Design and Development of an Autonomous Underwater Vehicle for Monitoring Harbor Ships

Kishan P, Ajay N.V, Varsha Nagnur, Solomon G
Manjunatha K N

Abstract

Autonomous Underwater Vehicles (AUVs) are now viable platforms used in marine exploration, environmental, sub-sea inspection and defense services. Their development has been based on the development of hydrodynamic modelling, structure design, intelligent control, human-robot interface and sustainable marine technologies. Current studies on AUVs focus on strong hull, pressure resistant materials, high performance propulsion, and biometric controls that improve the maneuverability of AUVs and energy efficiency. At the same time, the use of wireless sensor networks, embedded systems and real-time data processing architectures make it possible to have dependable underwater communication, navigation and mission execution in low visibility and harsh environments. Newer strategies combine deep learning to identify the system, plan the way, and control the system deceptively, to create a better autonomy on dynamical ocean environments. The challenges associated with corrosion, biofouling, deep-sea pressures, and the environment are further mentioned in marine technology studies, which provokes the use of high-end materials, anti-fouling approaches, and smart monitoring devices. Also, human-machine interface developments, such as teleportation systems, acoustic communications, and mixed-reality interfaces, further increase capability and safety of operation. This study combines multidisciplinary expertise to create an effective AUV system that has an optimized structural integrity, stable sensing, strong motion control, and improved autonomy, which has a huge potential in scientific surveying, assessing underwater infrastructure, ecological monitoring, and future implementation of ocean engineering.

Keywords: Autonomous Underwater robotics, Biomimetic Propulsion, Hydrodynamic Modeling, Structural Design, Sensor Networks, Embedded Systems, Path Planning, marine robotics, Deep Learning, Human-Machine Interaction.

I. INTRODUCTION

One of the most revolutionary technologies in the current ocean engineering has become the Autonomous Underwater Vehicles (AUVs) which allows exploration, surveillance and intervention in underwater environments that are challenging, unsafe or inaccessible by human divers. The development of AUVs has gained momentum in the last decades following the improvements in hydrodynamic modeling, structural framework, embedded computing, sensationalize, artificial intelligence, and marine materials engineering. These developments have influenced the development of underwater robot systems to greater levels of autonomy, greater capacity and more capability to perform tasks in complex marine environment.The operational environment of the AUVs is one that is highly pressurized, high-current, low-visibility as well as unpredictable environmental disturbances. To come up with a vehicle that is stable, maneuvers precisely, and performs missions reliably, fluid dynamics, buoyancy, drag forces and also multi-directional motion control should be considered carefully. Structural integrity is a major need especially in operations in deep-sea conditions where the pressure hull design should be able to meet extreme loads, yet it should be lightweight and corrosion resistant. In such systems, pressure-resistant cylindrical hulls, polymer domes and the newest composite materials are often used to trade strength, maneuverability, and operational efficiency.

The other important factor on the development of an AUV is on propulsion strategies. Conventional propeller-driven propulsion is both simple and efficient, although recent studies consider biometric propulsion based on fish locomotion. Flapping fin, oscillatory caudal, and multi-degree-of-freedom connectors have shown to be more manoeuvrable, less noisy and less consuming. This enables the AUVs to operate in sophisticated environments like the coral reefs, underwater structures, and narrow passages where the normal thrusters might not be appropriate. Combining an effective propulsion system with proper modeling of the system will make sure that the vehicle will be able to react to the hydrodynamic interactions and also be able to control its path.Sensing and communication systems are also very important in facilitating autonomy together with propulsion and structural considerations. When underwater, GPS cannot be used, and the electromagnetic signal is degraded, thus localization and data transmission become difficult. In order to overcome this, the contemporary AUVs have inertial sensors, Doppler velocity logs, depth sensors, sonar, wireless sensor networks and acoustic communication modules. This information needs to be processed by embedded downloadable controllers in real time to aid navigation, obstacle avoidance and environmental mapping. Enhancement of sensor fusion and reliability of data improves accuracy of the mission and flexibility in mission during dynamic or uncertain situations.Artificial intelligence has also increased the capabilities of AUV. Non-parametric modeling, system identification, and path planning are supported by deep learning techniques such as temporal convectional networks, recurrent neural networks and optimization algorithms. These methods deal with nonlinear vehicle equations, environmental perturbations as well as the multi-dimensional interactions that take place in underwater motion. Smart control systems enable the AUV to choose the best routes, evade dangers and respond to unforeseen external forces. The current AUVs have increased autonomy and robustness through the application of machine learning in conjunction with classical control techniques.The maintenance of marine operations also has its recurring problems including corrosion, biofouling, energy constraints and environmental effects. In order to enhance the performance in the long term, scientists explore anti-fouling material, copper-nickel corrosion-resistant alloys, hull designs that are easy to maintain, and alloys that are less susceptible to corrosion. Biofouling is a process of microorganisms, algae, and marine attachments, which is a major drag, fuel consumption, and energy demand. Observation and suppression of the same is necessary toward sustenance of hydrodynamic efficiency. Ecological disturbance can also be limited by using sustainable materials and designing methods when deploying AUVs.Moreover, as recent trends reveal, human-machine interaction is a key concept in underwater robotics. Although AUVs are independent, there are still numerous missions that are too complicated or unsafe that are not conducted under human control or operated telemanually. The contemporary interfaces incorporate immersive visualization, augmented and virtual reality-based displays, gesture controls and natural-language interaction. These technologies increase operator situational awareness, decrease cognitive load, and make missions more successful. Human-robot cooperation is essential in case of the emergency or intervention situation to perform the underwater operations as safe and precise as possible.Their growing variety and significance are evidenced by the growing range of applications of underwater robots in these fields: offshore energy, sub sea inspection, marine habitat exploration, disaster response, and scientific research. Applications of AUVs include oceanographic survey, pipeline inspection, ship hull inspection, underwater archeology, climate research and biodiversity survey. Their capability of operating without cables, their ability to operate in harsh conditions, and their high-resolution data collection capability makes them a source of invaluable tools to both civilians and military.This study implements concepts of multidiscipline to design and analyze an AUV system to achieve optimum hydrodynamic characteristics, structural safety, sensing reliability and intelligent navigation. Through the research conducted on underwater materials engineering, biomimetic propulsion, embedded system engineering, marine robotics, and artificial intelligence, the project will contribute to providing a complete picture on the AUV development. The system that results will lead to the development of the underwater exploration technologies, ensure the sustenance of the marine work, and allow the future development of the ocean engineering to perform complex tasks.

II. LITERATURE REVIEW

Autonomous Underwater Vehicles (AUVs) have been extensively researched and developed in the last few decades, and much progress has been realized in propulsion strategies, structural design, control systems, navigation methods, sensing technologies and emerging intelligent structures. All the literature points to the complexity of underwater operations, the difficulty of working in harsh marinine conditions, and constant innovation requirement in order to make autonomous operations robust. In this part, the author discusses the main contributions of the previous studies in various thematic fields, strictly basing on the given source files.

Makam (2019) AUVs- Historical Development and Evolution.The development of AUVs dates back to the early underwater vehicles like the torpedo of Robert Whitehead in 1886, which is seen as the first autonomous vehicle that revealed itself as a powered underwater movement [5]. Further developments like the Special Purpose Underwater Research Vehicle (SPURV), which could descend to 3650 m and do precise missions based on trajectory are milestones that led to some important improvements in deep-water research and collection of scientific data [5]. Within the past twenty years, various models of AUVs have been deployed with a variety of applications (mine countermeasures, environmental surveillance, geological survey and infrastructure inspection) which show the ubiquitous importance of AUV systems in both science and industry [5]. These advancements showed that the AUV applications have increased beyond the defense related missions to more advanced multi domain functions that demand high mobility, precision and autonomy.

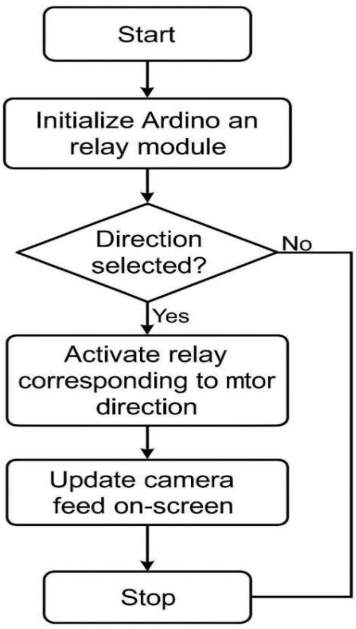

Fig 1: operation of the AUV control system

Gonzalez (2004) AUV Design, Modeling as well as Dynamics Approaches.Hydrodynamic and Mechanical Dynamics. The dynamics of underwater vehicles are complex because of the nonlinear forces on the system such as the drag, buoyancy, hydrodynamic damping, added mass and crossflow forces, which require accurate modeling. The main nonlinearity source in the motion of AUVs is hydrodynamics,

which makes the process of modeling and controlling challenging [23]. This is further complicated by the inability to measure underwater and the time consuming nature of gathering dynamic data.
Dynamic modeling research behaviour encompasses both traditional 6-DoF rigid based systems, and more intricate models which include biomimetic processes. As an illustration, the Mako AUV project demonstrated the use of traditional modeling where the entire system was identified using onboard sensors and then parameter estimates were made via the least squares techniques [9]. Also the thrust and drag relations have been defined in an effective manner and the power usage has been stated as a product of speed cubed, showing the compromise between the endurance and speed [5].

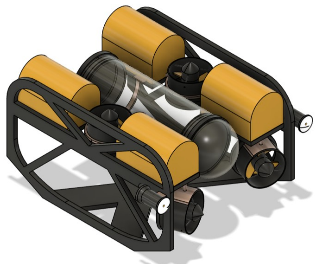

Fig 2: 3D model of AUV

Algarín-Pinto (2022) Biomimetic Hydrodynamic Modeling.The biomimetic AUVs (BAUVs) incorporate undulatory or oscillatory swimming modes like fish, which offer more maneuverability and efficiency. BAUDs replicate fin driven propulsion by flapping rear fold propagators or moving robot legs. Research reports better turning, hovering and thrust generation without the use of standard propellers [3].The elaborated modeling of such systems involves re-estimation of the hydrodynamic coefficients, because the fin-based motion brings up different profiles of drag, lift, as well as added-mass. As an example, dynamic models that combine parallel processes in order to actuate a caudal fin must parameterize expressions of fin-generated thrust and moment, include frequency and bias modulation in flapping profiles [3]. The simulations using these models have shown accuracy of more than 80% of the trajectory-tracking in flapping dynamics which have been optimized [3].

Meschini (2019) Structural and Hull DesignThe design of pressure hulls is central to the provision of structural integrity in deep sea operations. Cylindrical hulls of PMMA with domes formed thermoform have been studied in terms of collapse pressure, buckling, and failure modes, which is a trade-off between manufacturability, optical transparency, and mechanical strength [15]. The behavior of the hull under different pressures has been tested through experimental and FEM based techniques.Additional research emphasizes the use of hydrodynamic drag reduction via refined shape hulls and streamline tail, as well as, numerical simulations influence the refinement of hull geometry [16].

Brown (2010) Navigation, Localization and Sensing Technologies.One of the most demanding factors is underwater navigation because there is no GPS and the electromagnetic signals propagability is limited in water. Traditional navigation uses fundamental positioning and dead-reckoning [11]. Long Baseline (LBL) positioning uses acoustic positioning as an absolute positioning method that has low update rates. On the other hand, Doppler Velocity Logs (DVL) and Inertial Navigation Systems (INS are high-resolution relative position systems which drift uncontrollably over time.In order to address them, research has been done on the perception-based navigation scheme including the underwater SLAM. SLAM algorithms use feature of environment to constrain the accumulating error of odometry but struggles in feature extraction and data association when the domain is unstructured in underwater environment [11].Distributed monitoring in harsh conditions has also been suggested to use wireless underwater sensor networks, where embedded sensing systems can collect environmental and mechanical data in challenging conditions have been demonstrated possible [11].

Algarín-Pinto (2022) Techniques of propulsion and energy concerns.In the traditional AUVs, the most prevalent propulsion is Thruster-based propulsion. It has been emphasized by research that the positioning of propellers influences maneuverability, noise interference and hydrodynamic interactions [1]. The power consumption is cubically dependent on thrust power and so grows very fast with higher speed, and therefore, energy management must be carefully handled during mission designing.An alternative that is offered to improve maneuverability and cut acoustic signature is biomimetic propulsion. Thunniform locomotion, fin oscillation mechanism, and compliant tails have been studied showing remarkable advantageous effects on energy consumption and environmental adaptation [3].

Controlling Systems and Autonomous Behaviors.
Many control measures have been implemented on AUVs, due to the necessity to contend with nonlinear behaviour, uncertain environmental effects,or multi-degree-of-freedom manoeuvring demands.

Classical and Linear Control Methods.The traditional PID controllers have gained popularity since they are easy to implement and experimental validation has been demonstrated with success in a number of AUV testbeds [24]. Linear Quadratic Gaussian (LQG) control is also in the previous designs, which are more robust to noise and track optimally.

Makam (2019) Adaptive and Intelligent Control.
Adaptive controllers deal with the dynamic hydrodynamics, ocean currents, and changes in the mass distribution of the vehicle. These methods are dynamic control gain adjustments and give dependable maneuvering in the face of uncertainty [5].The use of artificial intelligence has augmented the AUV control with the neural-network-based PID tuning, deep-learning-based motion modeling, and reinforcement learning autonomous navigation. The application of Deep Temporal Convolutional Networks (DTCNs) in nonparametric identification has made it possible to predict the nonlinear dynamics better to enhance the performance of path planning and trajectory tracking [24].

Makam (2019) Sliding Mode Control and Robust Control.Sliding Mode Control (SMC) is resilient to both disturbances and unknown dynamics. SMC has been used effectively in depth, heading and trajectory tracking, where it has been demonstrated to be effective in nonlinear and underactuated AUV systems [5].Strong adaptive controllers have features of both adaptive and sliding mode frameworks that offer strength in harsh operating conditions [5].

Abdullah (2025) Human Machines and Telerobotics. The use of Human-Machine Interfaces (HMIs) is becoming more and more topical as subsea missions include teleoperation, shared autonomy, and supervisory control. Conventional teleoperation with a small number of camera feeds does not provide sufficient situation awareness to the operator, which creates a soda-straw effect with a small field of view and high cognitive load [12].The new developments include gesture recognition, VR/AR displays, haptic feedback, and natural-language interaction, which enhance the mission safety and performance of the operators. Digital twins and simulation engines enable the use of training and mission rehearsal, as well as the integration of real-time feedback [12].
These HMIs are a transition to intelligent interactive systems that enhance autonomous functions.

Boulton (1990s) Materials, Biofouling and Marine Environmental concerns.Biofouling and corrosion are very important in marine vehicles. Biofouling raises the drag, power use and the interference of the sensors. It has been found out that copper-nickel alloys and enhanced coatings have the potential to reduce the extent of fouling growth and lower the maintenance requirements [14]. Imaging and sensor-based methods have been developed to monitor biofouling on marine equipment and hulls to do preventative imaging [19].The morphology of canyons and the distribution of marine litter has been demonstrated to be influenced by ocean currents and canyons, applicable to the AUV environmental missions [19].Also, emerging technologies that assist in the restoration of deep-sea ecosystems are based on the use of AUV-mounted sensors and robotics, a shared characteristic of increasing ecological integration of underwater systems [20].

Brown (2010) Challenges and Opportunities in the AUV Research.The AUVs still have constraints with respect to communication, energy consumption, accuracy of perception and autonomous decision making even with the tremendous advancements made. Severe sea environments and unpredictable disruptions make the control and navigation more complex, and cybersecurity and reliability are also the big questions of developed autonomous systems [11].
The opportunities of the emerging AI, IoT, and embedded systems are related to the enhanced situational awareness, real-time learning, sensor fusion, and multi-vehicle cooperation.

Summary
The literature reviewed shows an immense advancement in the fields of AUV propulsion, modeling, hydrodynamics, sensing, navigation, control, structural design, and intelligent autonomy. Biomimetic systems, sophisticated control systems, deep learning, and enhanced sensing systems are changing the functions of AUVs in dynamic oceans. Nonetheless, the issues of underwater communication, environmental disruptions, structural strain, energy constraints, and nonlinear intricate dynamics remain a source of further innovation

III. COMPONENT DESCRIPTION

The autonomous underwater vehicle (auv) developed in this project comprises of a number of mechanical, electrical, and electronic integrated systems that collectively allow the autonomous underwater vehicle to navigate the underwater environment in a stable manner, provide real time monitoring, and move effectively. all the components were chosen according to various factors like durability, ability to be waterproof as well as efficient power usage, and the integration with the entire structure. in the next section, the complete description of all significant parts in the system used in the auv will be given.

- **HDPE FRAME STRUCTURE**

the major structural constituent of the auv is the frame that is made of the high-density polyethylene (hdpe). hdpe was selected because of its high strengths to weight ratio, corrosion and buoyancy properties. it is a cross-shaped frame which has curved arms that give the frame rigidity but still retains the streamline shape to allow smooth movement in its hydrodynamic. intentionally placed cut-out minimizes weight and allows the water to free-flow around the structure which reduces drag. frames channels assist in installing wiring, and in ensuring that it is not damaged by external forces. the hdpe material guarantees that it is long lasting when in underwater conditions.
.

- **MICROCONTROLLER- ARDUINO UNO R3.**

arduino uno r3 is the board that forms the central processing unit of the auv. it processes data fed by sensors and controls the thrusters using relays and driver circuits as well as, interprets input signals on the surface control joysticks. all basic logic of the navigation, direction reversal, and communication with other parts is performed by the microcontroller. it is easy to use, reliable, and has a large community that provides support to underwater robotics projects of entry level.

- **WATERPROOF CAMERA MODULE**

in front of the auv a waterproof usb camera is installed to give real-time underwater visual feedback. the camera sends the pictures to a laptop interface by the tether cable, ensuring the operator maneuvers through the obstacles and underwater structures. it has a waterproof enclosure to provide safe usage even in case of constant submersion.

- **DC MOTOR THRUSTERS (RS-775 MOTORS)**

the propulsion system has rs-775 high speed dc motors which have propellers. these motors help to provide thrust to propel the auv forward and backward and help in turning. the motors are known to be high torque, durable and compact in size which are mounted after the customized holders of hdpe material are used to ensure that the motors are properly aligned to avoid vibration and also to achieve stable movement.

- **ULTRASONIC SENSOR**

to identify the barriers the auv is equipped with an ultrasonic sensor (jsn-sr04t waterproof model). this sensor is used to detect the distance of the objects surrounding it and can avoid collisions in low visibility or turbid environment. it is waterproof and therefore can be used under water safely during its missions.

- **TETHERING CABLE**

a powerful multi-core tether cable is used to carry all communication and transmission of power between the surface control unit and the auv. the cable will have motor signals, video feed, and control instructions. its insulation allows signal perfection at even wet conditions and shields against electric interference

- **BATTERY PACK**

the motors, microcontroller, sensors, and camera are powered by the battery module. safety and a long underwater operating time are guaranteed by a well sealed battery set up. the battery offers constant voltage supply to ensure that the thrust and control performance are consistent.

- **MOTOR DRIVER - L298 MODULE**

the l298 motor driver controls the current flowing to the motors and allows to control the direction using h-bridge switching. it operates with the arduino to transform pwm signals to motor movements to achieve smooth thrust generation and prevent motors operating on too much current.

- **RELAYS (2-CHANNEL RELAY MODULE)**

the direction of the motors is reversed through a 2-channel relay module to switch the direction. this enables moving forward/backwards and accurate maneuvers. the relay is powered by the arduino and it is isolated so as to operate safely.

IV. METHODOLOGY AND OUTPUTS

The design and development process of the Autonomous Underwater Vehicle (AUV) incorporates structural construction, electronic system development, propulsion design, integration of sensing and repetitive testing. The procedure starts with conceptual design planning in which design targets like underwater manoeuvrability, stable buoyancy, collision evasion and real-time visual surveillance are established. These goals are in accordance with the current AUV research concepts regarding the hydrodynamics and propulsion management and also environmental resilience.

The structural methodology entails making the AUV frame out of High-Density Polyethylene (HDPE),

Fig 3 High-Density Polyethylene (HDPE)

which is a material of choice based on its hydrodynamic effectiveness, buoyancy and resistance to corrosion. The frame is planned via CAD modeling software like Fusion 360, which is used to simulate load distribution, is used to plan wiring routes and optimally fit the buoyancy pods and motor holders. This computerized prototyping makes it possible to find out the structural problems at early stages before they are fabricated. Upon CAD validation, HDPE sheets are cut, assembled and equipped with buoyancy pods to give them neutral buoyancy and stability in water.

The electronics functionalities involve- connecting the Arduino microcontroller to thrusters, relay, sensor modules and camera system. The surface station joystick controls are connected to the Arduino which receives the analog signal, processes it and sends relay-based motor control commands. The L298 driver controls the power given to the high torque RS-775 thrusters so that it can move forward, reverse, and turn smoothly. All electronic connections are waterproofed by use of waterproofing methods which include use of silicone sealing, shrink tubing as well as insulated conduit.

Sensor integration entails the installation of ultrasonic sensors to detect obstacles and a waterproof camera to monitor what is going on under water in real-time. The camera feed is sent to the operator through a tether cable to the laptop where the operator can see continuously as they navigate. The ultrasonic sensor detects the distance to the object hence allowing the AUV to avoid crashing in low visibility or murky ocean waters.

The testing methodology is done in several steps. The preliminary pool tests confirm the floating, course control, and integrity. Adaptations are carried out on the pod placement, motor alignment, and the quality of waterproofing on the basis of the initial outcomes. The following tests are used to assess the camera clarity, relay responsiveness, and sensor accuracy. The last tests confirm the unity of the system, which consists of the navigation control system, sensor feedback system, and live video streaming system, to guarantee that there will be a qualified work when real-time underwater movement exploits the system.

The products of this methodology are a fully operational AUV with forward and reverse propulsion, stable turning movement, effective obstacle detection as well as continuous underwater video surveillance. The trials indicate a higher stability and increased reliability of waterproofing and accurate maneuverability through operator control and this confirms the successful adoption of the design objectives.

V. CHALLENGES

The creation of an Autonomous Underwater Vehicle (AUV) is a problem that is fraught with a variety of engineering issues that arise due to the environmental limitations provided by the underwater conditions, the complexity of the system integration and the constraints of sensing and actuation. The fact that it was difficult to attain stable buoyancy and appropriate weight distribution was one of the key challenges in this project. Despite the use of buoyancy pods, any slight mispositioning led to the AUV tilting or drifting off, which meant that the placement of the pods and the mass balancing had to be repeated to reach a state of neutral buoyancy.

Waterproofing was another serious problem. Any little leakage would cause electrical problems since motors, wiring and connectors are usually near water. The first pool tests demonstrated that there was slight entry of water in the electronics casing and this necessitated the redesign of the sealing techniques with silicone coating, shrink tubes and gasket based reinforcement of the enclosure. Waterproof integrity during dynamic movement under water was always a design issue.Hydrodynamic forces also resulted in structural difficulties. The HDPE frame is lightweight and not corrosive, but it had to be optimised carefully in order to balance strength and flexibility. Every effort was being made to ensure that there is less drag and at the same time accommodate as many components as possible, including thrusters, sensors, and camera modules, which proved to be hard to achieve to ensure that the overall design is small and functional.The issue of control and navigation was also an issue. The AUV was controlled by the joystick that was tethered thus complicating the stabilization of the robot in quick directional maneuvers. This was done by the fact that the lack of completely autonomous algorithms required human operators to respond promptly to underwater obstacles particularly during low visibility scenarios.

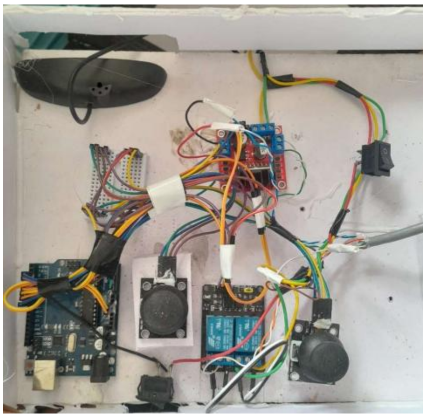

Fig 4 Control System unit

The sensors used, which were ultrasonic, were helpful, however, at angles, sensor blind spot, and scattering of signals at the water decreased accuracy.

The addition of electronics was another obstacle. Arduino, relay boards, motor drivers, and camera boards needed to be synchronized to allow them to work without signal interference. The high torque of the thrusters brought about vibrations which might have an impact on sensor readings and stability of the cameras. The flow of power between motors and sensors and the camera also had to be carefully planned so that the voltage would not drop during the high-thrust mode.

Lastly, real world testing was challenging. The pool setting is very different compared to the natural waters where currents, turbidity and lighting imbalance may influence performance. One of the long-term problems that should be enhanced in the future is preparing the AUV to work in these unpredictable conditions.

VII. CONCLUSION

The design of the Autonomous Underwater Vehicle (AUV) is a sophisticated whole-system, synthesis in the realms of mechanical design, a real-time embedded control system, underwater sensory design and in-water tests. The project managed to convert the theoretical knowledge about hydrodynamics, propulsion mechanics, underwater buoyancy control, and underwater navigation into a working prototype through a systematic approach to conduct the project. The structural design of the AUV using HDPE gave the best combination of strength, lightness construction, and corrosion resistance to allow the AUV to work effectively under submerged conditions. Buyancy pods, Thruster modules and Sensor systems were incorporated and guaranteed that the structure was stable and manoeuvrable to carry out any undertaking in underwater.

The electronic control system, which is focused on the Arduino microcontroller, relay-based motor control, ultrasonic sensor, and live video feedback proved to be effective in coordinating the movement, obstacle detection, and visual observation. The tethered control strategy was very robust in terms of the real-time navigation and provided a baseline on how to go forward in the future towards the semi-autonomous or fully autonomous nature.

Issues with waterproofing, balancing of structures, electronic isolation and variability in the environment were solved by testing and refining of designs in an iterative manner. These difficulties emphasized the problems related to the underwater robotics, especially the dynamic character of the fluid forces, sensor constraints, and the necessity to use accurate sealing methods.

The demonstrated final result proves the fact that the developed AUV can be propelled steadily, controlled in directional movements, avoid the collisions, and be visually inspected in real-time, which is why it can be applied to the shallow waters of the sea, where it is applicable to monitoring the harbor, structural inspection, and environmental control. The project serves not only the intended purposes but also provides a solid foundation in the future, such as enhanced autonomy, sensor fusion, machine learning-driven navigation, and increased depth of operation. Finally, the AUV leads to the increasing scope of low cost underwater robotic systems and introduces opportunities to develop new research and implement new applications to the marine sphere.

REFERENCES

[1] M. Shahrieel M. Aras, H. A. Kasdirin, M. H. Jamaluddin, and M. F. Basar, "Design and Development of an Autonomous Underwater Vehicle (AUV-FKEUTeM)," MS Garden, Kuantan, Malaysia, 2009.

[2] G. C. Goodwin, S. F. Greabe, and M. E. Salgado, *Control System Design*, Prentice Hall, 2001.

[3] J. A. Algarín-Pinto, L. E. Garza-Castañón, A. Vargas-Martínez, and L. I. Minchala-Ávila, "Modeling, Trajectory Analysis and Waypoint Guidance System of a Biomimetic Underwater Vehicle Based on the Flapping Performance of Its Propulsion System," *Electronics*, 2022.

[4] T. Le Sage, A. Bindel, P. Conway, S. Slawson, and A. West, "Development of a Wireless Sensor Network for Embedded Monitoring of Human Motion in a Harsh Environment."

[5] R. Makam, P. Mane, S. Sundaram, and P. Sujit, "A Comprehensive Study on Modelling and Control of Autonomous Underwater Vehicle," IISc and IISER, India.

[6] D. Widhalm et al., "Design and Development of the MeCO Open-Source Autonomous Underwater Vehicle."

[7] J. W. Ringsberg and C. Soares, "Advances in the Analysis and Design of Marine Structures."

[8] G. Clauss and S. Hoogb, "Deep Sea Challenges of Marine Technology and Oceanographic Engineering."

[9] L. A. Gonzalez, "Design, Modelling and Control of an Autonomous Underwater Vehicle," M.Sc. Thesis, 2004.

[10] J. Cerrillo-Escoriza et al., "Origin and Driving Mechanisms of Marine Litter in the Motril, Carchuna, and Calahonda Canyons."

[11] H. C. Brown, A. Kim, and R. Eustice, "An Overview of Autonomous Underwater Vehicle Research and Testbed at PeRL."

[12] A. Abdullah et al., "Human-Machine Interfaces for Subsea Telerobotics: From Soda-straw to Natural Language Interactions."

[13] B. Mei, C. Li, D. Liu, and J. Zhang, "Deep Learning-Based Nonparametric Identification and Path Planning for Autonomous Underwater Vehicles."

[14] D. Wu, J. Hua, S. Chuang, and J. Li, "Preventative Biofouling Monitoring Technique for Sustainable Shipping."

[15] A. Meschini et al., “Pressure Hull Design Methods for Unmanned Underwater Vehicles.”

[16] R. A. Shenoi et al., “Composite Materials for Marine Applications – Key Challenges.”

[17] F. Khan, R. Kumar, S. Kadry, Y. Nam, and M. Meqdad, “Autonomous Vehicles: A Study of Implementation and Security.”

[18] A. D. Papanikolaou, “Developments and Potential of Advanced Marine Vehicle Concepts.”

[19] L. H. Boulton, C. Powell, and W. Hudson, “Aspects of Biofouling and Corrosion on Ship Hulls Clad with Copper-Nickel.”

[20] I. Davidson et al., “A Review of Biofouling of Ships’ Internal Seawater Systems.”

[21] J. Aguzzi et al., “New Technologies for Monitoring Marine Ecosystem Restoration in Deep-Sea Environments.”

[22] F. B. K. Ayissi et al., “Impact of Stratospheric Geoengineering on Sea Surface Temperature.”

[23] Electronics 2022, “Vehicle Dynamics, Hydrodynamic Modelling, and Control of BAUV.”

[24] Assistive Robotics, “Sliding Mode Controllers, Adaptive PID, and Nonlinear Trajectory Tracking Approaches.”

[25] Draft-Copy Project Report, “Design and Development of Autonomous Underwater Vehicle,” Acharya Institute of Technology, 2025–2026.