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Design and Development of a Vector Thrust Remotely Operated Vehicle

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***Abstract* - This paper presents the design and development of a low-cost underwater Remotely Operated Vehicle (ROV) incorporating a servo-based vector thrust mechanism for improved maneuverability. Conventional ROV systems require multiple fixed thrusters to achieve multi-degree-of-freedom motion, resulting in increased complexity, power consumption, and cost. The proposed system addresses these limitations through thrust vectoring, where servo-actuated mechanisms dynamically adjust the direction of thrust. The mechanical design consists of a compact symmetrical frame, a cylindrical acrylic pressure housing, and four ducted thruster modules each equipped with a servo-driven tilt mechanism supported by a planetary gear system. The control architecture employs an ESP32 microcontroller interfaced with a PCA9685 PWM driver to control electronic speed controllers (ESCs) and servo motors in real time. Theoretical analysis of thrust, buoyancy, and hydrodynamic drag guided the design. A prototype was fabricated using 3D-printed components and validated through shallow water testing. Results confirm successful forward motion, yaw control, and limited vertical displacement using vectored thrust, demonstrating the feasibility of this modular, cost-effective platform for underwater inspection applications.**

***Keywords* - ROV; vector thrust; thrust vectoring; ESP32; underwater vehicle; servo mechanism; PCA9685; planetary gear; hydrodynamic drag; buoyancy.**

I. INTRODUCTION

Underwater robotics has emerged as a critical field in marine engineering, enabling tasks such as subsea inspection, environmental monitoring, pipeline maintenance, and deep-sea exploration. Remotely Operated Vehicles (ROVs) are widely deployed in these applications owing to their ability to operate in hazardous and inaccessible underwater environments under real-time surface control [1].

Conventional ROV designs rely on multiple fixed thrusters to achieve motion across different degrees of freedom. While such configurations permit multi-DOF control, they significantly increase mechanical complexity, power consumption, and overall system cost. Fixed-thruster architectures also suffer from inefficient force distribution and limited maneuverability in confined spaces [2].

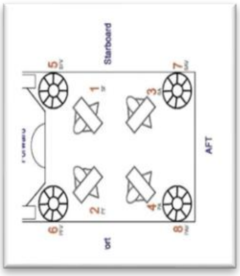

Fig. 1. Typical Conventional ROV with Multiple Fixed Thrusters

Thrust vectoring, a concept borrowed from aerospace engineering, offers a promising alternative. By allowing a single thruster to redirect its force vector dynamically, thrust vectoring can achieve multi-directional motion with fewer actuators, thereby reducing weight, cost, and complexity [3]. Recent research on orientation-adjustable thrusters for autonomous underwater vehicles (AUVs) has demonstrated full six-DOF motion with a reduced actuator count [3].

The present work designs and develops a low-cost shallow-water ROV prototype that integrates servo-based thrust vectoring. The system uses an ESP32 microcontroller, a PCA9685 PWM driver, 3D-printed structural components, and an acrylic pressure housing, making it suitable for academic research and educational experimentation.

II. LITERATURE REVIEW

A. ROV Systems and Propulsion

ROVs are tethered underwater robotic systems equipped with propulsion units, sensors, cameras, and control electronics. Azis et al. [1] identified key problem areas in ROV design, including thruster efficiency, waterproofing, and communication reliability. Aguirre-Castro et al. [4] and Ramos et al. [5] demonstrated low-cost ROV implementations that maintain acceptable performance while simplifying the system architecture. Aras et al. [8, 10] explored thruster modelling via system identification methods to improve propulsion accuracy.

B. Thruster Modelling and Control

The thrust T generated by a marine propeller is approximated using momentum theory [15]:

$$T = \rho A U^2$$

where ρ is fluid density, A is propeller disk area, and U is induced velocity. The general motion equation of an underwater vehicle is:

$$M\ddot{u} + C(v)v + D(v)v + G(\eta) = T$$

accounting for inertial, Coriolis, hydrodynamic drag, and restoring force terms [15]. Yoerger and Slotine [17] and Healey and Lienard [18] provided foundational control strategies for ROV trajectory tracking.

C. Vector Thrust Mechanisms

Wang et al. [3] introduced an orientation-adjustable thruster AUV capable of six-DOF motion with four thrusters. Thrust decomposition in a vector thrust system is expressed as:

$$T_x = T\cos\theta\,, \quad Ts = T\sin\theta$$

This decomposition allows a single tilted thruster to contribute simultaneously to horizontal and vertical motion, reducing the total actuator count while retaining control flexibility.

D. Research Gap

Despite advances in thruster modelling and vector thrust concepts, a gap exists in developing low-cost, modular ROV platforms that integrate servo-based vectoring with simple embedded control architectures. The present work addresses this gap.

III. DESIGN AND THEORETICAL ANALYSIS

A. System Overview

The developed ROV is a compact, modular underwater vehicle incorporating a vector thrust propulsion mechanism. The system integrates mechanical, electrical, and control subsystems for controlled underwater motion. The architecture consists of:

- A central cylindrical acrylic pressure housing
- Four thruster modules with servo-based vectoring
- A distributed control system (ESP32 + PCA9685)
- A tether-based communication interface

B. Mechanical Design

The ROV frame adopts a symmetrical X-configuration 3D-printed in PLA, ensuring balanced force distribution and a centred mass distribution. The frame supports thruster mounting, pressure housing attachment, and cable routing.

Electronic components are enclosed in a cylindrical acrylic tube sealed with end caps and silicone gaskets. Buoyancy force and hydrostatic pressure are governed by:

$$F^b = \rho g V \quad \text{and} \quad P = \rho g h$$

Each thruster module consists of a brushless DC motor-driven ducted propeller combined with a servo-driven tilting mechanism. A planetary gear stage amplifies servo output torque:

$$T_{out} = T_{in} \times \text{Gear Ratio}$$

ensuring reliable actuation under hydrodynamic loading. Key design parameters are summarized in Table I.

TABLE I. KEY DESIGN PARAMETERS

Parameter	Value
Total Weight	6.32 kg
Thrust per thruster	16.7 N
Total thrust (2 thrusters)	33.4 N
Estimated drag force	0.6 – 1.0 N
Total power draw	168 W
PWM range	1000 – 2000 µs

C. Electrical and Control System

The control architecture follows a distributed model. A Python GUI on the host computer reads gamepad inputs and transmits commands to the ESP32 over USB serial. The ESP32 generates I²C signals to the PCA9685 PWM driver, which independently controls four ESCs (thruster speed) and four servo motors (thrust direction). Signal flow:

Gamepad → Python → ESP32 → PCA9685 → ESC / Servos

D. Theoretical Calculations

Thrust per thruster was estimated at 16.7 N using momentum theory, giving a combined thrust of ~33.4 N. Hydrodynamic drag was estimated as:

$$D = \tfrac{1}{2} \rho C_D A v^2 \approx 0.6 - 1.0\ N$$

yielding a thrust-to-drag ratio of approximately 30:1, confirming efficient motion capability. The vertical thrust component from a tilted thruster at angle $\theta = 18°$ is $T_s = T \sin 18° \approx 5.2$ N per unit.

IV. IMPLEMENTATION AND TESTING

A. Fabrication

Structural components were manufactured by FDM 3D-printing in PLA. The pressure housing was fabricated from a 100 mm diameter acrylic tube with machined acrylic end caps sealed using silicone O-rings. Thruster assemblies integrated brushless DC motors within 3D-printed ducts, connected to the frame via servo-driven pivot mounts incorporating a planetary gear stage for torque amplification.

Fig. 2. Fabricated ROV Prototype

B. Electronics Assembly

ESP32, PCA9685 PWM module, four 30 A ESCs, servo motors, and a 3S LiPo battery were mounted inside the pressure housing. A buck converter stepped the 11.1 V battery voltage to 5 V for the logic circuits. Wiring was routed through the end caps using waterproof cable glands, and the housing was sealed with silicone adhesive on all joints.

C. Experimental Setup

Experimental validation was conducted in a shallow concrete water tank. A tethered gamepad interface connected to the host laptop transmitted motion commands. Testing was performed under open-loop (manual) control at short durations to assess thrust, buoyancy, and directional response.

D. Buoyancy Testing

Initial tests revealed positive buoyancy due to the sealed air volume within the pressure housing. Temporary ballast (wooden blocks) was attached to the frame to approach neutral buoyancy. The condition $F^b = W$ was verified experimentally, confirming near-neutral buoyancy after adjustment.

E. Motion Testing

Forward motion, yaw (turning), and limited vertical displacement were evaluated:

- Forward motion: Achieved — the ROV translated forward with consistent thrust.
- Yaw control: Successful — differential thrust vectoring produced effective turning.
- Vertical motion: Limited — constrained by small tilt angle and absence of closed-loop depth control.

Air bubble formation at weld joints indicated minor sealing deficiencies requiring rectification in future iterations.

V. RESULTS AND DISCUSSION

A. Performance Summary

The propulsion system delivered a combined thrust of ~33.4 N, far exceeding the estimated drag force of ~1 N, confirming adequate propulsion margin for low-speed shallow-water operation. Table II summarises the measured versus theoretical performance.

TABLE II. PERFORMANCE SUMMARY

Parameter	Theoretical	Observed
Total Thrust	33.4 N	Adequate
Drag Force	~1 N	Low resistance
Buoyancy	Slight positive	Adjusted manually
Vertical Thrust	~5.2 N @ 18°	Limited
Stability	Ideal (assumed)	Moderate

B. Discussion

Thrust vectoring successfully enabled multi-directional motion with only four thrusters. However, tilting the thrusters reduces the horizontal thrust component ($T_x = T \cos\theta$), and the small tilt angle (18°) limited vertical authority. The absence of closed-loop feedback caused orientation drift during directional changes.

Excess buoyancy highlighted the sensitivity of underwater vehicles to small volume discrepancies. Precise buoyancy tuning via a dedicated ballast module is recommended for future work. Minor sealing failures (observed air bubbles) indicate a need for O-ring compression validation.

Overall, the vector thrust concept was validated as a feasible approach for low-cost ROVs. The modular design permitted rapid iteration and troubleshooting, a key advantage for academic platforms.

VI. CONCLUSION

This paper has presented the design, fabrication, and experimental validation of a low-cost vector thrust ROV. The primary contribution is the integration of a servo-actuated planetary gear thrust vectoring mechanism with a distributed ESP32-based control system in a single, modular prototype.

Experimental results confirmed that forward motion and yaw control are achievable with the proposed propulsion approach, and that the thrust-to-drag ratio (approximately 30:1) is sufficient for low-speed underwater operation. Limitations identified — including buoyancy imbalance, reduced vertical thrust authority, and the absence of sensor-based feedback — provide clear directions for future work:

- Integration of IMU (MPU6050) for closed-loop stabilisation via PID.
- Replaceable ballast modules for precise buoyancy control.
- Enhanced waterproof sealing for deeper operation.
- Camera integration for real-time underwater inspection.
- Autonomous navigation using onboard processing.

The developed platform serves as a reproducible, low-cost foundation for further research in underwater robotics and thruster optimisation.

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