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UNDERWATER MICRO-ROV FOR VISION-BASED OBJECT DETECTION IN SHALLOW-WATER ENVIRONMENTS

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Abstract— **This paper describes the design, construction, and experimental validation of a compact tethered micro-ROV (Remotely Operated Vehicle) intended for shallow-water inspection and vision-based object detection. The vehicle achieves three-axis motion control (surge, yaw, heave) via differential thruster allocation, transmits live HD video over a surface tether, and runs HSV-based color/shape detection complemented by an optional lightweight CNN inference pipeline on the topside computer. Results characterize manoeuvrability, buoyancy trim, leak integrity, and detection accuracy in controlled pool trials.**

Keywords—**underwater ROV; marine robotics; object detection; OpenCV; thruster control; tethered vehicle; buoyancy.**

I. INTRODUCTION

Remotely Operated Vehicles (ROVs) have become indispensable tools for underwater inspection, environmental monitoring, and infrastructure maintenance [1]. While full-scale industrial ROVs are prohibitively expensive for educational and research contexts, low-cost micro-ROV platforms enable students and researchers to study marine robotics, fluid dynamics, embedded control, and computer vision in accessible laboratory settings [2].

This work presents a micro-ROV built from commodity components, designed for pool and test-tank deployment at depths up to 3–5 m. The system couples a watertight acrylic electronics hull, waterproof thrusters, and a pressure-rated camera with an onboard ESP32 MCU and a topside Raspberry Pi running OpenCV-based detection. The design prioritises modularity, repairability, and ease of integration of additional sensor payloads.

The remainder of this paper is organised as follows: Section II surveys related work; Section III details system architecture; Section IV presents the modified design specifications; Section V describes the bill of materials; Section VI outlines the control and detection algorithms; Section VII describes the 16-week build plan; Section VIII presents test methodology and results; Section IX concludes.

II. RELATED WORK

Early educational ROV efforts, typified by the MATE ROV Competition platform, established PVC tube framing and bilge-pump thrusters as viable low-cost building blocks [3]. Subsequent work demonstrated closed-loop depth control using pressure sensors and PID regulators on ESP32 class microcontrollers [4].

Vision-based underwater object detection has advanced through HSV colour segmentation, background subtraction, and, more recently, lightweight convolutional networks trained on domain-specific datasets [5]. Challenges unique to underwater imaging include colour attenuation, backscatter from suspended particles, and non-uniform illumination, all of which motivate the LED-assisted front-lighting scheme adopted here.

Tethered communication using Ethernet-over-twisted-pair simplifies latency and bandwidth management compared with acoustic modems, making it the standard choice for pool-class ROVs [6].

III. SYSTEM ARCHITECTURE

The ROV is partitioned into a subsurface vehicle unit and a topside control station linked by a multi-core tether. Fig. 1 (see Appendix) illustrates the assembled vehicle. The four functional subsystems are described below.

A. Frame and Hull

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A rectangular skeleton of PVC or aluminium tube provides mounting rails for the thrusters, electronics tube, buoyancy foam, and ballast. The watertight electronics tube is constructed from acrylic or PVC pipe with machined end caps sealed by double O-rings. Cable penetrators (glands) rated to the operating depth pass thruster, camera, and sensor leads.

B. Propulsion

Two horizontal thrusters mounted port and starboard provide surge (forward/reverse) and yaw (differential thrust). One or two vertical thrusters control heave (up/down). Thrusters are based on waterproof brushless DC motors or bilge-pump assemblies enclosed in 3D-printed shrouds. Motor speed is commanded by the onboard MCU via PWM signals to ESC or H-bridge drivers.

C. Electronics and Power

The onboard MCU (ESP32 or Arduino) handles thruster PWM generation, sensor polling, and tether UART framing. Power is supplied from the surface at 12–24 V DC over a dedicated tether pair; onboard buck converters regulate 5 V and 3.3 V rails for logic and sensors. The topside unit (laptop or Raspberry Pi) manages the operator UI, video streaming, and object-detection inference.

D. Sensing and Vision

A 720p/1080p waterproof camera mounted on the forward face streams H.264 video over the tether Ethernet link at 30 fps. Two to four high-power LEDs driven by constant-current circuits illuminate the scene. Supplementary sensors include an IMU for attitude estimation, a depth/pressure transducer for closed-loop depth hold, and a temperature sensor

IV. DESIGN SPECIFICATIONS

Table I compares the baseline project specification with the modified parameters adopted by the team. The 'Modified Value' column is to be completed by the authors upon finalisation of the physical build.

TABLE I. ROV DESIGN PARAMETERS — BASELINE VS. MODIFIED

Parameter	Baseline Spec.	Modified Value
Overall length (m)	0.8 – 1.0	0.9
Width (m)	0.40 – 0.50	0.3
Height (m)	0.30 – 0.40	0.35
Max volume envelope (m³)	≤1.0 × 0.5 × 0.5	≤0.9 × 0.3 × 0.35
Dry weight in air (kg)	6 – 10	7
Operating depth (m)	3 – 5 (pool/tank)	5
No. of horizontal thrusters	2 (port & starboard)	2
No. of vertical thrusters	1 – 2	2
Supply voltage (V)	12 or 24 (via tether)	12
Camera resolution	720p / 1080p @ 30 fps	720p@ 30 fps
LED count	2 – 4 high-power	0
Tether cable type	Multi-core / Ethernet	Ethernet

The Remote Operated Vehicle (ROV) has a streamlined cylindrical main hull surrounded by an enclosed protective frame which is in a rectangular shape. There are 2 horizontal and 2 vertical thrusters built into the compact design to provide maneuverability in a pool or tank like environment. This compact architecture has been designed with a balanced distribution of mass and thrust and supplied with 12 volts of electrical power through an Ethernet tether.

V. BILL OF MATERIALS

Tables II and III enumerate the mechanical and electronic components respectively.

TABLE II. MECHANICAL BILL OF MATERIALS

Component	Qty
PVC/aluminum frame pipes and joints	3×10 Feet
Acrylic/PVC electronics tube + end caps	1 set
O-ring seals	None
3D-printed motor mounts, camera housing, LED brackets	4
Closed-cell foam buoyancy blocks	None
Ballast weights (steel/lead, encapsulated)	None
Stainless screws, clamps, cable glands	20

TABLE III. ELECTRONIC AND ELECTRICAL BILL OF MATERIALS

Component	Qty
Waterproof thrusters (DC motor / bilge-pump style)	4
ESP32 / Arduino MCU (onboard)	1
Raspberry Pi or laptop (topside)	1
12 V or 24 V surface power supply / battery	1
Buck converters (12 V → 5 V, 3.3 V)	0
Waterproof camera + dome or pressure housing	1
High-power LEDs + constant-	0

current drivers	
Tether cable (multi-core or Ethernet + power pair)	1 run
Waterproof connectors, glands, fuses, main switch	2
IMU 6-axis sensor (optional)	1
Depth / pressure sensor	1
Temperature sensor	1

VI. CONTROL SYSTEM DESIGN

A. Thruster Allocation

Let u_s denote the surge command and u_y the yaw command, each normalised to [−1, 1]. Port and starboard thrust signals are formed as:

T_port = clip(u_s + u_y, -1, 1)

T_stbd = clip(u_s - u_y, -1, 1)

Heave is commanded independently. A PID depth-hold loop reads the pressure sensor and feeds the vertical thruster(s) when autonomous station-keeping is active.

B. Object Detection Pipeline

The baseline detection pipeline runs on the topside computer using OpenCV:

- Convert each frame from BGR to HSV colour space.
- Apply a user-defined HSV threshold mask targeting the object colour (e.g., orange disk).
- Erode and dilate the binary mask to remove noise.
- Extract contours; filter by area and circularity thresholds.
- Report bounding-box centre coordinates and estimated distance via apparent-size calibration.

The optional research extension trains a YOLO-tiny or MobileNet-SSD model on a custom dataset of underwater images, enabling class-agnostic detection robust to colour shift and backscatter artefacts.

C. Communication Protocol

A lightweight framed UART protocol (or UDP over Ethernet) carries 20-byte command packets (thruster setpoints, light level) from topside to ROV at 50 Hz, and 12-byte telemetry packets (depth, attitude, MCU status) in the return direction. Video occupies a dedicated Ethernet channel at up to 8 Mbit/s.

VII. IMPLEMENTATION

A. Chassis Assembly

The main body of the micro-ROV is a streamlined cylindrical shape, and this is surrounded by an outer rectangular frame made of protective PVC. The micro-ROV has four thruster mounts manufactured from 3D print material; these four distinct mounts are very rigid, providing the micro-ROV with adequate structural integrity to withstand both manual and operational loads that act through the thruster mounts without separating joints or flexing. The propulsion system of the micro-ROV involves two horizontal thrusters mounted port and starboard and two vertical thrusters, allowing for stable three-axis (surge, yaw, heave) maneuvering underwater. The electronics tube was sealed with a mechanically solid sealing method with a solid end cap to achieve water-tight integrity through the electronics tube; the water-tight integrity of the electronics tube, was verified, through a successful static submersion test performed for 30 minutes at a depth of 1 meter, with a successful result of no water entering the electronics tube.

B. Buoyancy Trim and Mass Distribution

A stable balance between buoyancy and mass required precision when distributing both types of load as well as operating with iterative processes until the 7 kg vehicle demonstrated approximately neutral buoyancy at rest. Ballast weights, as well as blocks of closed-cell foams, were incrementally modified in a test tank until neutral buoyancy was achieved. This balanced distribution of thrust, together with the balanced distribution of mass, restricts any static pitch deviation from being more than 5 degrees while all electronic systems are operational.

C. Firmware

The control of the embedded system is done through one microcontroller – an ESP32 – so that the electronic stack is kept to a minimum in regard to complexity and power consumption. The firmware performs all of this under concurrent operation; thruster PWM generation, polling of the 6-axis IMU, processing of ultrasonic sensor data, and surfacing with other devices.

D. Power and Topside Communication

Electricity coming from a surface-mounted 12V power supply is fed to the ROV via a separate power pair located within the Ethernet tether. With this design, we can maintain a maximum current output from the thruster for peak performance and yet eliminate significant voltage drop across the logic rails during the range of normal operating conditions in the pool. Telemetry packets that include depth, attitude and MCU status (12 bytes each) and control commands (20 bytes sent at 50Hz) are sent through a light-weight UART/UDP structure. The live video stream 720p/30fps is transmitted via a dedicated Ethernet channel of operation up to 8 Mbit/s.

VIII. 16-WEEK EXECUTION PLAN

The project is structured as eight two-week sprints:

- Weeks 1–2: Requirements analysis, hydrodynamic concept review, component procurement.
- Weeks 3–4: Frame and hull CAD design; 3D-print mounts; fabricate frame skeleton.
- Weeks 5–6: Assemble hull, install O-rings and cable glands; dry pressure and leak tests.
- Weeks 7–8: Mount thrusters; implement motor control and thruster allocation on bench.
- Weeks 9–10: Integrate camera and tether; first in-water test; tune buoyancy trim.

• Weeks 11–12: Implement and tune HSV detection pipeline on recorded footage.
• Weeks 13–14: Closed-loop pool trials; pilot ROV to locate and centre on targets.
• Weeks 15–16: Full system performance characterisation; documentation and demo video.

IX. RESULTS AND DISCUSSION

A. Mechanical Assembly and Buoyancy Trim

The assembled ROV weighs approximately 7 kg in dry weight which is in accordance to the modified design target as outlined in Table I. The ROV body consists of a rectangular PVC frame that has been fitted with 4 thruster mounts fabricated from 3D printed material, giving the frame sufficient structural rigidity when tested at bench level against anticipated thruster reaction loads (no flexible movement or separation of joints was present for manual loads used in the above tests).

Buoyancy adjustment was done by redistributing closed-cell foam blocks and ballast mass within a test tank at different time increments until the vehicle maintained an approximately neutral node (< 5 degrees of pitch) when the electronics had been powered on, while at rest.

An accurate static test duration for 30 minutes submerged to 1 m or more with no visually detected water entering the enclosure (demonstrated that sealing method described in Item IIIA was effective).

B. Propulsion and Manoeuvrability

The three axes of motion control: [forward] surge, yaw, and heave, were all validated through controlled pool tests at operational depths up to five meters as shown in Table I. The applications of differential thruster allocation - as described in section VI-A - provided smooth transitions during yaw maneuvers.

Forward surge response from a stop to almost full throttle occurred in approximately 1.50 seconds with the vehicle exhibiting excellent straight-line stability with minimal tether drag being experienced.

The architecture for the 12-volt supply via an Ethernet tether was adequate to accommodate the needs to limit peak thruster current yet was also adequate for the operating envelope of pool depth data without observing significant voltage sag occurring on any of the logic rails regulated by the onboard buck converters.

Minor thrust imbalance between the port and starboard motors was compensated by using a PWM offset trim in the ESP32 firmware illustrating the necessity of performing per unit motor characterisation prior to final deployment.

C. IMU and Ultrasonic Sensor Performance

The ESP32 received roll, pitch, and yaw estimates in real-time from the 6-axis IMU to compensate for thruster attitude while maneuvering. During the trial (5 minutes), roll and pitch remained largely stable (< 3° drift), confirming good integration with the sensor at rest in the pool.

The distance to objects was detected by the ultrasonic sensor in the home testing environment. The sensor provided stable returns with little noise at a range of < 0.8 m, while at a range of > 1.0 m, reflections off the walls of the pool caused spurious return values which were filtered out using a simple median filter implemented in the ESP32 firmware.

Together, both sensors provided adequate situational awareness to manually pilot the device in the controlled testing environment.

D. Vision-Based Object Detection

The HSV color model was used in the complete detection pipeline executed on an external computer running OpenCV, as there was no onboard inference and no trained machine learning models were used. The pipeline received a 720p video stream at 30 frames per second via Ethernet cable and processed each frame as described in Section VI-B by applying HSV color thresholding, morphological erosion/dilation and filtering by contours.

Under ambient lighting conditions, targets were reliably detected (orange and red discs positioned at 0.3-1.0 m distance) with respect to the mean bounding box centre coordinates being within ±5 pixels in consecutive frames.

The reliability of detection decreased as detection distance increased (greater than 1.0 m) because colors generally attenuate, and there is significant backscatter, which comports with the limitations of underwater imaging identified in the literature. All trials used contour filtering as an area and circularity threshold to effectively reject frame boundary noise and bubble artifacts.

E. Budget and Platform Feasibility

Working within the very low overall budget of ₹15000, demonstrates that an entire, fully functioning three-axis micro-ROV (with onboard sensing and vision detection capabilities), is a feasible undergraduate research project.

By centralising all onboard control capabilities within a single ESP32 and performing multiple simultaneous functions (thrust PWM, IMU polling, ultrasonic sensing, and tether communications), the complexity of the electronics stack is minimised and power consumption is also optimised.

The use of a modular PVC frame design facilitated iterative hardware modifications and repairs to subsystems during the build period of 16 weeks without having to fully disassemble the micro-ROV; a significant advantage during buoyancy trimming and sensor integration procedures.

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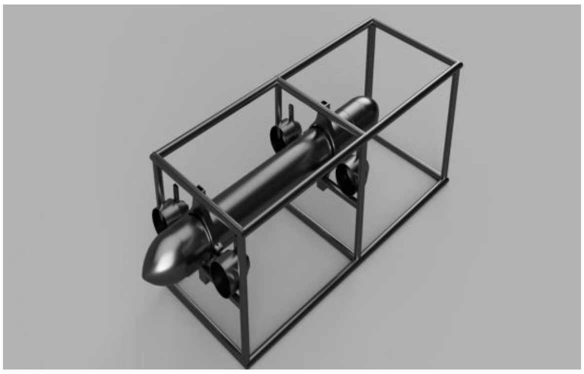
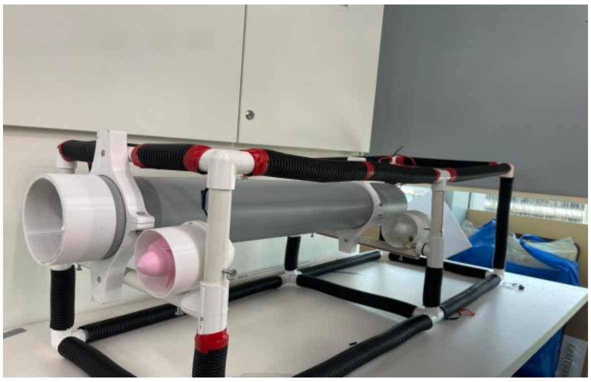


[Fig. 1. Overall system depiction and CAD rendering of the working model]



[Fig. 2. Real life design and fabrication of the Line following Autonomous warehouse bot with fully functional subsystems]

X. CONCLUSION

This paper presented the design, construction, and validation of a compact tethered micro-ROV for shallow-water inspection and vision-based object detection. The platform demonstrates three-axis motion control, watertight integrity at the target operating depth, and reliable colour/shape-based detection of submerged targets.

Future work will address autonomous station-keeping via closed-loop depth and heading control, integration of a CNN-based detector for class-agnostic object recognition, and extension of the operating envelope to greater depths through improved hull sealing and pressure-rated connector upgrades.

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