

Development of ‘AM’ ROV Design Inspired By Manta Ray Mobuliform

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Abstract— Remotely controlled submersible devices have become invaluable tools for enhancing safety and efficiency during surveillance, inspection, and rescue operations in various aquatic environments. However, in areas with significant debris or floating objects, traditional propeller-driven vehicles often face jamming and operational challenges. To address these limitations and improve usability in such constrained scenarios, it is crucial to develop remotely operated underwater vehicles (ROVs) that offer both agility and maneuverability. This paper presents the development of a bio-inspired mimicry approach for designing ROVs, taking inspiration from the elegant mobuliform movement observed in manta rays. By emulating the natural propulsion mechanism of these creatures, an efficient solution can be achieved for the physical requirements encountered in debris-laden waters. The proposed design adopts a simple modular morphology that enables flexibility and adaptability, while also emphasizing cost-effectiveness through the utilization of additive manufacturing methods for building the prototype. The research focuses on integrating principles from engineering technology, product design, and biomimicry to create an ROV that overcomes the limitations posed by debris-filled environments. By mimicking the graceful motion of manta rays, the ROV aims to offer enhanced maneuverability, agility, and operational performance, thereby reducing risks associated with human involvement in hazardous or challenging underwater tasks. The modular design approach and the utilization of additive manufacturing methods ensure scalability and cost-efficiency, allowing for widespread adoption of the technology. The outcomes of this research will contribute to advancing the field of underwater robotics, particularly in areas requiring effective surveillance, infrastructure maintenance, or search and rescue operations during disasters. The bio-inspired mimicry approach presents a promising pathway for designing ROVs that can navigate through debris-prone environments with ease, making them indispensable tools for a wide range of underwater applications.

Keywords— Biomimicry ROV, Biomimetic Propulsion, Mobuliform

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I. INTRODUCTION

Remotely operated underwater vehicles (ROVs) have revolutionized various industries by providing a safer and more efficient means of conducting surveillance, inspection, and rescue operations in aquatic environments. These versatile devices have been widely used in infrastructure maintenance, environmental monitoring, and search and rescue missions. However, when deployed in areas with high concentrations of floating debris or obstacles, traditional propeller-driven ROVs often encounter difficulties, such as jamming or entanglement, compromising their effectiveness and posing risks to both the equipment and human operators.

To address these challenges and improve the usability of ROVs in debris-prone environments, there is a growing interest in developing agile and maneuverable underwater vehicles inspired by natural systems. The study of biological organisms and their adaptation to complex environments has led to the emergence of biomimicry as a powerful design approach in engineering technology and product design. By emulating the functional and structural characteristics of organisms that have evolved to thrive in challenging conditions, engineers can develop innovative solutions to overcome existing limitations in underwater robotics.

One such organism that has captured the attention of researchers is the manta ray. With its graceful and agile mobuliform movement, the manta ray demonstrates an exceptional ability to navigate through debris-filled waters effortlessly. By mimicking the propulsion mechanism of this majestic creature, it is possible to design ROVs that exhibit similar agility and maneuverability, while also enhancing their operational capabilities in debris-prone environments.

In this paper, we present the development of a bio-inspired mimicry approach for ROV design, specifically focusing on the mobuliform movement observed in manta rays. Our objective is to create an ROV that can efficiently navigate through debris-laden waters, reducing risks associated with human involvement and enhancing operational performance. We emphasize the importance of simplicity and modularity in the

design process, as well as the utilization of cost-effective additive manufacturing methods for building the prototype. The integration of engineering technology, product design, and biomimicry principles offers a novel and promising pathway to overcome the challenges faced by traditional ROVs in debris-filled environments. By exploring the potential of manta ray-inspired designs, we aim to provide a practical and efficient solution that can be widely adopted in various underwater applications, including infrastructure maintenance, environmental assessments, and emergency response operations.

The subsequent sections of this paper will delve into the methodology employed for the design and development of the bio-inspired ROV, the materials and manufacturing techniques utilized, as well as the design evaluation and results obtained. We will also discuss the implications and potential applications of this research, highlighting the significance of blending engineering technology, product design, and insights from nature to push the boundaries of underwater robotics.

II. LITERATURE REVIEW

The development of bio-inspired modular remotely operated vehicles (ROVs) has drawn inspiration from various studies in the field. This section provides a literature review of key references that have contributed to the understanding and advancement of manta ray-inspired ROVs.

Cao et al. proposed a similarity evaluation rule and optimized the motion posture of a manta ray robot. Their research focused on the bio-inspired motion of manta rays and its application in robot design^[1]. Chen et al. and Chen et al. explored the use of ionic polymer-metal composites (IPMCs) as artificial muscles in a bio-inspired robotic manta ray^{[2] [3]}. Their work demonstrated the feasibility of IPMCs in achieving biomimetic movement.

Chew et al. investigated the development of a propulsion mechanism for a robot manta ray^[4]. They explored different propulsion methods to achieve efficient movement underwater. Gao et al. designed a robotic manta ray with flexible pectoral fins, emphasizing the importance of fin flexibility in achieving maneuverability^[6].

Liu et al. developed a manta ray robot with soft material-based flapping wings, highlighting the significance of wing flexibility for biomimetic propulsion^[6]. Sitorus et al. studied the locomotion of labriform fish and applied it to a fish robot, providing insights into the design and implementation of paired pectoral fins locomotion^[7].

Sun et al. validated the effect of viscosity-induced chord-wise undulation on a soft fin ray array, contributing to the understanding of fluid dynamics in manta ray-inspired propulsion^[8]. Wang et al. presented a micro biomimetic manta ray robot fish actuated by shape memory alloy (SMA) materials, demonstrating the potential of SMA in achieving biomimetic motion^[9].

Zhang et al. developed an integrated gliding and flapping propulsion biomimetic manta-ray robot, showcasing a novel approach to underwater locomotion^[10]. Zhou and Low improved the endurance and load capacity of a manta ray robot through design modifications, focusing on enhancing its practicality for real-world applications^[11].

These references collectively provide a comprehensive understanding of the design principles, propulsion mechanisms, materials, and control strategies used in the development of manta ray-inspired ROVs. By building upon these studies, the current research contributes to the field by presenting a bio-inspired modular ROV design that emphasizes simplicity, maneuverability, and cost-effectiveness.

III. MOTIVATION

During the development of a modular ROV inspired by the manta ray, several challenges emerged, primarily stemming from the operational environment and resource limitations. In order to mitigate potential risks of failure, a conscious decision was made to avoid the utilization of complex mechanical systems. Instead, a focus was placed on simplicity and robustness to ensure reliable performance.

To address the issue of water ingress, watertight seals were strategically implemented in areas prone to contact with water. While mechanical pivots and linkages were designed to be water-resistant, special attention was given to the protection of electronic components such as Brushed Electric motors, ESC, Batteries, and Transceiver, which are highly sensitive to moisture. Enclosures were carefully designed to create separate chambers, allowing for effective compartmentalization and control of the ROV's balance and buoyancy.

The body of the ROV was fabricated using 3D printing technology, enabling flexibility in design and production. To optimize strength and material usage, the infill density of the printed components was adjustable, providing a balance between structural integrity and efficient material utilization. This approach not only allowed for customization according to specific requirements but also facilitated the rapid prototyping process by reducing material waste and production time.

Throughout the development process, resource limitations were carefully managed to ensure cost-effective solutions without compromising performance. By strategically dividing compartments, implementing watertight seals, and utilizing additive manufacturing techniques, the design team aimed to achieve a balance between functionality, reliability, and affordability.

In the subsequent sections, we will elaborate on the specific design considerations, manufacturing techniques, and materials used to address these challenges. Furthermore, the performance and experimental evaluations of the bio-inspired modular ROV will be discussed, highlighting the effectiveness of the design

approach in achieving enhanced agility and maneuverability in debris-laden environments.

IV. DESIGN INSPIRATION

A. Bio-inspiration from Manta Ray

The manta ray, with its graceful and efficient swimming capabilities, has inspired several aspects of bio-inspired design in underwater robotics. They are summarized as follows:

Locomotion: The manta ray's unique swimming motion, characterized by undulating pectoral fins, provides inspiration for bio-inspired locomotion systems. By mimicking the undulating movements of the manta ray's fins, researchers have developed robots that can achieve efficient propulsion and maneuverability. The flexible and rhythmic motion of the fins allows for precise control and agility in underwater environments.

Material: The manta ray's skin has a unique structure that features a series of microscopic grooves, known as dermal denticles. These denticles reduce drag and turbulence, enabling the manta ray to glide smoothly through the water. Inspired by this design, researchers have explored the use of biomimetic materials that incorporate similar textured surfaces in the development of underwater robots. These materials can help reduce drag and increase maneuverability, enhancing the efficiency of robotic locomotion.

Sensing: Manta rays possess a highly developed sensory system, which includes electroreceptors that enable them to detect electric fields generated by other organisms. This sensory ability helps them navigate, locate prey, and communicate. Researchers have explored the integration of bio-inspired sensing systems in underwater robots, allowing them to detect and analyze electric fields in their surroundings. This capability has potential applications in environmental monitoring, navigation, and the detection of underwater objects or organisms.

Others: In addition to locomotion, materials, and sensing, the manta ray's unique shape and structure have inspired other aspects of bio-inspired design. Its streamlined body shape and large wingspan provide inspiration for the design of hydrodynamic shapes for underwater vehicles. The manta ray's efficient use of energy and its ability to maintain stable positioning in turbulent waters have also influenced the development of control algorithms and stabilization techniques for underwater robots.

By studying and emulating the manta ray's locomotion, materials, sensing abilities, and other characteristics, researchers are unlocking new possibilities for underwater robotics. These bio-inspired designs not only enhance the performance and efficiency of underwater robots but also allow them to navigate complex underwater environments, perform precise tasks, and contribute to various applications, including underwater exploration, environmental monitoring, and

underwater infrastructure inspection. The manta ray serves as a remarkable example of nature's engineering, providing valuable insights for the advancement of bio-inspired underwater robotics.

B. Inspiration for Design

The design inspiration for the bio-inspired modular ROV stems from the remarkable characteristics of the manta ray, a species of batoid fish known for its distinctive morphology and elegant locomotion. Manta rays possess dorsoventrally flattened bodies, with their head fused to their pectoral fins, creating a unique and streamlined shape that contributes to their exceptional swimming capabilities.

One of the key elements that inspired the design of the ROV is the flapping motion exhibited by the manta ray's pectoral fins during swimming. This motion resembles the flight of birds, where the wings generate lift and propulsion. By emulating this flapping motion, the bio-inspired ROV aims to achieve enhanced agility and maneuverability in underwater environments, particularly in debris-laden waters.

The locomotion of the manta ray is characterized by graceful undulations of its pectoral fins, allowing it to navigate through water with ease. This unique form of propulsion, known as mobuliform movement, is achieved by the coordination of muscle contractions and flexing of the fins. Understanding the mechanisms behind this locomotion has provided valuable insights for designing the modular ROV to mimic the manta ray's natural movements.

The notion of mimicry plays a pivotal role in the design approach, as it involves replicating the functional and structural aspects of the manta ray's locomotion system. By capturing the essence of the manta ray's efficient swimming techniques, the ROV design aims to offer similar levels of maneuverability and agility in challenging underwater environments. Through careful observation and analysis of the manta ray's movements, engineers and designers have gained inspiration for developing innovative mechanisms that can be incorporated into the bio-inspired ROV.

By mimicking the propulsion system of the manta ray, the bio-inspired ROV can navigate through debris-laden waters more effectively than traditional propeller-driven vehicles. The utilization of the manta ray's natural design principles not only enhances the performance of the ROV but also reduces the risk of entanglement and jamming, allowing for safer and more efficient operations in hazardous underwater conditions.

The design inspiration for the bio-inspired modular ROV stems from the unique morphology, locomotion, and mimicry principles observed in the manta ray. By integrating these characteristics into the ROV's design, engineers aim to create a versatile and maneuverable underwater vehicle capable of navigating through debris-filled environments with agility and

5. **Affordability:** The components used in the construction of the ROV should be cost-effective, without compromising performance and reliability. Careful consideration was given to the selection of materials and components to optimize costs. Additionally, the use of additive manufacturing techniques, such as 3D printing, was explored to reduce production costs and enhance affordability.
6. **Portability:** The dimensions and weight of the ROV were considered to ensure portability and ease of deployment. The design aims to strike a balance between size and functionality, allowing for easy transport and maneuverability in various aquatic environments.
7. **Modularity:** The bio-inspired ROV design incorporates modularity, allowing for flexibility and customization. It comprises interchangeable modules, mounts, and attachments, facilitating the adaptation of the ROV to specific mission requirements. This modularity enables efficient maintenance, upgrades, and repairs, reducing downtime and overall costs.

By addressing these requirements, the bio-inspired modular ROV aims to deliver a versatile and adaptable solution for underwater missions. It combines affordability, portability, maneuverability, and modularity to meet the demands of diverse applications while staying within the defined budget boundaries.

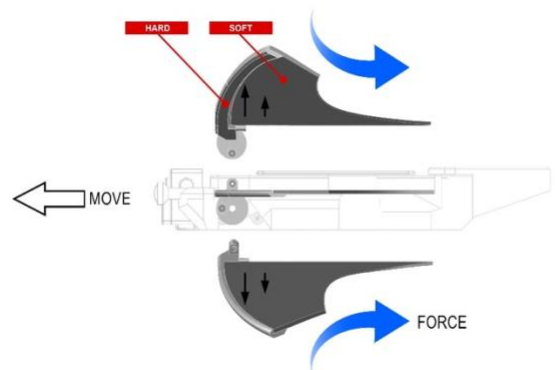


Fig 2. Forward Motion of The ROV

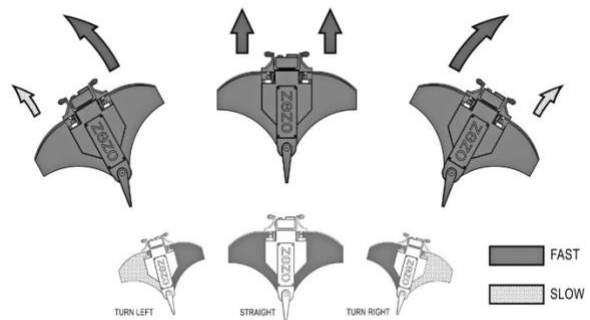


Fig 3. Turning Motion of The ROV

efficiency. Fig. 1 shows the principle of bio-inspired design from manta ray.

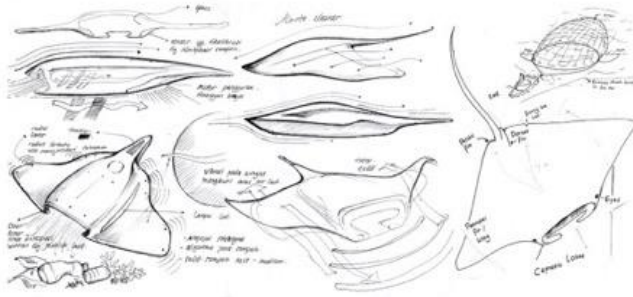


Fig 1. Bio-design inspiration of manta ray

C. ROV Requirements

The bio-inspired modular ROV is designed to meet specific requirements and considerations, driven by the scope of missions, budget boundaries, and performance specifications. The following points outline the key requirements that were taken into account during the design process:

1. **Scope of Missions:** The bio-inspired ROV is intended to be deployed for various missions, including surveillance, inspection, and search and rescue operations in aquatic environments. It should be capable of navigating through debris-laden waters, enabling efficient exploration and maneuvering in challenging conditions.
2. **Budget Boundaries:** A predefined budget was established to ensure the project's financial feasibility. Cost-effective solutions were sought throughout the design process, while maintaining the desired performance and functionality of the ROV.
3. **Specifications:**
 - a. **Range and Speed:** The ROV should have a suitable range and speed to cover the intended missions effectively. This requires a balance between battery capacity, motor power, and energy efficiency.
 - b. **Buoyancy and Water Tightness:** The ROV needs to be capable of operating at specific depths while maintaining water tightness. The design should incorporate adequate sealing mechanisms to protect sensitive electronics and ensure reliable performance in underwater environments.
4. **Maneuverability:** The bio-inspired ROV should be capable of moving forward and changing direction smoothly. Emulating the agile movements of the manta ray, the design should enable precise control and responsiveness, allowing the ROV to navigate through tight spaces and maneuver around obstacles efficiently. The locomotion mechanism of the ROV is depicted in Fig. 2 and 3.

D. Mechanical Design

The mechanical design process of the bio-inspired modular ROV encompasses various components, including the main body, circular crank, rigid arm, and flexible wings. Each component plays a crucial role in achieving the desired performance and functionality inspired by the manta ray. Here's an overview of the design considerations for each component:

1. **Main Body:** The main body serves as the central structure of the ROV, housing the essential components and providing buoyancy. It is designed to be streamlined and hydrodynamic, resembling the flattened shape of a manta ray. The main body is constructed using lightweight and durable materials, such as reinforced plastics or composites, to ensure both strength and buoyancy. It incorporates watertight seals to prevent water ingress and protect sensitive electronic components.
2. **Circular Crank:** The circular crank mechanism emulates the flapping motion of the manta ray's pectoral fins during swimming. It consists of a rotating circular component driven by a motor or actuator. The circular crank is strategically positioned within the main body to generate the desired undulating motion of the flexible wings. The size and geometry of the crank are designed to optimize efficiency and generate sufficient propulsion for the ROV.
3. **Rigid Arm:** The rigid arm acts as a supporting structure, extending from the main body to provide stability and attachment points for various modules or additional equipment. It is designed to withstand the forces exerted during operation and ensure the precise control of the ROV. The rigid arm is typically made of lightweight and rigid materials such as aluminum or carbon fiber to minimize weight while maintaining structural integrity.
4. **Flexible Wings:** The flexible wings are a critical component of the bio-inspired design, mimicking the manta ray's flapping motion for propulsion and maneuverability. They are typically made of flexible materials such as rubber or elastomers and are attached to the circular crank mechanism. The wing design incorporates a combination of rigidity and flexibility to generate lift and propulsion efficiently. The shape, size, and curvature of the wings are carefully optimized to achieve the desired performance characteristics, including maneuverability and efficiency in different water conditions.

Throughout the mechanical design process, considerations such as material selection, weight distribution, hydrodynamics, and integration with other components are taken into account. Computational modeling techniques, such as finite element analysis and computational fluid dynamics, may be employed

to validate the design and optimize its performance. The 3D model of the ROV is displayed in Fig. 4.

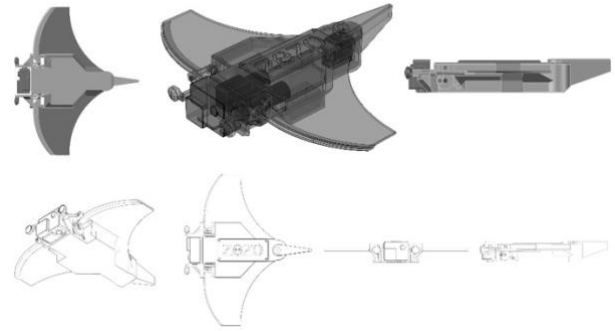


Fig 4. The 3D Model of The ROV

The collaborative efforts of engineers, designers, and researchers are crucial to ensure that the mechanical design of each component aligns with the bio-inspired principles and objectives of the ROV. By integrating the main body, circular crank, rigid arm, and flexible wings effectively, the bio-inspired modular ROV can achieve the desired mobility, maneuverability, and efficiency required for its intended missions.

E. Printing Process

The printing process of the bio-inspired modular ROV components using a 3D printer involves utilizing additive manufacturing techniques to create the desired parts layer by layer. This approach offers several advantages, including cost-effectiveness, design flexibility, and rapid prototyping. Here's an overview of the printing process for the ROV components:

1. **Design Preparation:** The first step in the printing process is to prepare the digital design files of the ROV components. These design files can be created using computer-aided design (CAD) software or obtained from existing designs. The design files define the geometry, dimensions, and structural features of each component.
2. **Material Selection:** Selecting the appropriate printing material is crucial to ensure the desired strength, durability, and performance of the ROV components. Common materials used in 3D printing for ROV applications include various thermoplastics like ABS (Acrylonitrile Butadiene Styrene) or PLA (Polylactic Acid) due to their strength, water resistance, and affordability. Additionally, specialized materials with enhanced properties, such as impact resistance or UV resistance, can be chosen based on the specific requirements of the components.
3. **3D Printing Process:** Once the design files and material selection are finalized, the printing process begins. The 3D printer reads the design files and employs a layer-by-layer approach to construct the components. The printer follows

a pre-defined path, depositing the printing material in thin layers and solidifying each layer before proceeding to the next. This process continues until the complete component is printed. This process is illustrated in Fig. 5.

4. **Post-Processing:** After the 3D printing is completed, post-processing steps may be required to enhance the quality and functionality of the printed components. Post-processing activities can include removing support structures used during printing, sanding or smoothing the surfaces, and applying additional treatments like surface coatings or sealing to improve water resistance.
5. **Quality Control and Testing:** It is essential to conduct quality control measures and testing on the printed components to ensure their integrity and functionality. This can involve dimensional accuracy checks, structural strength assessments, and fitment tests to verify compatibility with other ROV components. Any necessary adjustments or refinements can be made based on the results of these tests.

By utilizing 3D printing technology, the bio-inspired modular ROV benefits from the ability to create complex geometries, customize designs, and iterate quickly during the prototyping phase. The use of 3D printing also offers the advantage of reducing production costs, minimizing material waste, and facilitating efficient assembly due to the modular nature of the printed components.

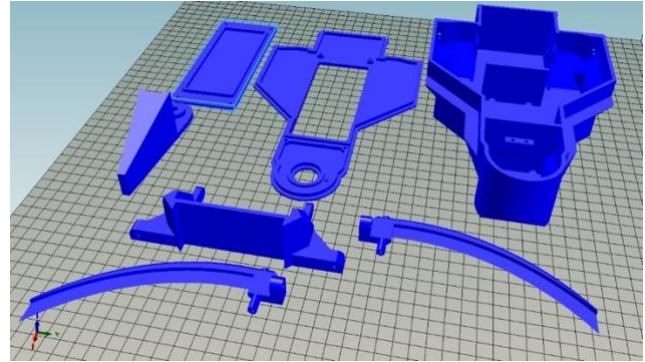


Fig 5. Printing of The ROV Components

F. Performance Parameter

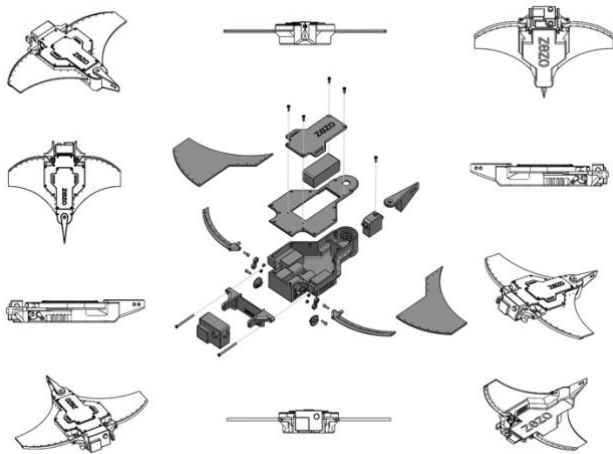
Parameter	Definition	Expected Range of Values
Range	Distance the ROV can travel per charge	2 KM (2000 mAH 2S 7.2V Battery)
Speed	Maximum velocity achievable by the ROV	5 KM / Hour
Depth Rating	Maximum depth the ROV can safely operate	<1 M
Maneuverability	Ability to navigate and change direction	High agility and responsiveness
Stability	Capability to maintain a stable position	Minimize drift and maintain steady operation
Payload Capacity	Maximum weight the ROV can carry	POV Camera (GoPro Equivalent)
Battery Life	Duration of operation per battery charge	1 Hour
Water Tightness	Effectiveness in preventing water ingress	IP level 7
Control Range	Maximum distance for reliable control	500 M
Imaging/Sensing Capabilities	Quality and resolution of cameras and sensors	1080P 60FPS
Environmental Adaptability	Ability to withstand varying water conditions	Temperature, salinity, and current resistance
Endurance	Overall operational duration of the ROV	Depends on battery life and maintenance

Reliability	Dependability and robustness of the design	Minimal risk of failure during missions
Efficiency	Energy efficiency and power consumption	Optimize battery usage and extend operation
Communication	Reliability and range of communication	2.4 GHz

Table 1 Performance Parameters of ROV

G. Assembly

The assembly of the bio-inspired modular ROV involves integrating the 3D printed components into a functional and cohesive system. The printed components, such as the main body, circular crank, rigid arm, and flexible wings, are carefully assembled according to the design specifications. This typically includes attaching the various components together using suitable fasteners, such as screws or bolts, and ensuring proper alignment and fitment. Wiring connections are made to integrate the electrical components, such as the control system, transceiver, speed controller, and visual sensors. The assembly process requires attention to detail and precision to ensure the components are securely joined, electrical connections are properly made, and the overall structure is robust and watertight. Thorough testing and quality checks are conducted to verify the functionality, integrity, and performance of the assembled ROV before deployment. Fig. 6 depicts the assembly process of the ROV components.

**Fig 6.** Assembly Process of The ROV Printed Components

H. Prototype

The culmination of the printing and assembly processes is a final prototype of the bio-inspired modular ROV that showcases the integration of innovative design, advanced manufacturing techniques, and functional components. The final prototype exhibits a streamlined and hydrodynamic main body resembling a manta ray, with carefully designed circular crank, rigid arm, and flexible wings emulating the efficient

motion observed in nature. The 3D printed components, constructed from durable and water-resistant materials, contribute to the lightweight yet robust structure of the ROV. The assembly ensures precise alignment, secure fastening, and proper integration of electrical systems, including control mechanisms, transceiver, speed controller, and visual sensors. The final prototype represents a significant advancement in underwater surveillance, inspection, and exploration, with its modular design, enhanced maneuverability, and reliable performance in various water conditions. It serves as a tangible testament to the successful convergence of engineering, technology, and nature-inspired design principles.

**Fig 7.** The Final 3D Mock Up of The ROV

V. FURTHER STUDIES & FUTURE WORK

A. Further Studies

In line with the design direction of creating a simple, low-cost, and easy-to-operate underwater vehicle, further studies can focus on the following aspects:

1. Submersible/low depth capability: The vehicle should be designed to operate effectively in submersible conditions and low-depth environments, such as urban flood scenarios. This would involve ensuring the vehicle can withstand debris-filled waters commonly encountered in such environments. By preventing propeller jamming, the vehicle can navigate through cluttered areas without compromising its propulsion system.
2. Modular design with additive manufacturing: To facilitate widespread adoption and easy replication of the vehicle, a

modular design approach can be adopted. This design allows for scalability and adaptability, enabling users to customize the vehicle based on their specific requirements. Additionally, utilizing additive manufacturing (3D printing) technology for manufacturing the vehicle components simplifies the production process. By sharing the .stl or 3D files, the vehicle can be easily printed or manufactured in other parts of the world, promoting accessibility and cost-effectiveness.

3. **Simplified complex motion:** The complex mobuliform motion of the manta ray can be simplified for practical implementation. Instead of replicating the intricate wing movements, a simplified mechanism using two motors and cranks can be employed to create vertical motion. The wings or arms of the vehicle can be connected to the main frame using elastic foam material. By tuning the form, such as area and direction, and adjusting the thickness to control elasticity, a sinusoidal movement can be achieved. This simplified design approach maintains the essence of the manta ray's motion while ensuring practicality and ease of operation.

By considering these design directions, the development of a low-cost, easy-to-operate underwater vehicle becomes feasible. Such a vehicle would be well-suited for urban flood environments, where debris is abundant and conventional propelled vehicles may encounter propeller jamming issues. The modular design and additive manufacturing enable widespread production and customization, while the simplified motion mechanism ensures practical implementation. This design approach opens up opportunities for underwater robotics in various regions and applications, promoting cost-effective and accessible solutions for underwater exploration, surveillance, and disaster response scenarios.

B. Future Work

The development of the bio-inspired modular ROV has presented promising results in terms of its design, printing, assembly, and initial performance. However, there are several avenues for future work that can further enhance the capabilities and expand the potential applications of this technology.

1. **Performance Optimization:** The performance of the bio-inspired modular ROV can be further optimized through iterative design improvements. This may include fine-tuning the wing geometry, adjusting the circular crank mechanism, or exploring alternative propulsion methods to enhance maneuverability, speed, and efficiency. Computational modeling techniques, such as fluid dynamics simulations, can aid in the analysis and optimization of the ROV's hydrodynamic characteristics.

2. **Sensory Enhancements:** The incorporation of advanced sensing capabilities can greatly enhance the ROV's functionality. Future work can focus on integrating additional sensors, such as sonar systems or advanced imaging technologies, to improve underwater navigation, obstacle detection, and environmental mapping. Moreover, the integration of autonomous capabilities, such as intelligent algorithms for object recognition or path planning, can enhance the ROV's autonomy and expand its range of missions.
3. **System Integration and Redundancy:** Further research can explore the integration of additional modules or equipment into the modular ROV design. For instance, integrating sample collection devices, environmental sensors, or additional robotic arms can expand the ROV's capabilities for scientific research or specific industrial applications. Additionally, implementing redundancy in critical systems, such as propulsion or communication, can enhance the ROV's reliability and fault tolerance.
4. **Battery Technology and Power Management:** Improving the energy efficiency and extending the operational endurance of the ROV is an important area for future work. Exploring advanced battery technologies, such as lithium-air or solid-state batteries, can enhance the ROV's power density and extend its runtime. Additionally, efficient power management systems, including intelligent power distribution and optimization algorithms, can help maximize the ROV's operational time and ensure optimal use of available energy.
5. **Field Testing and Real-World Applications:** While the development of the bio-inspired modular ROV has been largely focused on design, printing, and assembly, future work should involve extensive field testing and evaluation. Conducting trials in real-world environments, such as marine ecosystems or industrial settings, will provide valuable insights into the ROV's performance, durability, and practicality. Feedback from end-users and operators can guide further improvements and help identify specific applications where the ROV can deliver significant benefits.

The future work on the bio-inspired modular ROV should concentrate on performance optimization, sensory enhancements, system integration and redundancy, battery technology and power management, as well as rigorous field testing. By addressing these areas, the potential of this innovative technology can be further unlocked, paving the way for its successful deployment in a wide range of underwater missions, including infrastructure maintenance, scientific exploration, and search and rescue operations.

VI. CONCLUSION

The paper presents the development of a bio-inspired modular remotely operated vehicle (ROV) inspired by the efficient movement of manta rays. The use of 3D printing technology allowed for the creation of cost-effective and customizable components, while the assembly process ensured the integration of electrical systems and the overall functionality of the ROV. The resulting prototype showcased improved maneuverability, buoyancy control, and a streamlined design. However, there are ample opportunities for future work, including performance optimization, sensory enhancements, system integration, battery technology improvements, and real-world testing. These advancements will pave the way for the deployment of the bio-inspired modular ROV in various underwater applications, ranging from infrastructure maintenance to scientific research and rescue operations. By blending engineering technology, product design, and bio-inspired principles, this work demonstrates the potential for innovative solutions in underwater exploration and surveillance.

REFERENCES

- [1] Cao, Yonghui, et al. 'Similarity Evaluation Rule and Motion Posture Optimization for a Manta Ray Robot'. *Journal of Marine Science and Engineering*, vol. 10, no. 7, MDPI, 2022, p. 908.
- [2] Chen, Zheng, et al. 'Bio-Inspired Robotic Manta Ray Powered by Ionic Polymer--Metal Composite Artificial Muscles'. *International Journal of Smart and Nano Materials*, vol. 3, no. 4, Taylor & Francis, 2012, pp. 296–308.
- [3] Chen, Zheng, Tae I. Um, and Hilary Bart-Smith. "Ionic polymer-metal composite enabled robotic manta ray." *Electroactive Polymer Actuators and Devices (EAPAD) 2011* 7976 (2011): 854-865.
- [4] Chew, Chee-Meng, et al. 'Development of Propulsion Mechanism for Robot Manta Ray'. 2015 IEEE International Conference on Robotics and Biomimetics (ROBIO), IEEE, 2015, pp. 1918–1923.
- [5] Gao, Jun, et al. 'Development and Design of a Robotic Manta Ray Featuring Flexible Pectoral Fins'. 2007 IEEE International Conference on Robotics and Biomimetics (ROBIO), IEEE, 2007, pp. 519–523.
- [6] Liu, Qimeng, et al. 'A Manta Ray Robot with Soft Material Based Flapping Wing'. *Journal of Marine Science and Engineering*, vol. 10, no. 7, MDPI, 2022, p. 962.
- [7] Sitorus, Patar Ebenezer, et al. "Design and implementation of paired pectoral fins locomotion of labriform fish applied to a fish robot." *Journal of Bionic Engineering* 6.1 (2009): 37-45.
- [8] Sun, Yi, et al. 'The Validation of Viscosity Induced Chord-Wise Undulation on Soft Fin Ray Array Towards a Novel Robotic Manta Ray'. 2022 IEEE 5th International Conference on Soft Robotics (RoboSoft), IEEE, 2022, pp. 673–680.
- [9] Wang, Zhenlong, et al. 'A Micro Biomimetic Manta Ray Robot Fish Actuated by SMA'. 2009 IEEE International Conference on Robotics and Biomimetics (ROBIO), IEEE, 2009, pp. 1809–1813.
- [10] Zhang, Daili, et al. 'A Novel Integrated Gliding and Flapping Propulsion Biomimetic Manta-Ray Robot'. *Journal of Marine Science and Engineering*, vol. 10, no. 7, MDPI, 2022, p. 924.
- [11] Zhou, Chunlin, and Kin-Huat Low. 'Better Endurance and Load Capacity: An Improved Design of Manta Ray Robot (RoMan-II)'. *Journal of Bionic Engineering*, vol. 7, Elsevier, 2010, pp. S137–S144.