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Design and Fabrication of a Compact 3D-Printed Autonomous Underwater Vehicle (AUV) for Underwater Inspection

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Abstract: Underwater inspection is an essential activity for maintaining the safety and performance of marine and industrial structures such as ship hulls, bridges, pipelines, and reservoirs. Conventional diver-assisted inspections often face challenges such as limited accessibility, safety risks, and high operational costs. To overcome these limitations, Autonomous Underwater Vehicles (AUVs) have emerged as an efficient and reliable alternative for performing underwater monitoring and inspection tasks. This paper presents the design and fabrication of a fully 3D-printed compact AUV developed for small-scale inspection applications. The vehicle's design emphasizes hydrodynamic stability, lightweight construction, and ease of manufacturing using CAD modelling and 3D printing. The propulsion system employs multiple thrusters for accurate directional control, while onboard sensors and a camera module support visual feedback and inspection capabilities. The AUV operates using a microcontroller-based control unit managing thruster movement, stability correction, and data acquisition. Initial testing in controlled water environments demonstrated stable motion, good buoyancy balance, and effective sealing of internal components. The results confirm that a lightweight, low-cost, fully 3D-printed AUV can perform short-range inspection tasks efficiently and safely.
Keywords: Autonomous Underwater Vehicle (AUV), 3D Printing, Additive Manufacturing, Underwater Inspection, Hydrodynamics, Arduino, PLA, Thruster Control, Structural Analysis, ABS Plastic

I. INTRODUCTION

The exploration, monitoring, and maintenance of underwater environments have always posed significant challenges due to limited visibility, high pressure, and human safety concerns. Traditional inspection methods, often performed by divers, are time-consuming, expensive, and risky. To overcome these limitations, the use of Autonomous Underwater Vehicles (AUVs) has emerged as a transformative solution across various fields such as offshore infrastructure inspection, environmental monitoring, and underwater research. In recent years, advancements in additive manufacturing (3D printing) and affordable sensing technologies have opened new possibilities for designing compact, cost-effective, and customizable AUVs. The integration of 3D printing in the fabrication process allows engineers to rapidly prototype complex hull geometries, optimize hydrodynamic performance, and reduce manufacturing costs. Among the available materials, ABS plastic has proven to be ideal due to its high strength-to-weight ratio, corrosion resistance, and ease of fabrication, making it suitable for lightweight underwater structures. This paper focuses on the design and fabrication of a fully 3D-printed compact AUV capable of performing underwater inspections in shallow to moderate depths. The system integrates key components such as thrusters, waterproof housings, onboard electronics, and sensors within a streamlined body to ensure stability, manoeuvrability, and watertight integrity. By combining principles of hydrodynamics, control systems, and additive manufacturing, this work aims to create a low-cost yet efficient inspection platform for structural monitoring, pipeline inspection, and underwater surveys.

II. LITERATURE SURVEY

Sahoo et al. [1] explored the creation of a low-cost, fully 3D-printed AUV aimed at research and training purposes. The authors developed a modular hull fabricated from polymer materials to reduce both cost and weight while maintaining structural strength. Performance testing in shallow water demonstrated stable manoeuvrability and precise depth control, proving that additive manufacturing can deliver affordable yet functional AUV solutions for educational and prototype-level missions.

Li et al. [2] presented a detailed simulation environment for testing AUV dynamics, control algorithms, and sensor behaviour before physical fabrication. The authors developed a 3D-physics-based simulator integrating hydrodynamic modelling, thruster control, and virtual sensor feedback. Their results show that simulated responses closely match experimental outcomes, reducing design iterations and material costs.

Paraschos & Papadakis [3] investigated a hybrid vehicle capable of operating in both air and underwater environments. The research focuses on aerodynamic and hydrodynamic design integration, enabling smooth transitions between mediums. The study demonstrates that careful design optimization allows a single platform to achieve dual-environment capabilities without compromising stability or endurance.

Bogrekci et al. [4] introduced a comprehensive approach for AUV design and performance evaluation, focusing on control architecture, motion dynamics, and reliability testing. Experimental results highlight high positional accuracy, energy-efficient motion control, and adaptability to variable currents.

Hasnain Munir et al. [5] presented the design and construction of a low-cost, multi-purpose underwater Remotely Operated Vehicle (ROV) aimed at inspection, surveillance, and environmental monitoring applications. The thruster configuration was optimized for six degrees of freedom, allowing flexible underwater motion. Extensive pool tests demonstrated stable movement, responsive control, and reliable video feedback.

Akash Jain et al. [6] documented the complete design, development, and testing of Anahita, an AUV developed at IIT Kanpur. Advanced control algorithms were implemented to maintain depth and orientation stability, while onboard vision systems supported image-based navigation and object detection.

Wallen, Jeske, and Song [7] focused on co-design optimization of mechanical and control systems for underwater vehicle docking operations. By integrating computational fluid dynamics (CFD) with motion control simulations, the researchers evaluated docking alignment accuracy under varying current conditions.

Roman Alvin et al. [8] focused on developing an AUV structure using composite materials to achieve high strength, lightweight, and corrosion resistance. Fiber-reinforced composites were analyzed and optimized using finite element simulations for stress, deformation, and hydrostatic pressure effects.

Jiali Xu et al. [9] presented the design of a deep-sea AUV capable of operating at depths up to 10,000 meters. The propulsion and control systems were designed for energy efficiency and stability under high pressure, while redundancy in sensors and electronics ensured mission reliability.

Garin et al. [10] presented a cost-effective underwater positioning and communication system using acoustic-based communication networks. Experimental validation demonstrated a positional error margin below 0.5 meters.

Feng Liu et al. [11] introduced a Multidisciplinary Design Optimization (MDO) framework aimed at enhancing the overall efficiency, performance, and manufacturability of AUVs, integrating hydrodynamics and structural analysis simultaneously.

Eldred, Lussier, and Pollman [12] discussed the development of a spherical AUV designed for inspection in confined underwater spaces such as pipelines and storage tanks. The spherical geometry enables omnidirectional movement, allowing navigation in tight and complex environments.

III. PROBLEM DEFINITION AND OBJECTIVES

Underwater inspection plays a crucial role in maintaining critical infrastructures such as bridges, dams, ships, and pipelines. However, traditional methods involving divers or large remotely operated vehicles (ROVs) are often expensive, risky, and inefficient. Human-operated inspections are further constrained by limited diving depth, poor visibility, and safety hazards, while commercial AUVs tend to be costly and complicated to deploy.

This study aims to bridge that gap by designing and fabricating a fully 3D-printed AUV using PLA as the primary material. The use of aditive manufacturing allows for precise customization, lightweight construction, and simplified production of complex geometries. The design emphasizes watertight integrity, stability, and efficient manoeuvrability to ensure reliable performance during underwater inspection missions.

A. Objectives

The key objectives of this project are: (i) Design and fabrication of a compact, hydrodynamic AUV structure optimized for reduced drag and stable underwater operation; (ii) Acrylic top and bottom plates with PLA thruster housings ensuring watertight sealing; (iii) Integration of thrusters, sensors, and camera for navigation and inspection; and (iv) Implementation of a time-based control system where displacement is achieved by operating thrusters for predefined durations.

IV. METHODOLOGY

The development of the AUV follows a structured process. It begins with problem identification and requirement analysis, followed by conceptual design and 3D modelling. After performing hydrodynamic and structural analyses, the system proceeds to subsystem integration and component fabrication. Finally, testing and performance evaluation are conducted to obtain the final results.

The Gantt Chart was prepared to represent the progression and completion of various project activities on a monthly basis, covering problem definition, literature review, CAD design, hydrodynamic analysis, component procurement, fabrication, system integration, and testing.

V. SYSTEM DESIGN AND CONTROL ARCHITECTURE

The compact AUV is designed as a modular system integrating power, control, sensing, and propulsion subsystems. The vehicle is powered by a 14.8V Li-Po battery connected to a Power Distribution Board (PDB), which distributes appropriate voltage levels to various components. High-power thrusters receive power through Electronic Speed Controllers (ESCs), while sensitive electronics are supplied with regulated 5V output.

The central controller, Arduino Mega 2560 Rev3, processes sensor inputs and generates Pulse Width Modulation (PWM) signals to control the thrusters, enabling directional movements including forward, backward, lateral, and vertical motion. The sensing system provides real-time feedback for stable navigation. The BNO085 IMU measures roll, pitch, and yaw, transmitting orientation data via I^2C communication for balance and heading correction.

The propulsion system consists of eight thrusters — four for horizontal movement and four for vertical control — allowing precise manoeuvring and hovering capability. A USB camera is integrated for live underwater inspection and monitoring. Overall, the AUV operates as a closed-loop system where continuous sensor feedback enables dynamic adjustment of thruster outputs.

VI. DESIGN OF CHASSIS

The AUV chassis was designed using CAD modelling in SolidWorks 2024. The modular design enables easy assembly and maintenance. Two-dimensional engineering drawings were prepared for all major components including the main cylindrical pressure hull, top and bottom acrylic mounting plates, and thruster housings. The isometric, front, side, and top views were developed to guide the 3D printing process and verify dimensional accuracy.

The streamlined cylindrical body minimizes hydrodynamic drag and ensures uniform pressure distribution at operating depth. PLA material was selected for all 3D-printed components due to its excellent printability, structural strength, and corrosion resistance in fresh water environments. Acrylic components provide optical clarity for visual inspection and structural rigidity for the frame assembly.

VII. CALCULATIONS

A. Buoyancy and Weight Calculations

The total displaced volume was calculated to determine the buoyant force. For a cylindrical hull of diameter 150 mm and length 500 mm, the displaced volume $V = \pi r^2 L = \pi \times (0.075)^2 \times 0.5 = 8.836 \times 10^{-3}$ m³. The buoyant force $F_E = \rho g V = 1000 \times 9.81 \times 8.836 \times 10^{-3} = 86.68$ N. The total system weight including all components was estimated as W = 58.03 N, confirming positive buoyancy for the AUV.

B. Drag Force and Thrust Calculations

The drag force was calculated using the equation: $F_{drag} = 1/2 \text{ x } \rho_{water} \text{ x } V^2_{max} \text{ x } C_D \text{ x } A$, where $C_D = 0.4$ (drag coefficient for streamlined body), $\rho = 1000$ kg/m³, A = 0.01767 m² (frontal area), and V = 1 m/s operating velocity. This gives $F_{drag} = 0.5 \times 0.4 \times 1000 \times 0.01767 \times 1 = 117.5$ N. The net buoyancy force $= -(F_E - W) = -(86.68 - 58.03) \times 1.8 = -104.454$ N.

Total horizontal thrust required: $T_{horizontal, total} = F_{drag}$ x Manoeuvring Factor= 117.5 × 1.5 = 140.4 N.

Thrust per horizontal thruster = 140.45 / 4 = 35.1 N. Thrust per vertical thruster = 174.737 / 4 = 26.11 N.

C. Power Requirements

The power-force relationship gives: P = F × V = 93.6 × 1 = 93.6 W. Since each thruster provides 130 W, the selected thrusters provide sufficient power margin. Minimum propulsion power required is approximately 94 W to overcome drag at 1 m/s.

D. Battery Calculations

Total power consumption: $P_{total} = (N_{thruster} \times P_{thruster,max}) + P_{electronics} = (4 \times 130) + 30 = 550$ W.
Required energy: $E_{required} = P_{total} \times T_{misssion} = 550 \times 0.5 = 275$ Wh. Maximum current draw: $I^{max} = 550 / 14 = 39.28$ A.
Required capacity: $C_{required} = E_{required} / V_{battery} = 275 / 14 = 19.64$ Ah. Using 6 × 3 Ah batteries provides the required power.

E. Pressure at Operating Depth (30 m)

Hydrostatic pressure: $P = \rho gh = 1000 \times 9.81 \times 30 = 294{,}300$ Pa = 0.294 MPa.
The AUV structure must withstand approximately 0.3 MPa external pressure at 30 m depth.

VIII. MATERIAL SELECTION AND COMPONENTS

The AUV consists of several key components that work together to enable underwater navigation, data collection, and mission execution. Table I lists the major components with their specifications and quantities.

TABLE I
List of Major Components and Specifications

Sl. No.	Component	Specification	Quantity
1	Apisqueen U2 Mini Underwater Thruster	14V	8
2	Arduino Mega 2560 Rev3	5V	1
3	Buck Converter with USB	5V, 3A	1
4	HIGH FLY 14.8V 3700mAh 4S 40C Li-Po Battery Pack	14.8V, 3.7A	1
5	IMU BNO 085	3.3 to 5V	1
6	LED Underwater Light	5V	1
7	Arducam Fisheye Low Light USB Camera (IMX291, 2MP 1080P)	12V	1

IX. STRUCTURAL ANALYSIS

Structural analysis for the AUV was performed in SolidWorks 2024 using Finite Element Method (FEM). The material properties used for Acrylic (PMMA) are: Young's Modulus = 3.2 GPa, Poisson's Ratio = 0.35, Density = 1180 kg/m³, Tensile Strength = 65–75 MPa.

A. Von Mises Stress Analysis

TABLE II
Von Mises Stress Results

Name	Type	Max
Stress	VON: Von Mises Stress	57 MPa

The maximum Von Mises stress of 57 MPa is within the allowable tensile strength range (65–75 MPa) of the acrylic material, confirming structural integrity under operating loads.

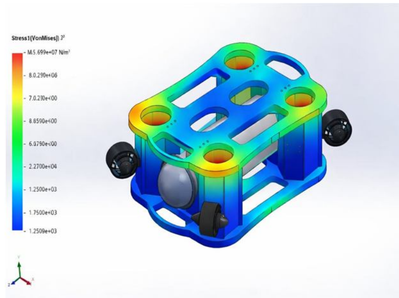

Fig. 1 FEM analysis of body

B. Resultant Deflection Analysis

TABLE III
Resultant Deflection Results

Name	Type	Max
Displacement	URES: Resultant Displacement	0.845 mm

The maximum resultant deflection of 0.845 mm is within acceptable limits for underwater structural applications, confirming the adequacy of the design.

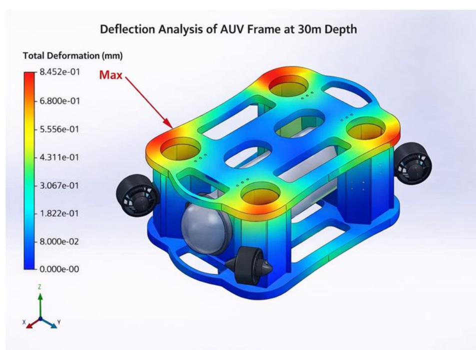

Fig. 2 Deflection analysis of frame at 30m depth

C. Conclusions from Analysis

The analysis confirms that the developed system successfully meets its design objectives. Detailed buoyancy, drag, and thrust calculations confirmed that the propulsion system can maintain stable hovering and controlled manoeuvrability up to 30 meters depth. Structural evaluation showed safe stress distribution within the acrylic-PLA frame under hydrostatic and operational loads.

X. WORKING PRINCIPLE

The AUV mission follows a defined sequence of operations. In the Arming Phase, after powering ON, the system enters a 40-second arming period for system checks and safe deployment. During the Dive Phase, vertical thrusters are activated and the AUV dives for 2 seconds to reach the operating depth. In the Forward Movement phase, horizontal thrusters push the vehicle ahead for 10 seconds. The Turning Mechanism uses differential thrust from one horizontal thruster operating in reverse, causing the vehicle to turn 180°. A second forward movement of 10 seconds follows, after which the Surfacing Phase activates vertical thrusters in reverse to bring the AUV to the surface within 2 seconds.

XI. TESTING AND RESULTS

The testing phase confirmed the AUV performed reliably under real-time conditions. After adjusting the ballast, the vehicle achieved near-neutral buoyancy and maintained stable hovering with minimal vertical drift, confirming accurate weight distribution and buoyancy calculations.

During submersion tests, no water leakage was observed even after 60 minutes underwater. The O-ring sealing and epoxy coating ensured proper waterproof protection. The thrusters provided smooth and responsive movement in forward, reverse, and vertical directions, responding well to PWM signals for controlled motion in confined water spaces.

Sensor data from the BNO085 was successfully processed, enabling stable heading control and depth regulation. The AUV demonstrated smooth turning and good manoeuvrability, with minor drift noted due to water disturbances. The 14.8V Li-Po battery delivered approximately 30 minutes of runtime under moderate load, with stable voltage regulation maintained across all electronic components.

XII. CONCLUSIONS

The design and fabrication of the compact Autonomous Underwater Vehicle (AUV) successfully demonstrate the feasibility of developing a low-cost, modular, and efficient underwater inspection platform for shallow-water and confined-space applications. Through systematic problem identification, detailed design calculations, structural analysis, and experimental validation, the project achieved stable buoyancy control, reliable manoeuvrability, and structural integrity up to the intended operating depth of 30 meters.

The control architecture built around the Arduino Mega 2560 Rev3, supported by orientation feedback from the BNO085 and propulsion using ApisQueen U2 Mini Thruster units, proved effective in achieving stable navigation and smooth directional control. Testing results confirmed watertight integrity, sufficient thrust generation, and approximately 30 minutes of operational runtime using the 14.8V Li-Po battery system. Overall, the project validates that a compact and economical AUV can serve as a practical alternative to large, expensive systems for inspection of submerged structures such as bridge piers, pipelines, and dams, while offering strong potential for future enhancements in autonomous navigation, extended endurance, and advanced sensor integration.

XIII. ACKNOWLEDGMENT

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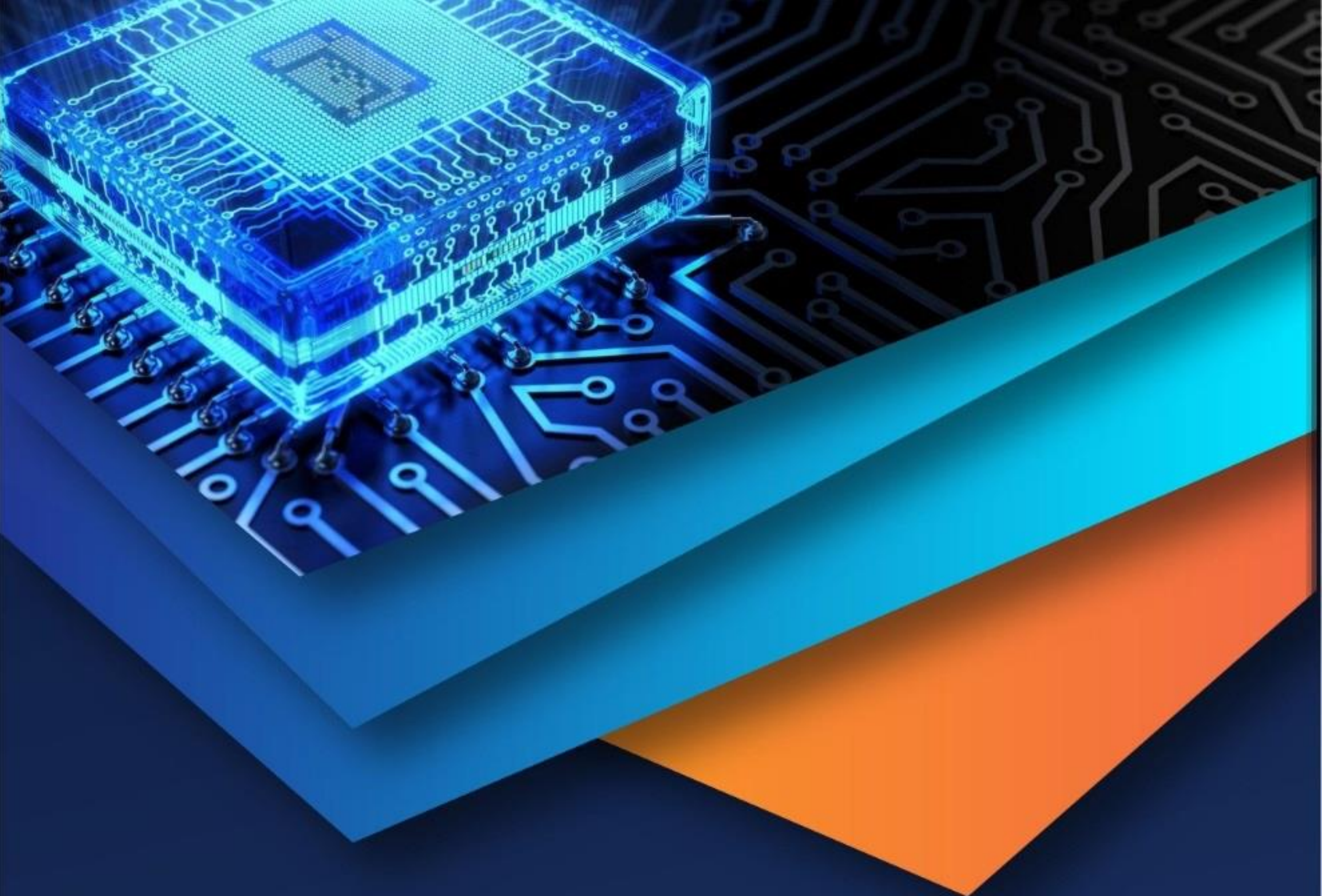

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