research utilized during the design and development process have been properly acknowledged and cited in the references section. This report does not contain any material that has been previously submitted for evaluation in any other competition, publication, or academic requirement without due attribution.

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