

TritonZ: A Remotely Operated Underwater Rover with Manipulator Arm for Exploration and Rescue Operations

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Abstract—The increasing demand for underwater exploration and rescue operations enforces the development of advanced wireless or semi-wireless underwater vessels equipped with manipulator arms. This paper presents the implementation of a semi-wireless underwater vehicle, "TritonZ" equipped with a manipulator arm, tailored for effective underwater exploration and rescue operations. The vehicle's compact design enables deployment in different submarine surroundings, addressing the need for wireless systems capable of navigating challenging underwater terrains. The manipulator arm can interact with the environment, allowing the robot to perform sophisticated tasks during exploration and rescue missions in emergency situations. TritonZ is equipped with various sensors such as Pi-Camera, Humidity, and Temperature sensors to send real-time environmental data. Our underwater vehicle controlled using a customized remote controller can navigate efficiently in the water where Pi-Camera enables live streaming of the surroundings. Motion control and video capture are performed simultaneously using this camera. The manipulator arm is designed to perform various tasks, similar to grasping, manipulating, and collecting underwater objects. Experimental results shows the efficacy of the proposed remotely operated vehicle in performing a variety of underwater exploration and rescue tasks. Additionally, the results show that TritonZ can maintain an average of 13.5cm/s with a minimal delay of 2-3 seconds. Furthermore, the vehicle can sustain waves underwater by maintaining its position as well as average velocity. The full project details and source code can be accessed at this link:

<https://github.com/kawser-ahmed-byte/TritonZ>

Index Terms—Underwater vehicle, Semi-wireless, Manipulator Arm, Underwater exploration, Rover

I. INTRODUCTION

Seven-tenths of the Earth's surface is covered by oceans, yet much of this underwater world remains unexplored [1]. This lack of exploration is largely due to the challenges and risks involved in deep-sea diving and exploration [1]. Underwater robots and vehicles have emerged as vital tools for addressing these challenges, enabling technology-driven exploration. The increasing use of Remotely Operated Vehicles (ROVs) in fields such as underwater exploration, environmental monitoring, and rescue missions has driven active research into efficient, lightweight designs with multi-dimensional applications [2]–[4].

Recent advancements have focused on improving ROV manipulation capabilities for tasks like water sampling [5], maritime security, environmental inspection [6], and archaeological data collection [7]. Advances in underwater imaging have further enabled applications like automatic fish recognition [8] and IoT-based water quality monitoring [9].

Efforts in this field include AUVs capable of withstanding extreme conditions [10] and cost-effective wireless robots for environmental monitoring [11]. Integration of underwater manipulator arms has improved control and interaction in subsea environments [12], [13].

However, commercial underwater systems often face challenges, including low accuracy, limited automation, and restricted control capabilities due to technical and environmental constraints [14], [15]. These gaps highlight the need for compact, efficient, and accessible ROV designs.

The paper is structured as follows: Section II reviews related works, Section III focuses on the mathematical modeling, Section IV outlines the proposed ROV methodology, Section V analyzes the investigation results and discussions, and Section VI concludes the study while offering suggestions for future work.

II. RELATED WORKS

Underwater robots, such as ROVs and AUVs, have transformed subsea exploration. ROVs have been used since the 1960s, while AUVs and USVs now offer autonomous access to hazardous environments, though their adoption faces technical and commercial barriers [16]. Efforts to enhance underwater safety include a rescue vehicle for drowning victims [17] and a low-cost AUV localization algorithm using acoustic signals, validated through simulations and sea trials [18].

Ali et al. [19] developed a twin-controller system combining PID and MRAC for faster convergence and reduced control error in underwater robots. Bykanova et al. [20] created a compact ROV with a rotating wing, ensuring efficient maneuverability during wreck surveys. Omerdic et al. [21] introduced a marine operation platform with 3D displays, voice navigation, and auto-tuning controllers to optimize underwater tasks.

In manipulation research, Perez and Vasquez [22] developed a 6-DOF mathematical model to improve stability and navigation, outperforming traditional systems. Other advances include precise sensor positioning for high-frequency seafloor data [23], SONAR integration for low-light conditions [24], and autonomous manipulators capable of target capturing [25].

Low-cost ROVs have also emerged, featuring battery protection, live camera feeds, and safety mechanisms for underwater exploration [26]. Another ROV focused on biofouling removal, reducing human intervention and enhancing maintenance efficiency [27]. The "ROVer," a lightweight hexagonal ROV for marine education, demonstrated enhanced payload capacity and effective video recording [28].

Despite advancements, commercial ROVs still struggle with low precision, limited automation, and high costs. This research presents TritonZ, a cost-effective, semi-wireless ROV with a robotic arm, 4-DOF navigation, and real-time video streaming for efficient underwater exploration and rescue missions.

III. MATHEMATICAL MODELING OF THE PROPOSED ROV

Mathematical modeling is fundamental for understanding the dynamics of ROVs. We wanted to maintain stability in roll and pitch direction due to the separation between their centers of gravity and buoyancy. With minimal roll and pitch motion under typical conditions, the ROV dynamics are best described by a coupled 3-degree-of-freedom (DOF) model in the XY-plane and a separate 1-DOF model in depth along the Z-axis [29]. In TritonZ's design, four vertically aligned thrusters are used for up-down motion whereas two horizontal thrusters are for left-right-forward-backward movement. This configuration aligns well with the theoretical framework of 4 DOF models. This section focuses on the 3-DOF XY-plane model, assuming independent depth control, equivalent to a 4-DOF ROV model. The general equation of finite-dimensional models is used to represent the 4 DOFs encompassing surge, sway, and heading, which can be expressed in the following form [30],

$$\mathbf{F} = \mathbf{M}\dot{\mathbf{v}} + \mathbf{C}(\mathbf{v})\mathbf{v} + \mathbf{D}(\mathbf{v})\mathbf{v} + \mathbf{b} \quad (1)$$

Here, $\mathbf{F} \in \mathbb{R}^{3 \times 1}$ represents the applied forces and moments, $\mathbf{v} \in \mathbb{R}^{3 \times 1}$ is the body-frame velocity, $\mathbf{M} \in \mathbb{R}^{3 \times 3}$ is the mass matrix, $\mathbf{C}(\mathbf{v}) \in \mathbb{R}^{3 \times 3}$ is the Coriolis matrix, $\mathbf{D}(\mathbf{v}) \in \mathbb{R}^{3 \times 3}$ is the drag matrix, and $\mathbf{b} \in \mathbb{R}^{3 \times 1}$ accounts for bias terms.

A. Mass Matrix

The symmetric mass matrix $\mathbf{M}$, combining vehicle mass and added mass, is:

$$\mathbf{M} = \begin{bmatrix} m_{11} & m_{12} & m_{16} \\ m_{12} & m_{22} & m_{26} \\ m_{16} & m_{26} & m_{66} \end{bmatrix} \quad (2)$$

Each portion represents a different feature of the ROV's inertia.

ROV's mass and weight: TritonZ has a total mass of 11kg, which is represented in the mass matrix by m_{11} , m_{22} , and m_{66} . This matrix considers the ROV's actual weight and also the added effect of the surrounding water. It helps to ensure the ROV is stable and moves smoothly in all directions including forwards, sideways, and rotation.

B. Coriolis Matrix

The Coriolis matrix $\mathbf{C}(\mathbf{v})$ for the 3-DOF system is:

$$\mathbf{C}(\mathbf{v}) = \begin{bmatrix} 0 & -v_6 m_{26} & v_2 m_{22} \\ v_6 m_{16} & 0 & -v_1 m_{12} \\ -v_2 m_{12} & v_1 m_{11} & 0 \end{bmatrix} \quad (3)$$

where v_1 , v_2 , and v_6 are the surge, sway, and yaw velocities, respectively.

Coriolis matrix and thruster configuration: The Coriolis matrix shows how yaw, sway, and surge can affect each other, potentially causing unwanted rotations when the ROV moves sideways. To prevent this, we added four vertical thrusters in TritonZ to stabilize the yaw axis and keep it level. Two horizontal thrusters were used to control forward and sideways movements without causing unwanted rotation.

C. Drag Matrix

The drag matrix $\mathbf{D}(\mathbf{v})$, illustrates the resistance the ROV faces as it moves through the water, with the matrix represented as:

$$\mathbf{D}(\mathbf{v}) = |v_1| \mathbf{D}_1 + |v_2| \mathbf{D}_2 + |v_6| \mathbf{D}_6 \quad (4)$$

where $\mathbf{D}_1$, $\mathbf{D}_2$, and $\mathbf{D}_6$ are quadratic drag matrices corresponding to surge, sway, and yaw.

ROV Shape by Drag Matrix: The drag matrix showed how different shapes affect the ROV's resistance in water. It revealed that a streamlined shape would reduce drag in forward and sideways movements, using less energy. Based on this, we chose a streamlined design with low drag, allowing the ROV to move more efficiently.

D. Bias Terms

The bias vector $\mathbf{b}$ represents systematic biases rather than buoyancy effects, as this model excludes heave, roll, and pitch:

$$\mathbf{b} = \begin{bmatrix} 0 \\ 0 \\ b_6 \end{bmatrix} \quad (5)$$

E. Transformation Matrix

The relationship between body-fixed and inertial frame velocities is described by the transformation matrix $\mathbf{T}(\theta)$:

$$\mathbf{T}(\theta) = \begin{bmatrix} 1 & 0 & \tan(\theta) \\ 0 & 1 & 0 \\ 0 & 0 & \sec(\theta) \end{bmatrix} \quad (6)$$

This matrix converts the ROV's body-fixed velocities to the inertial frame, crucial for accurate navigation and control. It shows how pitch changes affect velocity, allowing us to design a control system that adapts to these variations, ensuring steady movement and precise path tracking.

F. Rotational Matrix

The rotational transformation from body to inertial frame is expressed as:

$$\mathbf{R}(\theta, \psi) = \begin{bmatrix} \cos(\psi) \cos(\theta) & -\sin(\psi) & \cos(\psi) \sin(\theta) \\ \sin(\psi) \cos(\theta) & \cos(\psi) & \sin(\psi) \sin(\theta) \\ -\sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \quad (7)$$

G. Net Forces in the Body Frame

The net force $\mathbf{X}$ along the body-fixed axes, considering gravity $\mathbf{W}$ and buoyancy $\mathbf{B}$, is:

$$\mathbf{X} = \mathbf{R}(\theta, \psi)(\mathbf{B} - \mathbf{W}) \quad (8)$$

$$\mathbf{X} = \begin{bmatrix} (\mathbf{B} - \mathbf{W}) \cos(\psi) \sin(\theta) \\ (\mathbf{B} - \mathbf{W}) \sin(\psi) \sin(\theta) \\ (\mathbf{W} - \mathbf{B}) \cos(\theta) \end{bmatrix} \quad (9)$$

The expression balances the ROV's weight and buoyancy for stable vertical movement. By optimizing buoyant component placement, we achieve neutral buoyancy, reducing thruster reliance for better depth control. A comprehensive derivation of all the expressions of motion can be found in [31].

IV. PROPOSED ROV ARCHITECTURE

The proposed architecture of our underwater ROV has been carefully structured to optimize its functionality and performance. The architecture is divided into three key components: the 3D design, the internal architecture of the ROV, and the implemented system. The following sections provide a detailed description of these components.

A. 3D Design of TritonZ

After thorough mathematical modelling, we designed the 3D model which lays the foundation for physical implementation. The dimensions, components, and corresponding materials were aligned with our mathematical modeling and chosen carefully for underwater suitability. PVC pipe was selected for structural components due to its mechanical properties, influencing the ROV's maximum operational depth, calculated by $P = \rho \cdot g \cdot h$. The 3D design model shown in Fig. 1 was developed using AutoDesk's Fusion 360 [32].

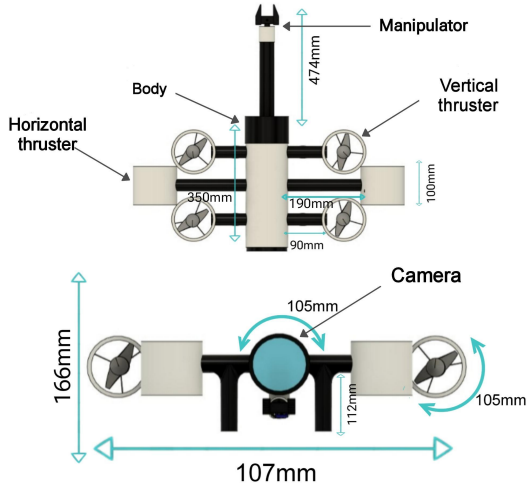


Fig. 1: Details view (Top and Side View) with dimensions of the proposed ROV.

The ROV, as shown in Fig. 1, has dimensions of 166mm height, 705mm width, and 640mm length, resembling a quadcopter drone. It features four vertically-oriented and two horizontal thrusters, custom-designed and 3D-printed using PLA+

material. The body, made of PVC pipe, supports a 474mm manipulator arm with an aluminum gripper. Components are assembled with 4-inch PVC pipes, T-joints, and elbows.

Weight distribution is crucial for underwater performance, with the body, motors, and propellers being the main contributors. The battery and buoyancy systems also play vital roles. Designed for lightweight, easy deployment, the ROV includes a Pi camera for real-time streaming, a gripper arm for manipulation, and a custom two-blade propeller for navigation. Control is semi-wireless, using ESP modules and WiFi.

TABLE I: Weight distribution of the ROV.

Serial	Item Name	Quantity	Weight	Total Weight
1	Body(PVC)	1	2.7kg	2.7kg
2	BLDC	6X	0.05kg	0.3kg
3	PLA propeller	6x	0.015kg	0.09kg
4	wire	1	0.3kg	0.3
5	glass	1x	0.15kg	0.15kg
6	components and sensors	1	1.33kg	1.33kg
7	gripper	1X	0.7kg	0.7kg
8	others	1x	5.43kg	5.43kg

B. Internal architecture of TritonZ

Our ROV's internal setup is designed with a strong and interconnected system, as shown in Fig. 2. At the center is the Arduino Mega microcontroller, which processes sensor data and controls the ROV's movements. Alongside it, the NodeMCU ESP8266 handles wireless communication, enabling remote control and real-time data sharing. For real-time video capture, we use a Raspberry Pi 3 with a camera module, which is essential for navigating underwater. The live video feed is sent to the operator's device, where it's used to control the ROV. The ROV's movement is powered by brushless motors, controlled by Electronic Speed Controllers (ESCs) for smooth and precise operation. Relays are used to manage direction, and a servo-powered aluminum gripper allows the ROV to interact with objects underwater. Environmental monitoring is handled by a DHT11 sensor, which tracks temperature and humidity. This data, along with other important information like battery levels, is displayed on an LCD screen. The ROV is powered by a LiPo battery, chosen for its good balance of power and weight, ensuring reliable performance during underwater exploration.

C. System Implementation

The ROV's control system uses wireless communication between two ESP8266 modules (operator and ROV) via the ESP-NOW protocol, enabling two-way control and sensor data transmission. The Arduino Mega handles motor control and sensor processing, while Electronic Speed Controllers (ESCs) manage motor speed and direction. The servo-controlled aluminum gripper allows precise object handling, and custom 3D-printed PLA two-blade propellers ensure efficient propulsion. The system integrates a Flask server with OpenCV and Python for live video streaming and object detection, with the Raspberry PiCam providing high-resolution underwater footage. A user-friendly HTML and CSS interface facilitates control and streaming.

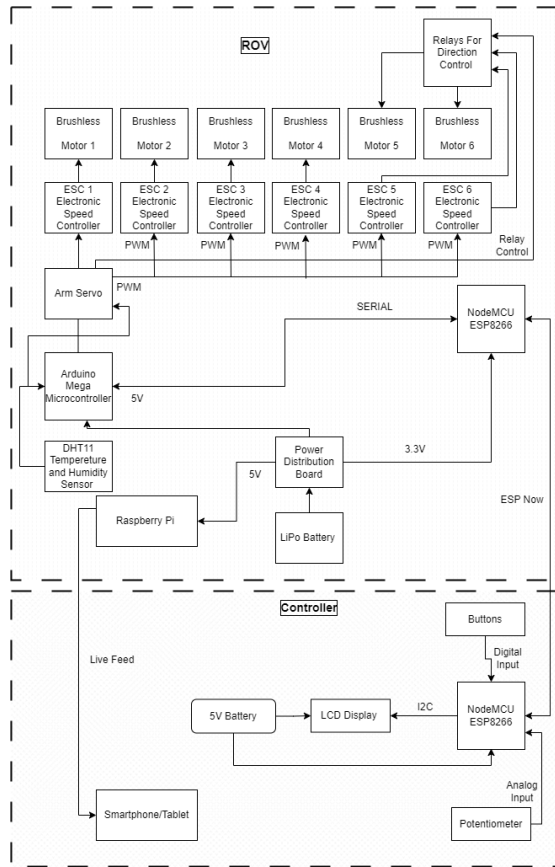


Fig. 2: Block Diagram of the Proposed Underwater ROV Architecture.

After developing the software and assembling the hardware, we successfully integrated the proposed underwater ROV. Fig 3(a) & (d) illustrates the overall hardware design and software's UI, highlighting all key components clearly marked and labeled.

The controller setup, shown in Fig. 3(b), includes an LCD display and connects with the ROV using wireless protocols, enabling precise control during underwater operations. Finally, Fig. 3(c) shows the ROV in navigation mode.

V. RESULTS & DISCUSSION

Comprehensive experimental trials to determine the efficiency of our ROV were performed. Despite its compact size (60 cm x 70 cm x 25 cm) and lightweight (11 kg), the ROV demonstrated impressive mobility and adaptability in varied underwater environments as shown in Fig. 3(c). The integrated manipulator arm exhibited precise and agile functionality. The Pi cam's real-time video streaming and object detection significantly enhanced situational awareness and mission accuracy. The ROV is equipped with a DHT22 sensor for monitoring water temperature and humidity, offering $\pm 0.5^\circ\text{C}$ and $\pm 2\%$ RH accuracy, with 98.15% reliability [33]. Additionally, the ROV features a voltage sensor with $\pm 0.1\text{V}$ accuracy for real-time battery status [34]. Both sensors performed reliably during trials, ensuring accurate measurements for underwater tasks, with future versions focusing on precision improvement and

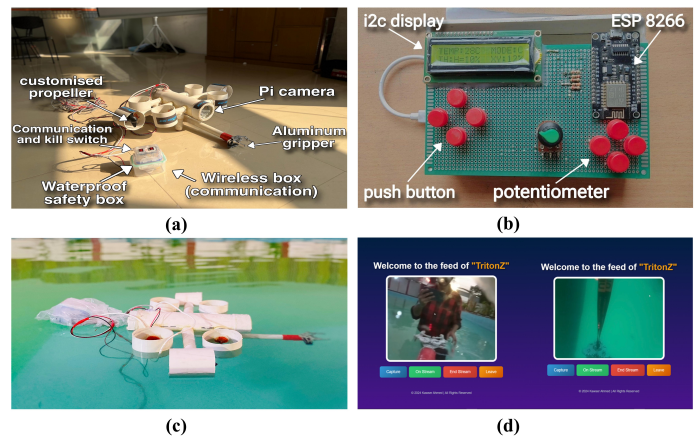


Fig. 3: Overall Hardware system of the implemented ROV, TritonZ: (a) Full Body Structure where each external components are shown, (b) Customized Controller with push-buttons using ESP8266, (c) Our ROV in submerged condition while navigating, and (d) Live Pi Cam Footage of the Underwater from the user-end.

additional sensor integration. Notably, the prototype surpassed runtime expectations, operating for 45 minutes using two 12.5V, 2200mAh batteries, showcasing enhanced operational capacity. Furthermore, the ROV's affordability, with a prototype cost of approximately 12,000 BDT (110 USD), shows its potential for widespread application.

The following discussion elaborates on the results related to the three main components of our ROV:

Aquatic Exploration: As shown in Fig. 3(c), the ROV's submersion capability is powered by brushless motors, which are ideal for high-density, high-pressure underwater environments. These motors ensure the ROV can reliably operate at depths of up to 5 cm and move in any direction, making it versatile for different underwater tasks. Fig. 3(c) provides a visual representation of this capability in action.

Underwater Object Retrieval and Live Streaming: The ROV's manipulator arm efficiently retrieved objects detected by the Pi camera, showing its precision in underwater tasks. At the same time, the camera streams live video through a Flask server, allowing real-time viewing of underwater environments on any device. This feature not only improves the control of the ROV but also supports collaboration in underwater research, as illustrated in Fig. 3(d).

A. Analysis of Motion

We performed several trials underwater to understand the motion capabilities of the ROV in submerged conditions. In each trial, the task of the ROV was to finish 400cm distances underwater while we observed the displacement and velocity of the ROV with time. Table II presents the four trial results among various trials we performed. In trial 1, the ROV covered the distance in 33 seconds, achieving an average velocity of 13 cm/s. Similarly, trial-2 and trial-3 took 30 and 31 seconds with velocities of approximately 14cm/s and 13.6 cm/s respectively. The first three trials were taken under a stable underwater

environment i.e. still-water condition. From table II, the results indicate the ROV takes an average 31.33 seconds to complete the tasks with an average of 13.5cm/s approximately.

TABLE II: Motion Analysis result for different trials

Trial No.	Distance (cm)	Time Taken (s)	Average Velocity (cm/s)
1 (still-water)	400	33	13
2 (still-water)	400	30	14
3 (still-water)	400	31	13.6
4 (wave-induced trial)	400	39	12.25

Furthermore, we also plotted the displacement and velocity vs. time in still-water testing to understand how the ROV behaves with time and the time it takes to reach the average velocity. Fig. 4 (trial-1) shows the velocity-displacement profiles over a displacement of 400 cm. We observe from Fig. 4 that the ROV achieves maximum velocity within 6s. After achieving maximum velocity under still-water condition, the ROV maintains this speed till the finish line. We also tested our ROV under wave-induced conditions in the water. The results of the wave-induced condition is shown in table II (trial-4). Due to the disturbance in the water, the ROV took 39s which is higher compared to previous trials and achieved less average velocity, 12.25cm/s. Fig. 5 shows the motion in wave-induced condition. Here, the ROV also achieves maximum velocity within 8s as we can see from the figure. Wave is induced in the environment at 30s and after that we see the velocity drops and displacement along the surge direction decreases. However, our ROV has been designed keeping the disturbance of the surrounding environment. Our trials demonstrated the ROV's capabilities in both normal and wave-induced water conditions, with consistent results observed across three tests in each scenario (Fig. 4, 5). However, broader testing in strong currents, varying water temperatures, and deeper underwater conditions is needed. Future work will focus on these challenges to provide a more comprehensive evaluation of TritonZ's reliability and versatility. The ROV can maintain its position due to the symmetric vertical thrusters and buoyancy system even under induced wave. This can be observed from (Fig. 5) where the ROV increases its velocity within 5s and reaches around 12 cm/s to complete the overall distance.

Our system showed a time delay of 6 to 8 seconds at startup, reduced to 2 to 3 seconds during navigation. This outperforms similar ROV shown in [35] reporting convergence times of 24 to 27 seconds, even with filters like the UKF. These findings confirm the ROV's capacity for controlled movement, balancing manoeuvrability and precision to meet diverse underwater exploration and rescue requirements. Previous research on underwater remotely operated vehicles (ROVs) has largely focused on basic features like navigation and image capture, often neglecting advanced capabilities such as object manipulation and real-time streaming. Our ROV addresses these limitations with a robotic arm for precise recovery and live-streaming functionality. Table III showcases how TritonZ outperforms existing models in transparency, control range, weight, and cost. Built with cost-effective PVC

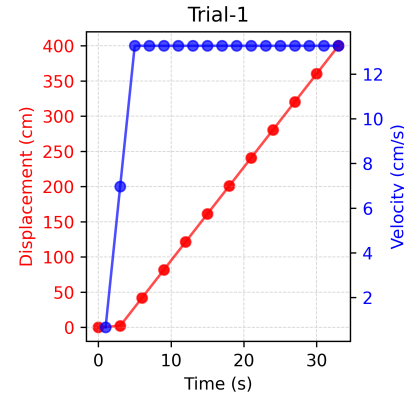


Fig. 4: Velocity-Displacement relation in surge direction under still-water condition (Trial 1)

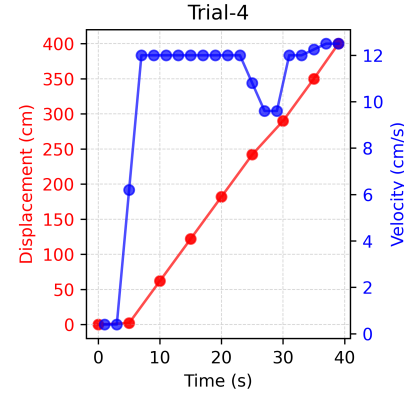


Fig. 5: Velocity-Displacement relation in surge direction under induced wave condition (Trial 4).

TABLE III: Cost comparison with Previous Works

Ref	Micro-controller	Camera	Weight	Cost
[3]	Raspberry Pi 3	Vemont 1080p	15.64kg	\$600
[5]	N/A	Go-Pro 6	Not given	\$1336
[9]	ESP 8266	No camera	Not given	\$370 (approx)
[11]	ATMEGA 328	Digital cam	Not given	\$430 (approx)
[8]	Raspberry Pi	Picam3 60	Not given	\$750 (approx)
TritonZ	ESP8266	Pi Cam	11 KG	\$110

and a 1000kv BLDC motor, TritonZ is lightweight, stable, and optimized for underwater operations, minimizing speed loss and ensuring steady buoyancy. These features make it ideal for education, marine research, environmental monitoring, and rescue missions.

While our ROV shows promising results, there are areas for improvement. Visibility underwater is a challenge, which we plan to enhance by using a Pi camera with advanced image processing. Communication underwater can be unstable, but we can improve this by using an air-tight floating box for the receiver. To help the ROV submerge properly, adding extra weight could be a solution. Accurate depth measurement is also an issue, which could be solved with a radar system. Lastly, maintaining stability was difficult, which we could

address by adding a gyroscope or accelerometer for better balance.

VI. CONCLUSION & FUTURE WORK

Our proposed system focuses on building a lightweight, efficient underwater vehicle with a cost-effective, semi-wireless, remotely controlled underwater ROV. The prototype demonstrates diverse capabilities, covering various functionalities, and rescue operations, including a Pi Cam and a manipulator arm for object interaction. The ROV can maintain reasonable speed and sustain waves and other disturbances in the water while navigating in 4 dimensions. Additionally, it can send live data to the user end such as live video footage underwater, humidity, and temperature of the water. In the future, we aim to enhance the accessibility of the ROV's arm by incorporating more degrees of freedom, addressing the current limitation of its 4-DOF design. This improvement will allow for better handling of complex manipulation tasks, increasing the ROV's versatility and effectiveness. Additionally, we want to enhance the performance and refine the structure of our ROV so that it can perform heavier tasks in real time.

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