

Underwater Vehicle System for Drowning Intervention

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Abstract—The rescue of an individual underwater in swimming pools, water parks and in lakes have become an increasingly critical need in the current world. Traditionally, drowning individuals have been rescued by the human divers; however, the need for safe and cost-effective rescuing has fostered the development of unmanned underwater vehicle (UUVs) which are capable of performing the underwater surveillance and rescue operations. This research presents the design and development of an unmanned underwater vehicle for operating in situations of search and rescue. The significant challenges addressed include reliable communication in the underwater environment, efficient manoeuvring, and an image processing for human detection.

The designed UUV has a single thruster configuration consisting of a cylindrical projection serving as thruster housings and inbuilt buoyancy chambers, arranged to provide multi-dimensional manoeuvrability and stability underwater. The UUV features an integrated victim retention system, which is operated along with a pool float deployment system through servo motor actuation.

A 3D CAD Model of the UUV was subjected to Finite Element Analysis to verify that the design allows for the structural integrity of the UUV in 10-meter-deep waters.

For the machine to detect human shapes in underwater environment, we trained YOLOv8 object detection algorithms on a custom dataset of 2400 underwater images. It was tested, and underwater humans were consistently detected with success. The proposed system improves on its accuracy and also shows considerable decreases in the time delay and amount of energy required by comparison with remotely operated underwater vehicles and conventional rescue systems.

The contributions of this research to advance UUV technology and possible applications towards public safety, disaster response, search operations, and opened space for the development of future AI enhanced aquatic emergency systems.

Keywords— Unmanned Underwater Vehicles, underwater communication, image acquisition, background subtraction, power supply, torpedo-shaped vehicles.

I. INTRODUCTION

An Unmanned Underwater Vehicle (UUV) is an autonomous submersible device used for underwater exploration, research, inspection, and various industrial tasks. UUVs are typically monitored by pilots on the surface who use wireless communication to monitor the vehicle underwater.

These devices are connected to the surface by a series of cables, which transmit power and control signals, allowing operators to stay updated and monitor the UUV. UUVs play a crucial role in scientific research, underwater inspections, and various underwater operations where human divers might be impractical or unsafe. The vehicle's design incorporates key elements such as buoyancy, propulsion, and robust communication systems, ensuring effective navigation and operation in various conditions. Designing and operating an underwater vehicle involves several important principles and considerations to ensure its functionality and effectiveness. They are:

- Buoyancy and propulsion: UUVs are required to be neutrally buoyant in water, meaning they neither sink nor float. Achieving the right balance of buoyancy is crucial to control the UUV's depth underwater.
- Camera Integration: UUVs are equipped with high-precision cameras, sonars, and environmental sensors, to collect and process data.
- Underwater Communication: The Stable, reliable communication between the surface control station and the UUV is crucial, often achieved through cables with waterproof connectors for real-time control and data transmission.
- Power Systems: Designing a suitable power system for the UUV is crucial to support all subsystems, including communication, propulsion, buoyancy, and image processing. We propose an unmanned underwater vehicle (UUV) as shown in Figure.1. designed for detection, rescue missions, and navigation. It integrates buoyancy, stability, propulsion, communication, and advanced control systems. The UUV swiftly locates drowning individuals in challenging environments, provides crucial data, and can handle underwater obstacles for delicate recovery operations. Its components include navigation controls, communication units, sensors, actuators, and a battery powered system, all housed in a submarine-like design.



Figure.1. Working model of the proposed UUV.

II. RELATED WORK

Summarizing the literature survey to construct the desired UUV for our application it is necessary to look into all the four aspects of the UUV. Starting with reliable communication for the UUV. The UUV requires an efficient communication system to communicate the necessary information to the operator. Given that UUVs must operate in deep water, the communication system's complexity grows.

Optical communication [1] [2], acoustic wave [3], and wired communication [4] [5] [6] are among the different forms of underwater communication, according to the literature review that was completed. The optical communication mode uses a laser beam to transfer information. Both articles address different aspects of optical communication, such as turbidity, varying water channels, and nonline-of-sight communication. Additionally, a useful photo receiver that can be used for both information reception and energy capture has been designed by the paper [1]. An extensive analysis of the application of acoustic waves for underwater communication is done in the paper [3], which also designs an acoustic node network. The same paper addresses temperature and salinity as two of the factors influencing acoustic waves. Since a communication medium is isolated from water, underwater communication uses wired communication, such as Ethernet [4] [5] [6], which lowers the complexity of the communication system. The limitations of wired communication, including its fixed length, are covered in the same paper. Ethernet is most utilized in UUVs and has the least amount of complexity among the various communication modes examined for underwater communication. More research is required to determine the impact of using a single twisted wire in a CAT6 Ethernet cable intended for Power over Ethernet (PoE) mode for RS485 communication to reserve the entered bandwidth for video transmission.

In [7], they discuss using the Faster Region Convolutional Neural Network (FRCNN) algorithm in an ROV to detect drowning humans. It combines image processing with GPS for real-time detection and location tracking via a video feed. In [8], sea-thru removes water effects from underwater images using RGBD data. It estimates backscatter and varying illuminant to correct range-dependent attenuation, surpassing traditional models in colour correction. In [9], the authors suggest using Sonar and Thermal detection to locate human bodies underwater. It uses PIR sensors for thermal detection and ultrasonic sensors for sonar, initiating rescue only

when both sensors confirm a match, ensuring high accuracy. In [10], the paper employs structure-from-motion and photogrammetry to generate 3D scenes, estimating water properties for image correction. This method addresses attenuation, backscatter, vignetting, and lighting to improve colour consistency in underwater imagery. In [11], The study uses a simplified hazy image formation model to enhance underwater images, applying dehazing algorithms like WCID, dark-channel, chromatismbased, and histogram equalization to correct for scene depth estimation errors and foreground object misjudgements.

In tandem with refining human detection techniques for underwater rescue bots, the outer structural features and manoeuvring techniques are pivotal in their overall effectiveness. In [12], The paper provides a method that employs monolithic IPMC fins for propulsion and manoeuvring. A monolithic IPMC (Ionic Polymer-Metal Composite) fin functions by utilizing the bending and deformation properties of the IPMC material in response to applied electrical voltage, allowing for precise and efficient control of the fin's movement in underwater applications. This methodology would prove effective for miniature-sized UUVs. In [13], they provide a sophisticated approach toward a manoeuvring system and utilize multiple thrusters to navigate the UUV in all directions. It uses a total of six thrusters oriented in various directions to provide mobility. This approach will be useful in the case that the UUV is oversized and heavy and needs multiple thrusters to exert enough force to manoeuvre. In [14], their approach to UUV design is a submarine-like model that consists of a single thruster and multiple fins for manoeuvring in certain directions. Two horizontally placed fins are used for navigating vertically, and the other two are used to navigate towards right or left.

The bot's swift motion and strength require a well-designed power system for underwater UUVs to ensure propulsion and data collection in challenging conditions. The paper proposes a voltage regulation strategy for a 6000m-deep ROV system, solving the nonlinear relationship between compensated voltage and active current using a piecewise linear fitting with the least-squares method. A feedback PID controller achieves a faster dynamic response and stable load-side voltage. The system includes an uncontrolled rectifier, SPWM generator, and PID controller to convert AC input into controlled DC voltage [15]. The head-keeping controller is crucial due to the umbilical cable's vulnerability to twisting, with navigation sensors and cameras used for cable detection and inspection [16]. The paper also discusses a pressure-tolerant lithium-ion battery for the HUGIN 1000 mine reconnaissance system and compares various AUV power sources, including lead-acid, Ni-based rechargeable technologies, lithium-ion batteries, and semi-fuel cells based on aluminium metal anodes [17].

III. PROPOSED UUV

The block diagram of the proposed system showcases the various subsystems of the UUV including the hardware components and the communication modules. The UUV system has 2 platforms of computing, each of which has a different purpose and resources. The first one is a mother ship which is supposed to float on the surface, and the second is the rescue vehicle which is inside the water body as shown in Figure.2.

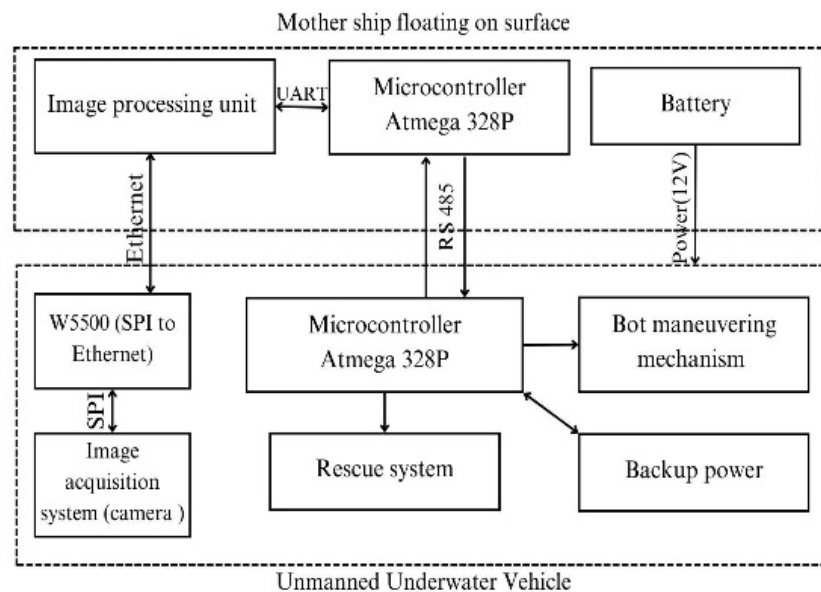


Figure.2. Overview of the system block diagram.

The microcontroller in the mothership receives instructions and the created attributes from the image processing unit, which also performs picture detection and processing. An RS 485 wired medium is used for communication between the mothership and the bot. The bot is equipped with a camera, Ethernet interface, mechanical system for manoeuvring, rescue system, small battery device as a backup, and all of this is interfaced with a microcontroller. The bot communicates with the mothership using Ethernet cable, and RS485.

A. 3D modelling of the proposed system

A 3D model was designed in Solid Edge before hardware implementation to ensure accurate planning and visualization. The front view of the model is shown in the Figure.3. This design, is a cylindrical vessel geometrically stable and is thereby quite functional within fluid vicinity. The extended 150.64-unit diameter, with a length of 670 units, will distribute the buoyancy uniformly along the cylinder's centreline so that no unbalanced forces occur. The length-to-diameter ratio of nearly 4.45 is favourable for streamline motion due to drag force reduction; hence the tipping off is avoided along with directional stability from the relation between the minimal ratio of stability per unit volume and simplicity of structure. It is thus believed to best suit underwater vehicles and floating systems.

Other features which would assist in stabilizing fluid motion and mitigating fluid-dynamic disturbance are: A Tailed tail that suggests fluid natural flow to be smoothened within an acceptable drag to stem off disturbances/oscillations or turbulence at the tail end. Stabilizing fins placed symmetrically on the tail effectively link passive stability with active balance while reducing roll (which contributes to rotational instability through momentum) and improving directional control for yaw and pitch stability. Both the size and angle change in order to balance drag and improve stabilization.

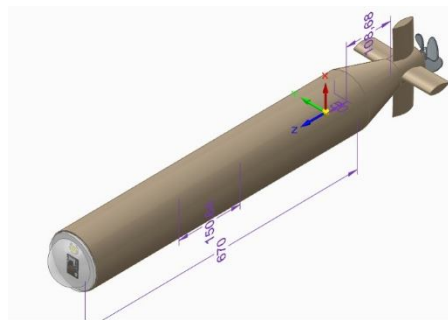


Figure.3. Design of the UUV in Solid Edge.

The internal structure of the UUV is the most critical part due to the space constraints and the complexity involved in the mechanism. Fig.4 shows the internal view of the UUV with each part labelled. This internal structure diagram illustrates the placement of electronic components and how the ballast tanks are controlled. Proper organization and efficient use of space are essential to ensure that all components fit correctly and operate without interference, thereby maintaining the UUV's functionality and performance.

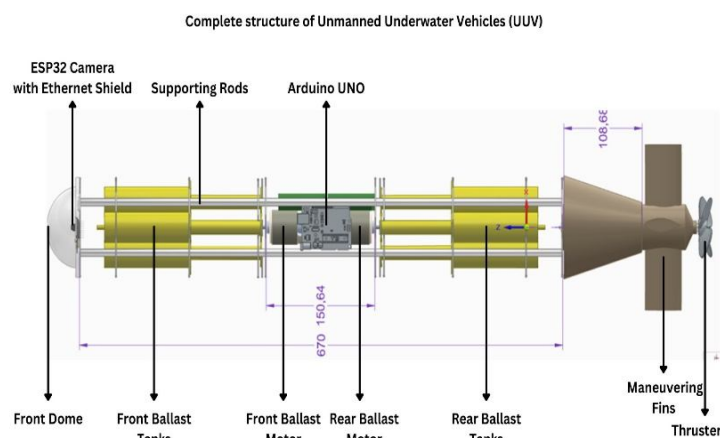


Figure.4. Internal structure of the proposed UUV design.

B. Finite Element Analysis

Once the Solid Edge design was complete, the next critical phase was to assess the structural integrity of the hull. For this purpose, Finite Element Analysis (FEA) was performed using Solid Edge for a depth of 10m. FEA enables engineers to simulate and analyse complex structures to understand their mechanical behaviour under various conditions. The important parameters in FEA analysis are Von Mises stress and the factor of safety.

Von Mises stress is a value used to determine if a given material will yield or fracture. It is primarily used for ductile materials, such as metals. The von Mises yield criterion states that if the von Mises stress of a material under load is equal to or greater than the yield limit of the same material under simple tension, then the material will yield.

The Factor of Safety (FoS) is the ratio of the actual strength of a structure/material (ultimate stress) to the maximum stress it should sustain in service (allowable stress). It measures how much stronger a system is than it needs to be for an intended load. The formula for the Factor of Safety (FoS) is given by:

$$\text{Factor of Safety (FoS)} = \frac{\text{Yield Stress}}{\text{Working Stress}} \quad (1)$$

This analysis ensures that the design is robust and can withstand the operational stresses without failure.

C. Hardware setup

The hardware implementation is carried out by considering all the findings from the design phase and based on the hardware requirement analysis. A proper terminal diagram is built to streamline the hardware build process. The terminal diagram of the UUV is shown in Figure.5. It illustrates how the motor driver, servo, RF module, MAX485 module, and limit switches are connected to the development board, which contains the microcontroller. This detailed diagram ensures that all components are correctly interfaced, enhancing the reliability and efficiency of the hardware setup.

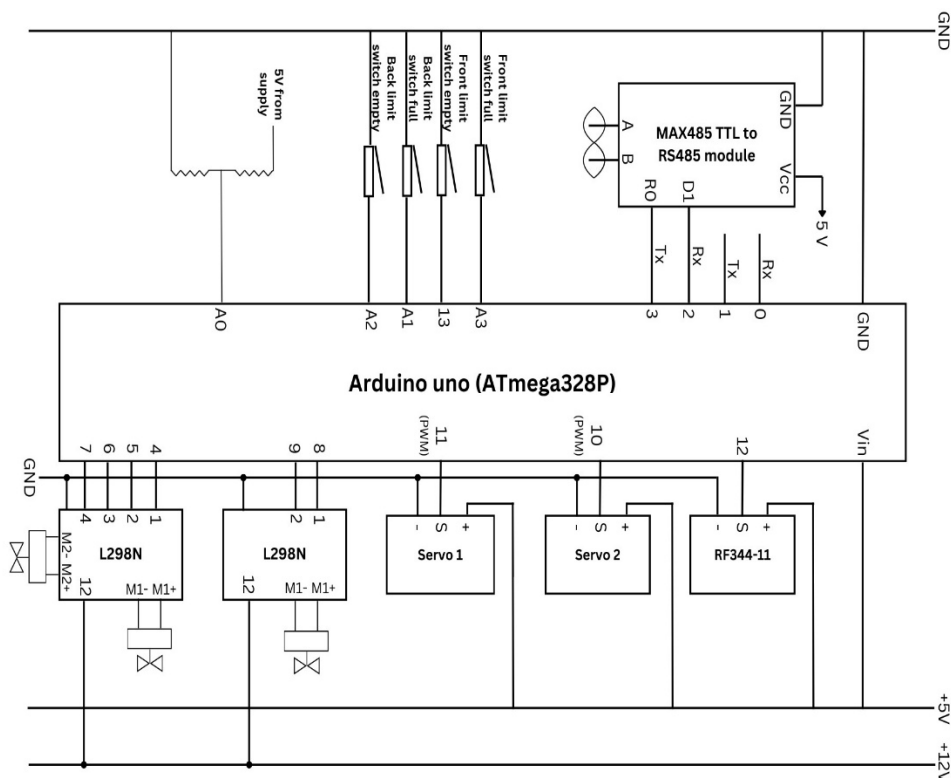


Figure.5. Terminal diagram of the UUV.

An image acquisition system consists of an ESP32-CAM which is used to capture video. Typically, the ESP32-CAM has wireless connectivity; however, an Ethernet shield is used in this setup to send video signals over Ethernet.

This enhances the reliability and range of video transmission compared to the standard wireless connection.

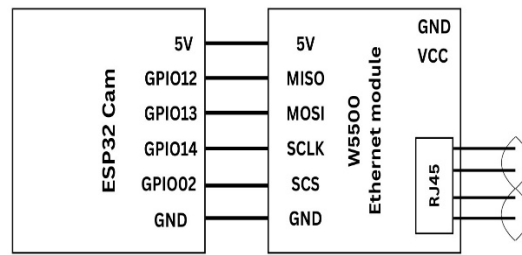


Figure.6. Image acquisition system.

In a Cat-6 cable, there are four pairs of twisted wires. One pair is used for RS485 communication, while two pairs are utilized for Ethernet communication, specifically for transmitting (TX) and receiving (RX) data. The remaining pair is unutilized, providing flexibility for future expansion or additional functions. The same is represented in Figure.6. To power up the subsystems like the image acquisition system, Servo motor, microcontroller and the RF module there is a need of a power system, this system employs a TP5100 battery charging module to keep the battery charged. The XL6009 booster ensures the robot receives sufficient power to run its main systems. If the main power supply fails, a backup power supply (7805) is used to maintain operation without any failure. This setup guarantees that the UUV always has power, whether from the main system or the backup, ensuring continuous functionality.

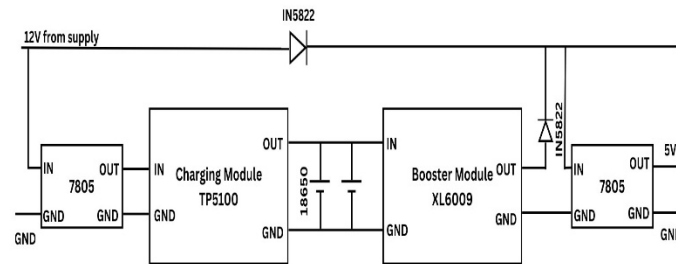


Figure.7. Backup circuit block diagram.

This comprehensive power and control setup ensures reliable and efficient operation of the UUV under various conditions.

The motor driver interfacing with the Arduino Uno is to control the geared motors, which manage the front and rear ballasts for precise buoyancy control. Additionally, a relay module is incorporated to control various other functions, enhancing the overall control and versatility of the system. The direction of the motors is controlled using the motor driver (L298N) which are used to change the position of the syringe piston to attain the required buoyancy. This precise placement and control mechanism ensures accurate and reliable movement of the syringe piston, which is critical for the UUV's functionality. Thrusters and fins are used to control the position of the UUV. The thrusters provide propulsion, while the fins enable precise manoeuvring and stabilization of the UUV. This combination allows for accurate control over the UUV's movement and orientation in the water, ensuring effective navigation and operational efficiency. Servos are utilized to drive the fins, providing precise control over their movements as shown in Figure.8. These servos are connected to the fins through control rods, ensuring a direct and responsive linkage. To prevent water infiltration and maintain functionality, the control rod passage is isolated using rubber tubes. This design ensures reliable and efficient operation of the fins, contributing to the UUV's manoeuvrability and stability in aquatic environments.

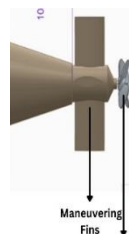


Figure.8.: placement of the fins on the UUV to achieve precise control

The ESP32 camera, with its integrated microcontroller and SPI connection to the W5500 Ethernet module, efficiently captures images and video feeds. The W5500 module's RJ45 port, coupled with a CAT-6 Ethernet cable, ensuring high-speed data transfer to a high-power computing unit, minimizing latency in relaying live video feeds.

This computing unit employs the YOLOv8 object detection algorithm, trained to detect humans in real-time with high accuracy. Its processing capabilities, coupled with the ESP32W5500 setup, enable immediate responses based on visual data, making it suitable for applications requiring quick and reliable video analysis and decision-making.

IV. RESULTS AND DISCUSSIONS

A. Results of Finite Element Analysis

The finite element analysis (FEA) was conducted to assess the structural stability of the Unmanned Underwater Vehicle (UUV) structure. The materials considered for the analysis included ABS (Acrylonitrile Butadiene Styrene), polycarbonate, and polyvinyl chloride (PVC). ABS was selected due to its common use in 3D printing, aligning with the team's plan to 3D print the external structure. Polycarbonate was chosen because of its widespread application in construction, indicating its robustness. PVC was included in the study because of its availability and lower cost. The displacement Results for PVC material is shown in Figure.9.

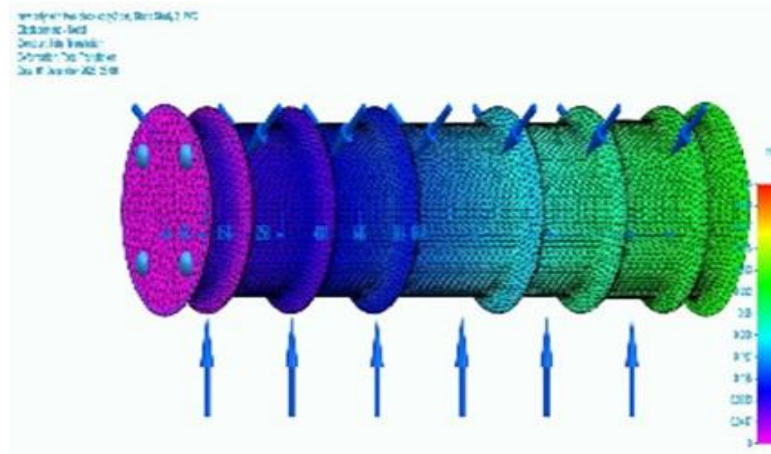


Figure.9. Displacement results for Poly Vinyl Chloride (PVC) material at a depth of 10 m.

Finite Element Analysis (FEA) with Solid Edge was done on the integrity of the hull structure given the characteristics of a 10m waterbody. Hence, FEA is an efficient tool that allows a designer to assess operational response of the structures under consideration by variable tuning of considerations like Von Mises stress and Factor of Safety (FoS). As shown in tab 1., Polyvinyl Chloride (PVC), Polycarbonate (PC), and Acrylonitrile Butadiene Styrene (ABS) are studied under uniform compressive loads of 100 kPa. Maximum displacements indicated were 0.5 mm, 0.571 mm, and 1 mm for PVC, PC, and ABS, respectively; this gives a fair idea regarding relative stiffness shown by these materials. Von Mises stress values were correlated with yield stress of each material to ultimately evaluate safety with regard to operating stresses. Generally, PVC exhibited a very low yield stress of 6.89 MPa with a minimum FoS of 1.63, which shows that there could not have been enough structural safety for the hull under these operation conditions. PC seems to show some strength, with yield stress of 58.6 MPa and minimum FoS of 13.9, thus highly suited for the application. Also, ABS could provide safety, with yield stress of 31 MPa and a minimum FoS of 7.35. These values duly reemphasize the importance of the selection of materials with FoS greater than 1, as a measure to maintain hull structure robustness and assurances of reliability in service. Finally, among these materials PC comes out as the most resilient one, giving a higher margin of safety against possible failures of the structure. In conclusion, hence the FEA employed herein gives an implicit assurance of robustness by design, capable of withstanding operational stresses.

Polycarbonate, theoretically the strongest, would be justifiable for use in hull design applications with PVC due to some practical and economic considerations. It is found that with higher mechanical strength and a FoS of 13.9, a very high material and manufacturing costs in design objectives will hinder the applicability of PC in

cost-sensitive studies. PVC still meets a safety requirement: FoS greater than one for bare operational conditions, although with lower yield strength, namely 6.89 MPa and 1.63, respectively.

With respect to the geometrical application displacements, PVC is also showing maximum displacements lower than PC, which when compared, is still 0.50 mm compared to 0.571 mm, respectively; actually, they performed slightly better in the view of stiffness and structural stability for compressive loads. Perhaps this feature has particular merit in preserving dimensional integrity in the vast majority of other applications. Ease of fabrication, good availability, and corrosion resistance in the marine environment make PVC preferable in hull designs. Cheaper production and maintenance of PVC support this conclusion and asserted its suitability under considerations where other parameters became secondary to cost.

TABLE I. COMPARATIVE ANALYSIS BETWEEN DIFFERENT MATERIALS

Material	Load Type	Load Value	Load Direction	Displacement Results		Von Mises Stress Results		Yield Stress	Factor of Safety	
				Min	Max	Min	Max		Factor of Safety	Factor of Safety
Polyvinyl Chloride (PVC)	Pressure	100kPa	Compressive	0 mm	0.5 mm	8.18e-09MegaPa	4.22 MegaPa	6.89 MegaPa	1.63	8.42E+08
Polycarbonate (PC)	Pressure	100kPa	Compressive	0 mm	0.571 mm	4.69e-09 MegaPa	4.23 MegaPa	58.6 MegaPa	13.9	1.25E+10
Acrylonitrile Butadiene Styrene (ABS)	Pressure	100kPa	Compressive	0 mm	1 mm	5.9e-09 MegaPa	4.22 MegaPa	31 MegaPa	7.35	5.26E+09

B. Image processing results

There was training for the YOLOv8 object detection algorithms on a custom dataset of 2400 underwater-images specifically for the machine to detect human shapes in underwater environments with great challenges across the line, including light distortion, turbulence, occlusions, etc. They were focused on as significant during training. So many fine-tuning aspects led to precision in identifying the human forms underwater. A web-based application was built around that interfaced with the ESP32 camera, while the real-time taken video images were run through the YOLOv8 algorithm, one of the best models, at the time, for human detection against fast-moving backgrounds. This holds true with a certain degree of importance in dynamic and active underwater environments, where movements take place continuously under some sort of disturbance. The main aim was to let the robot to follow and rescue human beings in disasters like drownings. One corner of results shows detections from the YOLOv8 models as in Figure.10. Each image is seen to show successful detection of underwater humans tagged with red boxes and percentages of confidence. The results demonstrate just how robust was the performance of the algorithm against changing situations in terms of depth, posture, and levels of visibility.

The system is capable of real-time detection and tracking of humans which makes it one of the most definite alternatives for critical applications in search-and-rescue operations in underwater environments.



Figure.10. Results of human detection using YOLOv8 algorithm.

C. Hardware implementation results

The illustrated block diagram in Figure.11. is a control panel for an Unmanned Underwater Vehicle (UUV) which exemplifies the working of each component. The central label indicating this is the interface for controlling the UUV. The propulsion unit is shown towards the back, while there exist cylindrical modules located at midsection. The sensor and the camera are assumed to be at the shiny dome at the front. The buttons placed there around allow control over specific functionalities of the UUV allowing the operator to operate the UUV.

Move to the left for directional buttons that allow forward, backward, left, and right movement, respectively, in slight motion. Control angles of thrust upward or downward with other controls. Situated to the right are the push-button switches for the on-board lighting system. The switching arrangement controls the brightening of the cockpit light when in underwater navigation. The fluid control buttons with labelling (F_B FULL, EMPTY, STOP) that affect the ballast tanks are meant for controlling buoyancy.

This design provides a user-friendly interface that is clear about the operations to be carried out to anchor itself efficiently, whether exploration, mapping, or maintenance operations that can be performed underwater.

Field tests were conducted on an available water body within the campus of the college to check whether the UUV was leak-proof construction, being that this is a prerequisite for underwater credibility as shown in Figure.12. Various functional tests combined forward and backward propulsions by observing the thrusters, fins' movements for manoeuvrability, and clarity of the camera video feed for observation purposes. The external light was also tested to verify that it actually works in comparatively low-light conditions underwater.

The performance of the ballast system has been presented in Figure.13. When the tanks of ballast were filled, the black markings on the UUV sunk far below the water surface, successfully proving that the system could readapt buoyancy and make the transition from a still state to a submerged state. This feature proves vital when operations beneath the surface are to be carried out at various depths.

The UUV structural integrity and functionality performance were confirmed in accordance with the designs at the completion of the testing phase. In that regard, the vehicle was successfully transitioned from surface navigation to underwater, whereupon maintaining control over its depth and reliability of operation was rendered. Construction allowed for leak-proof, credible propulsion and manoeuvrability features with on board systems validating the design and engineering of it.

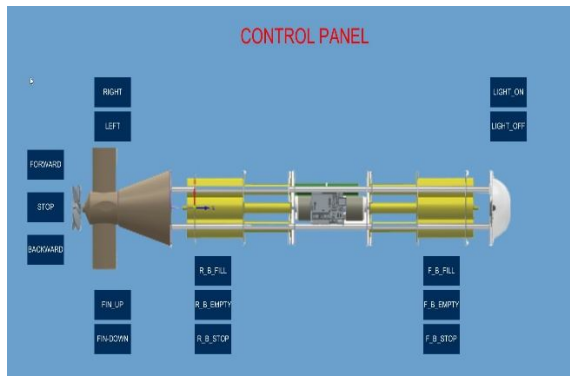


Figure.11. Interface of the control panel to control the UUV manually



Figure.12. Testing the UUV in stagnant water

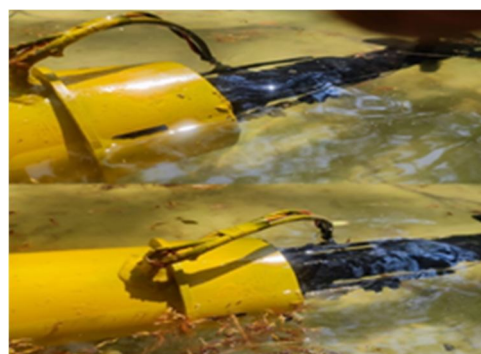


Figure.13. Position of the UUV before and after taking in water through ballast tanks.

V. CONCLUSIONS AND FUTURE SCOPE

A variety of technologies in the manoeuvre practices of the UUV hint at a new paradigm in underwater rescue and exploration. The UUV's operational capabilities involve a well-coordinated synergy of hardware and software components; it is bound to be an emblematic field for underwater safety, primarily, if not exclusively, for rescue operations in emergency scenarios where some form of quick rescue of drowning victims is required. Probably the most ideal design of UUV aims at total synergy between buoyancy, stability, and manoeuvrability in submerged operation grounding. Tough and durable materials such as polycarbonate are its basis for structural support, while FEA guarantees the vehicle's stress-free operation in an atmosphere of extreme conditions.

The hoodoo attributes, such as the technique of using a YOLOv8 object detector to allow real-time identifying action on any underwater setting, are mostly a made-to-order solution. Unquestionably, such concerns could be considerable under the kind of extremity of light refraction and agitation it creates. The concern for these conditions insists efficient and expeditious responses that certainly are a prime necessity in an emergency. The communication network of a UUV through Ethernet and RS485 interfaces is to operate the data transmission between the mother ship and the rescue vehicle. This proposal creates a UUV for underwater safety and introduces the possibilities of innovation design linked to new technology. In addition, field-testing has clearly established the concept of UUV design as having real potential under operating conditions in the future search-and-rescue efforts.

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