INDIAN INSTITUTE OF TECHNOLOGY, GUWAHATI

Underwater Vehicle Design Challenge (UVDC) Report

TEAM SUBNAUTICA

Team Lead: **Siddarth Gupta**

Orthographic View of the ROV

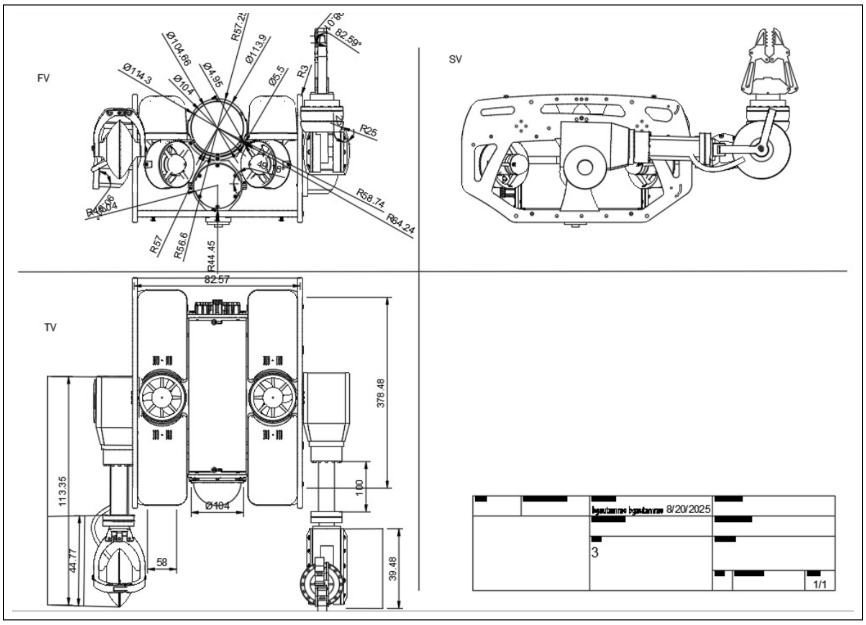

Figure 1: Orthographic view of the ROV.

Isometric View of the ROV

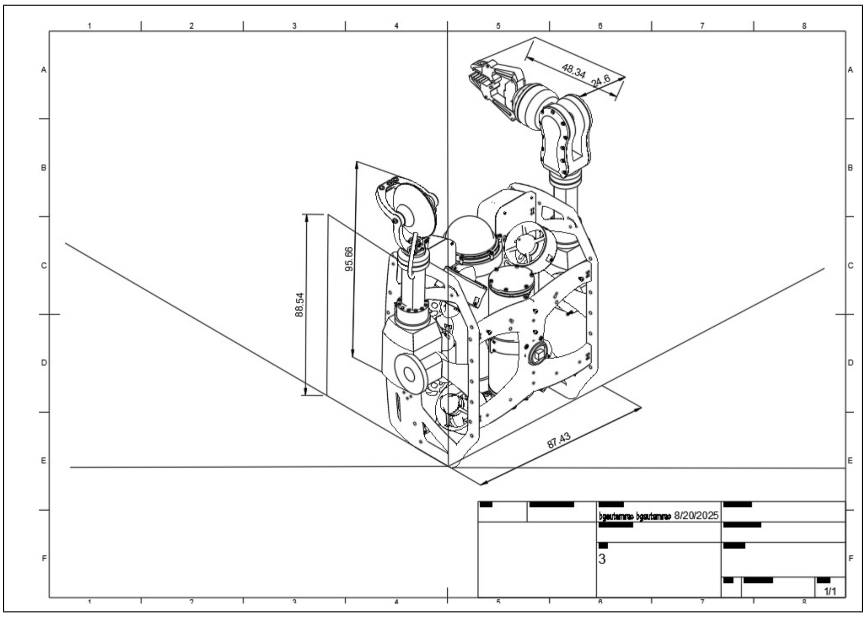

Figure 2: Isometric view of the ROV.

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1 Introduction

1.1 Overview of the Challenge

This report outlines the design and development of a Remotely Operated Vehicle (ROV) created in response to the **Underwater Vehicle Design Challenge (UVDC)**. The primary objective is to build a vehicle capable of executing a complex mission focused on the exploration of uncharted underwater caves and sinkholes. Our design directly addresses the core requirements of the competition by providing a comprehensive solution for navigation, data acquisition, and in-situ analysis in a high-pressure, turbulent environment. The ROV is engineered to fulfill the following critical mission parameters:

- **3D Mapping and Navigation:** The ROV is capable of 3D mapping and reconstruction of the entire cave system using advanced Sonar technology to generate precise terrain models. This is crucial for navigating complex, GPS-denied cave systems.
- **Environmental and Anomaly Detection:** The vehicle is capable of detecting, avoiding, and reporting anomalies such as volcanic vents, zones of extreme temperature or acidity, and chemically hazardous regions. Where possible, the ROV measures and quantifies the severity of such conditions.
- **Continuous Data Acquisition:** The system continuously logs geographical data, including pH, temperature, pressure, salinity, and current dynamics.
- **In-situ Analysis:** The vehicle incorporates integrated soil and water sample analysis modules for detecting and categorizing mineral content, pollutants, or unusual biological markers. It also systematically records mineral and oil concentrations every 100 square meters to aid in geological and environmental surveys.
- **Resilient Mobility:** The ROV's design includes resilient mobility systems that allow it to traverse turbulent water flows, which are common in submerged cave networks.
- **Ecological Responsibility:** The design prioritizes ecological safety, ensuring zero disturbance or harm to the surrounding ecosystem.
- **System Reliability and Recoverability:** The design prioritizes a robust and recoverable platform. The mission has a maximum length of two days.

1.2 Mission Statement

Our mission is to design a multi-functional Remotely Operated Vehicle (ROV) capable of pioneering a new frontier of underwater exploration. The ROV will perform comprehensive tasks, including the 3D mapping and reconstruction of complex cave systems, real-time detection and reporting of environmental anomalies, and the continuous logging of vital geographical data. Central to this mission is the ability to conduct non-invasive marine biology analysis and analyze soil and water samples, all while prioritizing ecological safety and ensuring zero disruption to the delicate underwater ecosystem.

1.3 Mechanical Subsystem

Frame — Design Summary

Primary Geometry

The ROV frame is based on a modular space-frame constructed from anodized Al-6061-T6 extrusions with 6–8 mm plate nodes. The overall structure consists of four corner uprights, a top and bottom deck, and removable cross-members that form an internal equipment bay. Structural rigidity is achieved through X-bracing in plan and short K-braces in elevation, which stiffen both the fore–aft and lateral directions while leaving a central tunnel clear for housings and cable routing. Mission payloads are mounted to indexed hard-points on the front ring and to slotted rails on the lower deck, allowing adjustments to center of gravity (CG) and trim as required.

Thruster Placement

The ROV employs a vectored 6-degree-of-freedom (DOF) thruster layout, reinforced with gusseted bosses tied into both decks:

- **Surge pair (port/starboard, mid-height):** Oriented at approximately 20–30° toe-in, enabling combined surge and yaw authority in confined or narrow passages.
- **Sway pair (port/starboard, forward of CG):** Mounted on ring-stiffened side plates to provide precise lateral translation for operations such as cave wall following. Protective guards prevent contact with obstacles.
- **Heave pair (low, near skids):** Located beneath the CG to minimize pitch coupling during vertical station-keeping and manipulator operation.

Service gaps have been maintained to prevent thruster wash from impinging on sensor intakes or the suction arm nozzle.

Buoyancy Foam

Depth-rated syntactic foam blocks are distributed along the upper deck and corner uprights to maintain the center of buoyancy 20–30 mm above the CG, providing passive self-righting capability. The blocks are chamfered to minimize flow separation and are designed as removable cartridges for ease of field servicing. Thin Delrin shoes are used to isolate the foam from aluminum surfaces, preventing water tracking and galvanic corrosion.

Ballast System

The principle of controlled buoyancy is fundamental to ROV operations, facilitated primarily by the vessel's ballast system. This system allows for the precise management of the submarine's density relative to the surrounding water, enabling it to submerge, surface, and maintain specific depths. The core components are the main ballast tanks, which are flooded with seawater to increase the vessel's overall mass and achieve negative buoyancy for diving. To surface, compressed air is injected into these tanks, expelling the water and restoring positive buoyancy.

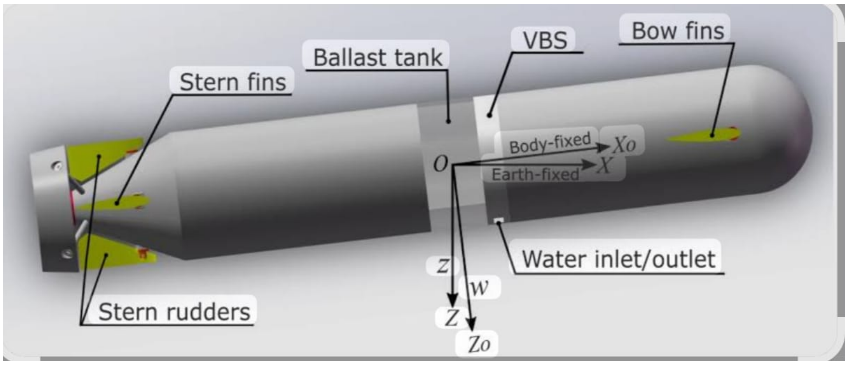

Figure 3: Balast Tank

Manipulator Arm Placement

Primary Manipulator

A manipulator arm is mounted on the lower left section of the front ring, reinforced by a continuous doubler plate spanning both front uprights. This pincher-type arm provides dexterous capability for selective collection and gentle handling of benthic targets, such as rock fragments, mineral nodules, and marine plant or biomat samples. It also serves utility functions, including placement of markers and operation of simple mechanical devices within cave environments.

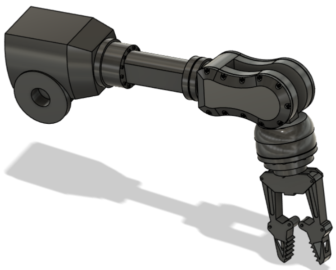

Figure 4: Primary Manipulator Arm

Seabed Sampling Arm

In addition to the primary manipulator, a seabed sampling arm is integrated on the lower right section of the front ring. This specialized tool uses a claw-like mechanism to scoop and retain sand and water slurry. Once collected, the material is transferred via a peristaltic pump into an onboard separation chamber. Inside this chamber:

- A sieve mechanism separates water from sand.
- In-situ analysis systems run tests on both the sediment fraction and the water sample.

The claw features an integrated soil-cutting saw with teeth facing inwards, which is automatically activated when hard or compacted soil is detected. This enables efficient penetration without requiring operator intervention.

The arm is also telescopic, allowing it to extend further into narrow fissures or deeper seabed regions where access would otherwise be limited.

Together, these features make the sampling arm a versatile scientific tool capable of sampling across a wide range of seabed conditions, enhancing the ROV's ability to support multidisciplinary exploration missions.

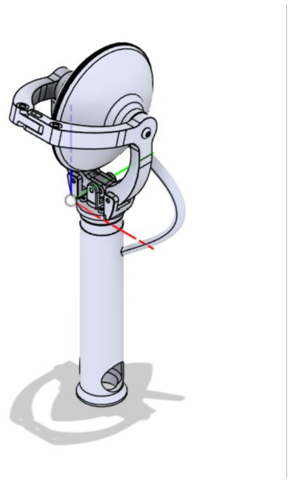

Figure 5: Slurry Collecting Arm

1.4 Electronic Subsystem

The electronic subsystem represents the core intelligence of the ROV, integrating sophisticated control, data acquisition, and sensing capabilities. The system is architected to facilitate both autonomous and teleoperated control, enabling the vehicle to navigate and perform complex tasks in uncharted underwater environments.

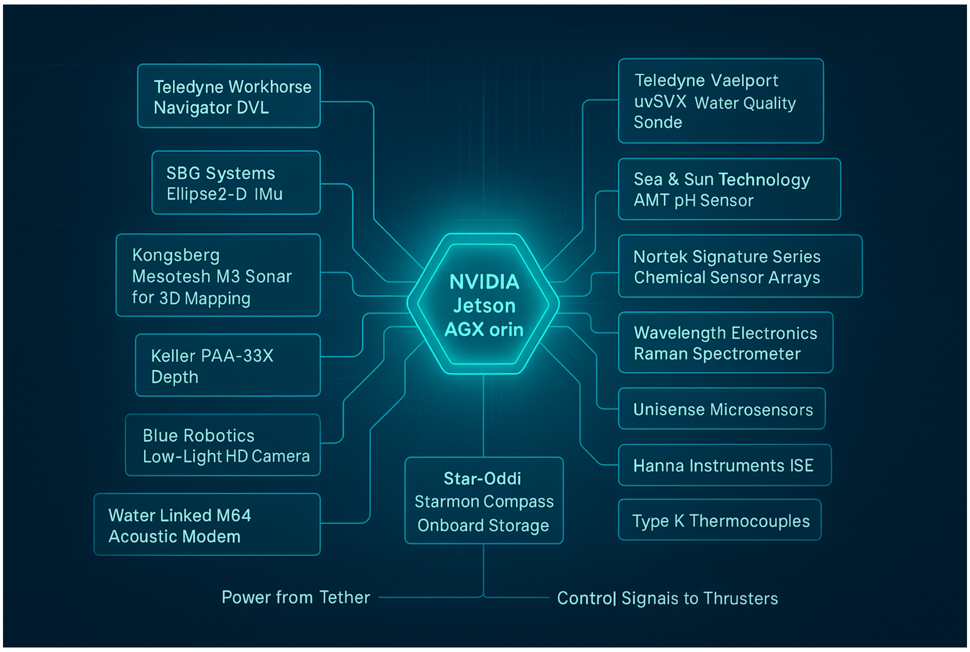

Figure 6: Block diagram of the ROV's electronic subsystem.

1.4.1 Central Processing and Control

The central processing unit, or "brain," of the ROV is an **NVIDIA Jetson AGX Orin**. This single-board computer provides the necessary computational power for demanding tasks such as real-time sensor data fusion, complex control algorithms, and machine learning models for automated navigation and anomaly detection. A custom **Printed Circuit Board (PCB)** serves as the main electronics hub, ensuring seamless and organized communication between the processor and all other electronic components. This board manages signal routing and provides a stable interface for the various subsystems.

1.4.2 Navigation, Odometry, and Mapping

Precise navigation in GPS-denied environments is achieved through a suite of integrated sensors. A **Doppler Velocity Log (DVL)** provides high-accuracy velocity measurements relative to the seafloor. This is complemented by an **Inertial Measurement Unit (IMU)**, which delivers continuous data for heading, attitude, and orientation. A multibeam **Sonar Array** is the primary tool for generating acoustic maps, crucial for 3D reconstruction and real-time obstacle avoidance.

1.4.3 Environmental and Chemical Analysis

A comprehensive array of sensors is integrated to fulfill the mission's data logging and in-situ analysis requirements. A **Water Quality Sonde** and a dedicated **pH Sensor** measure and record key geographical data. For detailed chemical analysis, the ROV is equipped with **Ion-selective electrodes (ISEs)** and a **Laser Raman Spectrometer**, which provide precise readings on water and soil composition. A **Portable X-Ray Fluorescence (pXRF)** system enables on-site elemental analysis of geological samples. The system also includes Type K Thermocouples for high-temperature readings, aiding in the detection of geothermal vents.

1.4.4 Imaging and Vision

The ROV's vision system provides real-time visual feedback and documentation. It consists of a high-definition, **low-light Camera** integrated with a Lighting System to illuminate the deep-sea environment. The imaging system is designed to support both remote visual inspection and advanced computer vision algorithms for object detection and visual navigation.

1.4.5 Data Acquisition and Power Management

All sensor data, including video footage and sonar scans, is managed by a robust **Data Acquisition and Recording** system. This includes onboard storage for continuous data logging throughout the mission. The power system is designed to be highly reliable, featuring voltage regulators to manage power from the main tether and distribute it to all subsystems, including the thrusters, sensors, and computing components.

1.5 Power and Communication Subsystem

The power and communication subsystems are critical for sustaining the ROV's mission, especially during extended operations in challenging deep-sea environments. Our design addresses the unique requirements of underwater power delivery and communication with robust and reliable solutions.

1.5.1 Power

The ROV is powered by a dedicated tether that provides continuous electrical power from the surface, eliminating the need for heavy onboard batteries. This design enhances manoeuvrability and allows for a maximum operational duration of two days without interruption.

The power system incorporates **intelligent distribution modules** that regulate and isolate high-current lines for thrusters from low-voltage electronics, ensuring clean and stable voltage for all subsystems, including the NVIDIA Jetson processor, navigation sensors, and communication devices. A set of **failsafe DC–DC converters** provides fault tolerance against voltage fluctuations or sudden load spikes, while surge protection safeguards sensitive electronics from tether-related disturbances. The system also includes **real-time power monitoring**, giving operators surface feedback on consumption trends to prevent overloads and enabling predictive maintenance.

In case of tether failure, the ROV is equipped with a **rechargeable backup battery** that enables a controlled shutdown sequence. This emergency power activates the acoustic modem for transmitting distress pings, maintains critical navigation electronics, and triggers a ballast release system for a safe, automated ascent. This layered safety approach ensures recoverability and minimizes the risk of permanent loss.

Furthermore, the power architecture is designed with **scalability in mind**, supporting additional payloads such as high-resolution sonar, extra cameras, or scientific instruments without major redesign. Thermal management is integrated into the power system, ensuring reliable operation of all electronics even under sustained high loads in challenging underwater environments.

1.5.2 Communication

Communication is managed via a hardwired connection through the tether. This method provides a high-bandwidth, low-latency data link for real-time control signals and high-resolution data telemetry. This solution overcomes the significant challenges of underwater wireless communication, such as signal attenuation and multipath interference, which can cause delays and data loss.

In the event of a tether failure, the ROV is equipped with an **Acoustic Modem** with a Received Signal Strength Indicator (RSSI) for emergency communication. This backup system allows for critical data transmission and status updates to the surface, providing a robust failsafe to help with recovery efforts. The **Acoustic Modem** is a low-power, low-bandwidth solution suitable for transmitting essential commands and sensor readings.

2 ROV Dynamics

2.1 Introduction

The dynamics of a Remotely Operated Vehicle (ROV) are described using six Degrees of Freedom (DoF), which include three translational motions—surge, sway, and heave—and three rotational motions—roll, pitch, and yaw. Understanding these dynamics is critical for designing precise control strategies for underwater navigation and operations.

- **Translational motions:**
  - Surge (x): Forward/backward motion
  - Sway (y): Sideways motion
  - Heave (z): Vertical motion
- **Rotational motions:**
  - Roll (ϕ): Rotation about x-axis
  - Pitch (θ): Rotation about y-axis
  - Yaw (ψ): Rotation about z-axis

2.2 Notations and Reference Frames

- **Position and orientation (Earth-fixed NED frame):**
  $\eta = [x, y, z,\phi,\theta,\psi]\ ^T$
- **Linear and angular velocities (Body frame):**

$$\nu = [u, v, w, p, q, r]^T$$

- **Generalized forces and moments:**

$$\tau = [X, Y, Z, K, M, N]^T$$

Reference frames:

- **NED (North-East-Down):** Earth-fixed frame for absolute position and orientation
- **BODY:** Frame attached to the vehicle's center of gravity, aligned with the ROV geometry

Orientation representations: Euler angles (phi, theta, psi) are intuitive but suffer from gimbal lock, while quaternions provide singularity-free, numerically stable representation suitable for real-time control.

2.3 Kinematics

The mapping from BODY-frame velocities to Earth-frame pose rates is:
$\eta\ ^{\cdot}\ =$J(η)ν
where J(eta) is the transformation matrix dependent on Euler angles or quaternions.

2.4 Dynamics

The 6-DoF dynamic model of the ROV is:
M ν $^{\cdot}$ +C(ν)ν+D(ν)ν+g(η)=τ

- M: Inertia matrix including added mass
- C(ν): Coriolis and centripetal forces
- D(ν): Hydrodynamic damping
- g(η): Restoring forces from gravity and buoyancy
- τ: Forces and moments generated by thrusters

2.5 Thruster Force Model

Each thruster produces a force proportional to its control input:
F$_i$ = $K_i u_i$
where K_i is the thrust coefficient and u_i is the control input.
For the ROV with 8 thrusters:
F=Ku, K=diag[K 1 ,K 2 ,. . . ,K 8]
A thruster at position $r = [l_x, l_y, l_z]^T$ relative to the center of gravity contributes:

- Force: $f = [F_x, F_y, F_z]^T$
- Moment: $r * f$

Stacking contributions from all thrusters gives the configuration matrix T in mathbbR 6times8 :
τ=TF=TKu

Thruster configuration:

- T1–T4 (horizontal): Control surge, sway, yaw; minor roll/pitch
- T5–T8 (vertical): Control heave, roll, pitch

2.6 Mapping Thruster Inputs to ROV Motion

The relationship between control inputs and ROV motion is defined by:
τ=TKu

- u: Control signals sent to thrusters
- K: Thruster strength coefficients
- T: Configuration matrix accounting for thruster placement and orientation
- tau: Resulting total forces and moments

The ROV's 8-thruster system provides redundancy for 6-DoF motion, allowing:

- Multiple ways to achieve the same motion

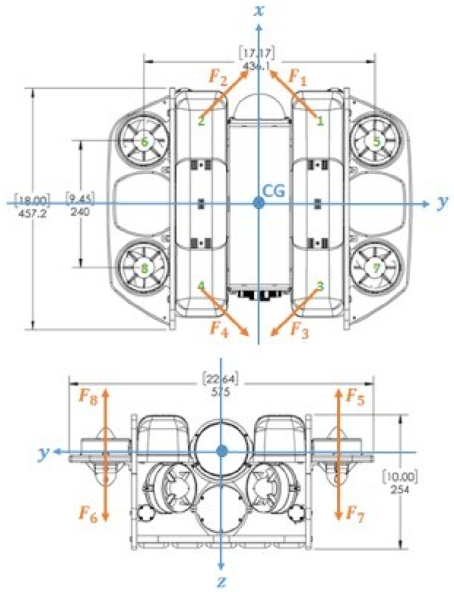

Figure 7: Top view and Front view of Thruster configuration

- Load sharing to reduce power consumption
- Continued operation in case of thruster failure

This redundancy enables flexible, efficient, and reliable control, ensuring stable maneuvering under various underwater conditions.

3 Mission-Based System Details

3.1 3D Mapping and Reconstruction

3.1.1 Overview

The navigation subsystem is designed for autonomous exploration in GPS-denied underwater environments. A real-time 3D **Simultaneous Localization and Mapping (SLAM)** algorithm helps create a 3D point cloud map of the surroundings while tracking the ROV's position.

3.1.2 Sensor Suite for Pilot Assistance and Mapping

Sonar Array: The primary tool for 3D map construction is a constellation of narrow-beam echosounders. This array provides a near-360-degree acoustic view of the surroundings. This data is fed into the SLAM algorithm.

- **Range:** Up to 200 meters.
- **Function:** Provides continuous range measurements to generate the live 3D map.

Inertial Measurement Unit (IMU): An IMU, incorporating a high-precision **ring laser gyro**, is vital for dead reckoning. It measures the ROV's acceleration and rotation, providing a stable orientation and motion track that is essential for the SLAM algorithm's calculations.

Doppler Velocity Log (DVL): To correct for the inherent drift of the IMU, the DVL uses sound waves to precisely measure the ROV's velocity relative to the seafloor. This provides an accurate, independent velocity measurement, ensuring the ROV's position on the map remains precise throughout the mission.

3.1.3 SLAM Algorithm in Action

The algorithm runs continuously on the surface or onboard computer, providing a map to the base.

- **Sensor Data Fusion** → Data from the sonar, IMU, and DVL are fused to create a coherent picture of the ROV's state and surroundings.
- **Probabilistic Modeling** → Sophisticated models interpret the data, filtering out noise to build a reliable map.
- **Iterative Refinement** → The system continually updates the map and the ROV's position, giving the pilot a real-time, improving model of the area.

3.1.4 3D Reconstruction and Visualization

The raw sonar data is saved as a **point cloud** (a collection of X, Y, Z coordinates). This is then converted into a solid **mesh** by connecting the points to form a polygonal surface. This final, high-fidelity model can be used for detailed scientific analysis and planning future expeditions.

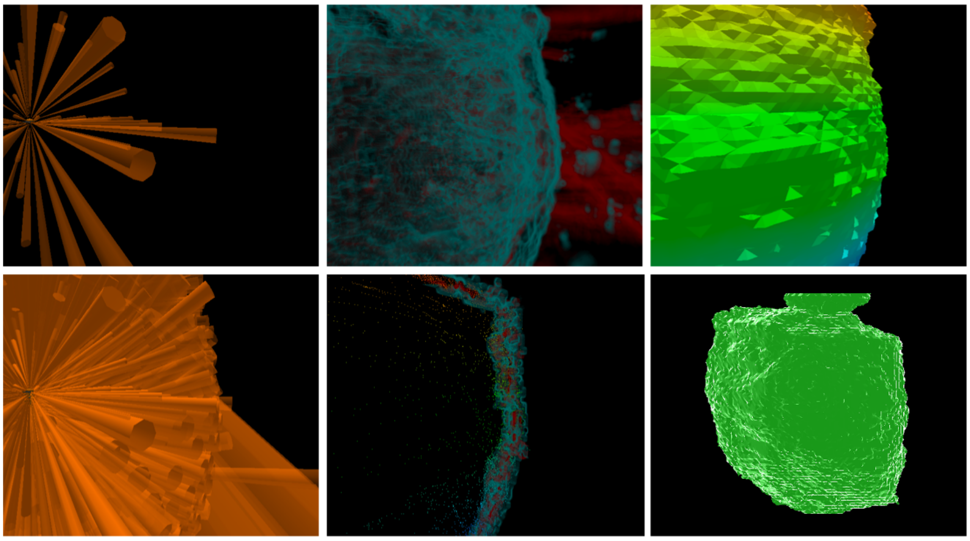

Figure 8: The 3D reconstruction process, showing the conversion of a raw sonar point cloud (left) into a solid mesh model (right).

3.2 Anomaly Detection and Avoidance

3.2.1 Detection Methodology

Anomaly detection will be facilitated by an integrated suite of on-board sensors, strategically positioned to provide continuous, real-time environmental data.

- **Thermal Sensors (Type K thermocouples):** These sensors detect rapid increases in water temperature. Their high precision allows the ROV to identify thermal plumes and extreme temperature zones, which are strong indicators of active underwater volcanic vents and geothermal activity. A rapid temperature increase to a value greater than 5°C above the ambient temperature of the surrounding deep-sea water (4°C). The ROV will also mark any region with a temperature exceeding 20°C as a critical anomaly.
- **pH Sensors (Sea & Sun Technology AMT pH sensor & Sea-Bird Scientific Deep SeapHOx V2):** This robust sensor will continuously measure the acidity of the surrounding water. A decrease in the pH level below 6.0 below signals the presence of acidic regions, which are often a byproduct of chemical emissions from volcanic or hydrothermal vents.
- **Chemical Sensors (Ion-selective electrodes for Sulphide):** The use of Ion-selective electrodes is crucial for identifying specific hazardous chemical compounds. By targeting Sulphide, a common and significant indicator of hydrothermal vents, the ROV can detect chemically hazardous regions that may not be immediately evident through thermal or pH changes alone. A concentration above 5 mM will be considered extremely hazardous.

These sensors will operate at a high sampling rate, feeding data to the ROV's central processing unit for immediate analysis.

3.2.2 Maneuvering and Pathfinding

The ROV will utilize a combination of precise thruster control and intelligent pathfinding algorithms like A star to find the shortest path to safety.

- **Vectoring Thruster Control:** The ROV's six-degrees-of-freedom (6-DOF) vectoring thruster system will allow for immediate and precise maneuvering. Upon detecting an anomaly, the thrusters will execute a calculated reversal or course change to move the vehicle away from the hazardous region.
- **Intelligent Path Planning:** The ROV's on-board navigation system will integrate data from its sensors with its 3D map of the cave system. It will dynamically reroute its mission path and use A star algorithm to bypass the hazardous zone, seeking the shortest and safest alternative route.
- **Failsafe Protocol:** In the event the ROV is in a confined space where no clear avoidance path is available, the system will execute an emergency ascent protocol, using its vertical thrusters to move toward the ceiling of the cave or sinkhole, or it will follow the recoverability program which will be talked about later.

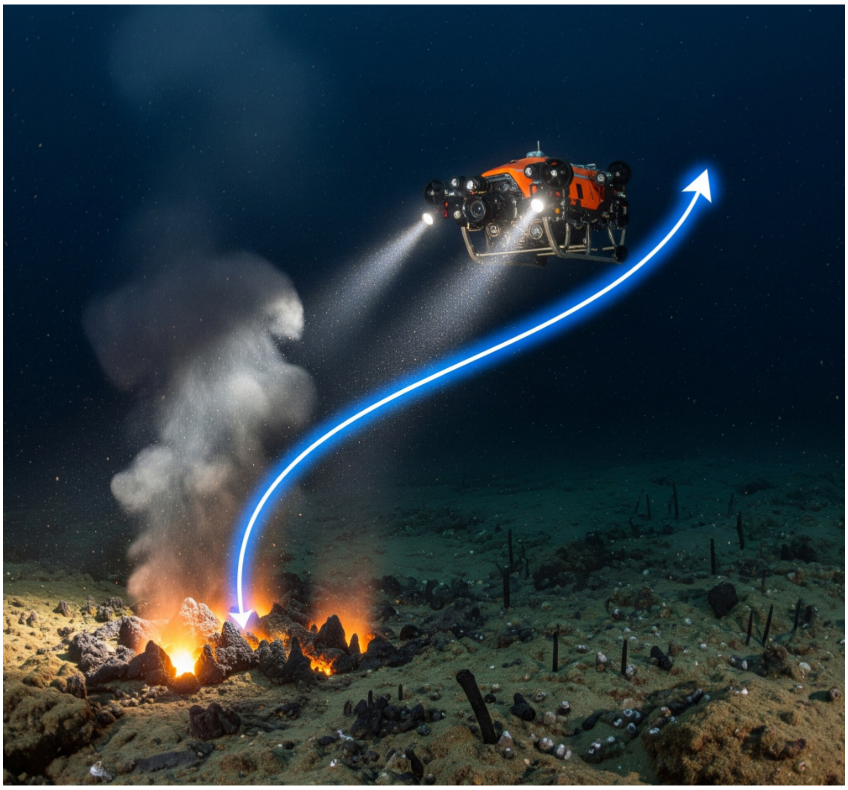

Figure 9: ROV Avoding Hydrothermal Vent

3.3 Geographical and Environmental Data Logging

The autonomous underwater vehicle (AUV) will systematically collect data on five key parameters: pH, temperature, pressure (depth), salinity, and water current dynamics.

3.3.1 Required Sensor Payload and Systems

To achieve the mission objectives at a target depth of up to 3000 meters, a specialized, deep-water capable sensor payload is mandatory. The instruments are selected for their robust housings (titanium or acetal) and the high precision required to resolve subtle environmental gradients.

- **Primary Environmental Sonde**: A configurable, deep-rated sonde is required. Model: Teledyne Valeport uvSVX Function: This single instrument provides synchronized, real-time measurements of pH, temperature, conductivity (for salinity), and pressure.
- **Doppler Velocity Log (DVL)**: A deep-water DVL is the core of the navigation and current measurement system. Model: Teledyne Workhorse Navigator DVL Function: Provides the AUV's 3-axis velocity over the ground for precise navigation (SLAM) and simultaneously measures the ambient water current vector.
- **Central Control Unit**: An onboard, radiation-hardened single-board computer (NVIDIA Jetson AGX Orin) serves as the robot's brain, orchestrating all tasks.

3.3.2 Methodology: Data Acquisition and Processing Workflow

The mission will be executed in two phases:

- **Phase 1: Autonomous Survey Execution**: The AUV is deployed to begin its autonomous exploration mission, surveying the seabed and entering caves as it discovers them. During operation, the control unit runs a high-frequency data fusion loop. In each cycle, it queries the sonde and the Doppler Velocity Log (DVL), retrieves their data packets, and fuses them into a single, comprehensive data entry. This entry, containing the Timestamp, X-Coordinate, Y-Coordinate, Z-Coordinate (Depth), pH, Temperature, Salinity, and the CurrentVector[x,y,z], is written to a solid-state data logger, creating a detailed, multi-layered map of the unexplored environment in real-time.

- **Phase 2: Data Analysis**: The dataset is processed to filter any anomalies or sensor noise. The data is then processed in real-time by a software stack that includes the NVIDIA JetPack SDK and ROS 2. This system performs advanced statistical analysis and uses GPU-accelerated libraries for to render interactive 3D visualizations of the cave's environmental conditions.

3.4 Resilient Mobility Systems

This outlines the objective for the autonomous underwater vehicle (AUV) project: to conduct a comprehensive, high-resolution survey of a submerged cave system. These environments are defined by high-velocity, turbulent water flow, constricted passages, and zero-visibility conditions. The objective is achieved through a synergistic approach combining a pragmatic structural design, an advanced vectored propulsion system, carefully selected materials, and a sophisticated sensor suite for precision navigation and control. This integrated system ensures the ROV can not only withstand the harsh environment but also maneuver with the accuracy required for successful exploration and data collection.

3.4.1 Hydrodynamic and Structural Design

The open-frame architecture in our design is a well-considered and highly practical solution for this specific application. This design represents a critical trade-off, prioritizing control authority, payload modularity, and serviceability over minimizing the drag coefficient alone.

Open-Frame Advantage: The open-frame structure allows turbulent water to flow through the chassis rather than impacting a large, solid surface area. This can reduce the effect of lateral currents and vortices that would otherwise induce significant instability on a solid-hulled vehicle.

Drag Force Management: The primary challenge is to overcome the drag force, which is governed by the equation:

$$F_D = \frac{1}{2}\rho v^2 C_D A$$

Where: F_D is the drag force ρ is the density of water v is the velocity of the fluid C_D is the drag coefficient A is the cross-sectional area Instead of solely minimizing C_D and A, our strategy focuses on building a propulsion system with sufficient thrust to counteract F_D and maintain absolute control authority, a critical requirement in high-flow environments.

3.4.2 Vectored Propulsion and Control System

To achieve the necessary agility in turbulent and confined spaces, a powerful and responsive propulsion system is essential. The design supports a vectored thruster configuration, which is the cornerstone of the ROV's mobility.

Six-Degrees-of-Freedom (6-DOF) Control: By mounting at least six thrusters (or more for redundancy) at strategic angles, the ROV achieves decoupled control over all six axes of movement: surge (forward/back), sway (left/right), heave (up/down), roll, pitch, and yaw (turning). This allows the ROV to perform complex maneuvers, such as moving laterally to dodge an obstacle while keeping its cameras and sonars pointed forward.

Dynamic Station-Keeping: When integrated with the sensor suite, this vectored system enables powerful dynamic station-keeping. The flight controller can command the thrusters to output precise, opposing force against external currents, allowing the ROV to hold its position and orientation with near-perfect stability. This is crucial for conducting detailed surveys or manipulating objects in a moving water column.

3.4.3 Material Selection for Extreme Environments

Chassis and Structural Components:

- **Anodized 6061-T6 Aluminum:** As a primary choice, this material provides an excellent balance of high strength-to-weight ratio, rigidity, and good corrosion resistance (when properly anodized). It is ideal for the main structural frame, providing a stiff platform for mounting thrusters and sensors.
- **High-Density Polyethylene (HDPE):** An excellent secondary material for mounting plates and guards. Its key advantages are its impact-absorbing properties (protecting against collisions with cave walls), immunity to corrosion, and positive buoyancy, which helps reduce the overall amount of syntactic foam required.
- **Syntactic Foam:** The blue blocks visible on the ROV frame are correctly identified as syntactic foam, the industry standard for deep-water buoyancy. Composed of microscopic hollow glass spheres in a polymer resin, it is incompressible at operational depths, providing consistent and reliable positive buoyancy. It can be precisely machined and distributed across the frame to ensure the vehicle is balanced and stable in the water.

Hardware and Fasteners: All fasteners (bolts, nuts, screws) must be made from 316 stainless steel or, for maximum corrosion resistance, titanium. This prevents galvanic corrosion and ensures structural connections do not degrade over time.

3.5 Soil and Water Collection and Analysis

3.5.1 Overview

The subsystem acquires combined soil–water samples at depths up to 3000 m, processes them through onboard sensors, and discharges the analyzed material. Fluid handling relies on peristaltic pumps for transport, check valves for isolation, and a sealed pressure-compensated chamber containing integrated sensors. All components are optimized for high-pressure, saline, sediment-rich environments.

3.5.2 Inlet System

- **Inlet Pipe:** Flexible tubing of 1 cm internal diameter, abrasion-resistant (reinforced PTFE/Santoprene).
- **Peristaltic Pump:**A compact peristaltic pump is positioned at the inlet to draw seawater and suspended sediments into the chamber.
- **Flow rate:**4–6 L/min at moderate internal velocity, ensuring sufficient sample for multi-sensor analysis.
- **Stone Trap / Pre-filter:**A small sediment trap is mounted upstream to capture coarse grains (>5 mm) and prevent clogging of the tubing.

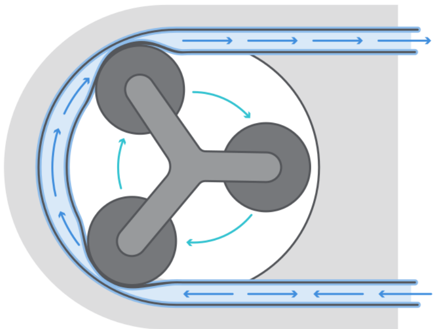

Figure 10: Peristaltic Pump

3.5.3 Analysis Chamber

A titanium or reinforced composite chamber, pressure-balanced for ∼300 bar, holds a fixed water-soil slurry sample volume for in situ analysis. Integrated instrumentation includes:

- pH, temperature, and depth sensors
- Ion-selective electrodes (nitrate, ammonium, chloride, heavy metals)
- Chemical/gas probes (O_2, H_2S, redox, nutrients, pollutants)
- Microelectrodes for fine-scale gradients
- Laser Raman spectrometer (molecular/mineral analysis)
- Portable XRF (elemental composition)
- Acoustic modem for data transmission

3.5.4 Outlet System and Flow Control

A second peristaltic pump discharges the used sample via a downstream check valve, preventing backflow. Operation proceeds in sequence:
1. Inlet pump ON → chamber filled.
2. Chamber sealed → sensors acquire data.
3. Outlet pump ON → sample expelled.
This dual-pump, dual-valve scheme ensures full turnover, prevents contamination, and blocks seawater intrusion.

3.5.5 Design Advantages

- Positive displacement flow with peristaltic pumps keeps fluids confined to tubing.
- Dual check valves guarantee one-way isolation.
- Compact chamber supports both liquid- and solid-phase analysis under deep-sea pressure.
- Intake–analysis–discharge cycle minimizes cross-contamination and ensures repeatability.

3.6 Environmental Sensing and Analysis

This section details the ROV's advanced capabilities for detecting and analyzing environmental and chemical parameters within the submerged cave network. The system employs a multi-sensor approach to collect high-resolution data on hydrocarbon and mineral concentrations, creating a comprehensive environmental profile of the surveyed area.

3.6.1 Hydrocarbon Concentration Recording

The ROV uses a multi-layered sensor system to detect and quantify oil and other hydrocarbons. This approach provides both a broad overview and a detailed chemical analysis.

- **Ultrasonic Transducers**: A high-frequency ultrasonic transducer mounted on the ROV's frame is used for initial detection. By emitting sound waves downward, the sensor measures reflections off the water-oil and oil-seafloor interfaces. The time difference between these reflections allows the ROV's computer to accurately calculate the thickness of the oil slick, providing real-time data on the presence and volume of hydrocarbons.
- **Laser Raman Spectrometer**: For a more specific chemical analysis, the ROV employs a laser Raman spectrometer. This instrument shines a laser on a sample and analyzes the way the light scatters. Each chemical substance, including different types of oil, has a unique spectral "fingerprint." The onboard software can compare this fingerprint to a database, allowing for non-destructive identification and quantification of the exact compounds present.
- **Chemical Sensor Arrays**: To confirm the presence of pollutants, the ROV also uses an array of small probes that detect specific chemical compounds dissolved in

the water. These sensors are calibrated to identify common hydrocarbon markers and other pollutants, providing an additional layer of data to confirm the presence of oil.

3.6.2 Mineral Concentration Recording

The ROV is equipped to perform on-site analysis of mineral content in both the water and sediment, which is essential for understanding the geological processes of the cave system.

- **Microelectrodes**: To analyze the sediment, the ROV's manipulator arm can deploy solid-state microelectrodes. These extremely fine probes are inserted into the sediment to measure dissolved mineral ions (such as Mn^{2+} and Fe^{2+}) and gases (like O_2) at a very high resolution. This is crucial for understanding chemical reactions and mineral formation processes happening within the sediment itself.

- **Portable X-Ray Fluorescence (pXRF)**: For solid rock or sediment samples, the ROV uses a portable X-ray fluorescence (pXRF) spectrometer. The ROV's manipulator arm positions the pXRF against the sample. The spectrometer then bombards the sample with X-rays, causing the atoms to emit secondary X-rays with energies specific to each element. This allows for rapid, on-site elemental analysis without the need to bring samples to the surface.

3.6.3 Systematic Data Logging and Navigation

The success of the survey depends on a systematic approach to data collection, which is managed by a combination of navigation and data logging systems.

- **Integrated Navigation**: The ROV's integrated navigation system is the core of this process. It uses a **Doppler Velocity Log (DVL)** to measure the ROV's speed and direction relative to the seafloor, along with an **Inertial Measurement Unit (IMU)** to track its orientation and acceleration. This allows the system to continuously calculate the ROV's precise position and travel distance, ensuring accurate georeferencing of all collected data.

- **Automated Sampling Protocol**: The ROV's control software is pre-programmed with a grid pattern for the survey. At every 100-square-meter waypoint, the navigation system triggers an automated sampling event. The ROV will pause, extend its sensors or manipulator arm, and perform the necessary measurements and collections.

- **Data Logging**: All data collected from the various sensors—including oil thickness, mineral composition, location, depth, and time—is automatically time-stamped and recorded in the ROV's internal memory. This creates a detailed, georeferenced dataset that can be used to generate a comprehensive 3D map of the cave's mineral and oil concentrations, which can be analyzed by scientists to identify areas of interest for further study.

3.7 Marine Biological Analysis

3.7.1 Problem Statement

Underwater caves and sinkholes are ecologically fragile, low-light, sediment-prone environments. Traditional biological sampling (nets, traps, physical capture) risks injuring organisms, disturbing habitats via thruster wash or light/noise, and contaminating samples. For the Abyssal Veins mission, we need a subsystem that can identify species and collect biological evidence while ensuring zero disturbance to the ecosystem and high-quality data for later analysis.

Key constraints

- Minimal hydrodynamic disturbance (no sediment resuspension).
- Minimal acoustic and optical disturbance (quiet propulsion, red-spectrum lighting).
- Non-contact evidence collection (eDNA) with reliable chain-of-custody.
- Turbid/low-light operations and narrow passages.

3.7.2 Solution Concept

We propose an Integrated Non-Invasive Biological Research Subsystem comprising:

Remote Observation: Ultra-low-light imaging + optional multispectral filters; passive acoustics (hydrophone); optional imaging sonar for turbid navigation.

Environmental Context: CTD (salinity, temperature, depth) + pH for correlating biology with physicochemical conditions.

eDNA Water Sampling: Gentle peristaltic pump drives cave water through inline sterile filters (Sterivex 0.22–0.45 μm to capture environmental DNA without contacting organisms.

Preservation and Chain-of-Custody: In-situ preservation (Longmire's/ethanol) and sealed sample cassette with unique IDs, timestamps, and environmental metadata.

Low-Disturbance Operations: Ducted thrusters, low-RPM "silent mode", station-keeping, red-spectrum lighting, and approach angles that avoid stress or wake.

Outcomes: In-situ species presence/absence through eDNA + visual/acoustic records; high-fidelity samples for lab sequencing; zero physical interference with fauna.

3.7.3 Technical Implementation

Architecture & Modules

The vehicle features a modular design with interchangeable pods for imaging, bio-sampling, and environmental sensing. The imaging pod contains a 4K camera and specialized LEDs. The bio-sampling pod uses a pump and filter system for eDNA collection. A sensing pod carries CTD and pH probes. The system is driven by ducted thrusters governed by a Pixhawk-class controller, with flexible power options.

Sensors & Electronics

Key sensors include a 4K low-light camera, submersible CTD and pH probes, and optional hydrophones or imaging sonar for advanced detection. The electronics are centered around a flight controller that manages propulsion, with an optional onboard computer for handling data logging and synchronizing sensor inputs.

Fluidics & Sampling

The sampling system uses a peristaltic pump to draw 2–5 liters of water through an inline Sterivex filter. After collection, the filter is immediately preserved with ethanol or Longmire's solution and stored in a sealed cassette. Strict protocols, including sterile tubing and blanks, are used to prevent contamination.

Software & Operations

Software enables stable station-keeping and automated sampling routines that log environmental data with each sample. The standard workflow is to detect a hotspot, switch to a low-disturbance mode for sample collection, preserve the filter, sync all data, and proceed to the next waypoint.

Safety & Ecology

Ecological safety is a priority, ensured by a non-contact design with shrouded thrusters to protect wildlife. Operations utilize red-spectrum lighting to minimize disturbance, and protocols are in place to avoid sediment resuspension and ensure proper decontamination.

4 Additional and Innovative Features

4.1 Recoverability and Fail-safes

4.1.1 Overview

The ROV is designed with a layered approach to reliability, incorporating failsafe mechanisms and component redundancy to mitigate critical failures. Each potential point of failure is monitored by dedicated sensors, and a corresponding automated response protocol is in place to ensure the vehicle can be recovered safely. The primary recovery strategy across multiple failure scenarios is the activation of a fail-safe buoyancy system, which brings the ROV to the surface for retrieval without reliance on the main propulsion or power systems.

4.1.2 Communication Failure Protocol

Detection Method: A software-based **Communication Status Sensor** continuously assesses the health of the communication link. It triggers the recovery protocol if the link is lost for a pre-set amount of time.

Response Protocol: If the signal is lost for a pre-set duration (e.g., 60 seconds), the ROV's onboard controller automatically triggers the autonomous **"return-to-surface"** protocol. This activates the fail-safe buoyancy system, making the ROV positively buoyant and allowing it to float to the surface for retrieval.

4.1.3 Power System Failure Protocol

Detection Method: A **Voltage/Current Sensor** continuously monitors the primary power system supplied via the tether.

Response Protocol: If the primary voltage drops below a critical threshold, the system automatically switches to an independent **emergency battery**. This backup power source is dedicated solely to recovery operations and initiates the following sequence:

- Activates the fail-safe buoyancy system.
- Deploys a **surface marker beacon** for GPS and visual location.
- Activates an **acoustic pinger** for underwater tracking during ascent.

4.1.4 Mobility System Failure Protocol (Entanglement)

Detection Method: A **Tether Tension Sensor** measures the force on the line. An abnormally high and sustained reading indicates the ROV or its tether is physically snagged.

Response Protocol: The primary recovery method is using the high-strength tether as a tow line to free the vehicle. If this is unsuccessful, an **emergency tether-release mechanism** can be activated. This allows the ROV to detach from the entangled tether, at which point it automatically initiates its standard buoyancy and tracking protocols to return to the surface.

4.1.5 Structural Failure Protocol (Water Ingress)

Detection Method: **Water Leak Sensors** (e.g., conductivity or float sensors) are installed within the ROV's watertight, pressure-resistant electronic compartments.

Response Protocol: The detection of any water ingress immediately triggers the emergency buoyancy protocol. This rapid, automated response is crucial to bring the ROV to the surface before a catastrophic flood can occur, minimizing damage to internal components and ensuring a successful retrieval.

4.1.6 Onboard System Failure Protocol (Software & Data)

Detection Method: A **watchdog timer** monitors the main control program for stalls or crashes. For data systems, diagnostic routines continuously check the health of critical sensors.

Response Protocol

- **Software Failure:** If the watchdog timer is not reset by the software within its cycle, it triggers a system reboot. If the failure persists, it activates the fail-safe buoyancy system.
- **Sensor Failure:** The control software automatically switches to a redundant backup sensor if a primary sensor provides anomalous readings or fails.
- **Data Integrity:** All collected scientific data is logged to **non-volatile memory** onboard the ROV. This ensures that even in a total communication failure, the mission data can be physically recovered from the vehicle.

5 Conclusion

The Remotely Operated Vehicle (ROV) detailed in this report presents a comprehensive and robust solution engineered to excel in the Underwater Vehicle Design Challenge. By integrating a sophisticated suite of subsystems, our design directly addresses the core mission of exploring and analyzing uncharted underwater caves in a reliable and ecologically responsible manner.

The ROV's strength lies in its integrated systems approach. The advanced navigation suite, centered around a Sonar Array and real-time SLAM algorithms, provides an effective solution to the critical challenge of operating in GPS-denied environments. This is complemented by a powerful electronics subsystem, driven by an NVIDIA Jetson AGX Orin, which enables complex data fusion and control. The vehicle's 8-thruster configuration, governed by a 6-DoF dynamic model, ensures precise maneuverability and provides crucial redundancy for system reliability.

Furthermore, the design prioritizes mission endurance and recoverability. A tethered power and communication system allows for extended, two-day operations, while the backup battery and acoustic modem create a robust failsafe protocol in the event of tether failure. The comprehensive sensor array for in-situ environmental and chemical analysis ensures that all data acquisition objectives, from 3D mapping to mineral detection, are met with high fidelity.

Ultimately, this ROV is not merely a collection of advanced components but a highly integrated platform designed for resilience, precision, and pioneering exploration. It is fully equipped to navigate the complexities of uncharted underwater environments and successfully achieve all mission objectives.

A Appendix

A.1 Citations

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