Scientific Research Publishing

Modern Mechanical Engineering, 2024, 14, 57-72
https://www.scirp.org/journal/mme
ISSN Online: 2164-0181
ISSN Print: 2164-0165

Design of a Novel Robotic Fish Structure Utilizing PVC Gel Actuators

Ruyhan[1*], Nazia Bibi[1], Sara Rahman[1], Abdullah Al Hossain Newaz[2], Abdul Kadir[2], Nasir Uddin[2]

[1]School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an, China
[2]School of Mechanical Engineering, University of Bridgeport, Bridgeport, USA
Email: *ruyhan19@gmail.com

How to cite this paper: Ruyhan, Bibi, N., Rahman, S., Al Hossain Newaz, A., Kadir, A. and Uddin, N. (2024) Design of a Novel Robotic Fish Structure Utilizing PVC Gel Actuators. *Modern Mechanical Engineering*, **14**, 57-72.
https://doi.org/10.4236/mme.2024.143006

Received: June 11, 2024
Accepted: July 29, 2024
Published: August 1, 2024

Abstract

In this research work, it has been designed a bionic robot fish structure, can swim underwater. The active compact body is powered by eight sets of symmetric PVC gel actuators with a caudal fin. The robot's 200 mm-long, fish structure design incorporates a 55.52 angle to optimize the fish dynamics movement. It's a fast and smooth operation and can swim. The robot can swim fast and quietly by using the right positions and the appropriate actuators on PVC gel actuators. This design entails a unique architecture that enables the robot to move safely and unobtrusively at the same time, which makes it suitable equipment for different exploration and surveillance missions in the water with speed and silent operation as the foremost concern.

Keywords

Biomimetic Robotics, Structural Design, PVC Gel Actuators, Swimming Mechanisms

1. Introduction

The latest research [1] [2] has shown that bionic robot fish possess the capability to transform the way the world underutilizes underwater environments. Being distinct from the other biomimetic robotics that were powered by a building and conventional motor drives of the systems [3], MIT Robotuna, a biomimetic robot fish that exhibited unprecedented efficiency in power consumption and operation, was pioneered in the field of bionic robotics [4]. Through the detailed observation of tuna moving, Robotuna's propulsion system employs one or more motors to make the robot fish oscillate in water, and it is then that this robot can be launched anywhere it is desired. By the means of cleverly reproducible movements of the live fish, those robots would bring a special juice to underwater exploration and research all over the globe.

This study embraces new designs for Io-liquid locomotion machines inherited from structural compliance to achieve thrust. A compliant mechanism model with high performance similar to that of real fish locomotion is proposed, which is later analyzed by another model through the next stage of development. Humans create just about everything, but most inventions are inspired by the way nature is made. It is this awareness that leads to the development of soft robotics. As opposed to hard robots, soft robots imitate natural systems; these are flexible and complex, thus optimal for solving underwater tasks. This essay looks at recent progress in this area through [5] [6]. This motor control driven by a silicone rubber flexible fishtail that swings continuously was like real fishtail. In addition to the research team at MIT, they have utilized the hydraulically controlled robotic fish for a new kind of novel underwater technology. The driving gear pump which is controlled by an electrical motor and is responsible for the regulation of the fluid pressure and creating an alternating bending and oscillating of the fish's tail is powering the device [7]. This world-changing machine may just provide a much deeper level of understanding about water worlds and take research to a more advanced level than before. Strong materials such as IPMC, DE, and SMA are introduced in the soft robotics fish creation for improved flexibility and efficacy. An IPMC-based EAP is one of the most common materials used in manufacturing robot fish as the hydrophilic nature and low voltage of this material are the two foremost reasons [8].

The bionic robot fish was created by a group of researchers, taking the lionfish as their guide, and also an inspiration. The robot, resembling fish, is powered by the most recent DE actuators, therefore making it fun with the flapping movement. Such a remarkable journey was achieved in the Mariana Trench that the invented technology lasted 45 minutes, suggesting the advent of new possibilities for ocean research with some scientific applications. [9] [10] created a domestic bionic cuttlefish controlled with SMA that can suddenly swim on its own. but these resources are more suitable for little robotic fish than for medium-sized or big robots [11]. This paper presents a new bionic robot fishtail structure that has multi degrees of freedom skeleton structure and stacked soft PVC gel actuators which can simulate fish muscle movements. Analyzing the mechanics and the frequencies of the fishtail and it responded optimally at 1 to amplitude of swing. Still, the generator component causes the reporter to hear 5 Hz underwater due to resonance. Like Flappy, the prototype was tested for water movement and proven to be operational, which will go a long way in creating a practical bionic fish design. S Sixtus concluded that contraction strain increased with changing load or voltage, and reached the frequency that the natural fish swims and they thus have potential in bionic usages of PVC gel actuators [12]. For this light weight structure, the optimized designs validate the efficacy of topology optimization in creating lightweight, high-performance light weight components, highlighting its importance in future design Advancements [13]. The study aims at developing a circular soft robot with SMA actuators, operated utilizing a newly developed control strategy encompassing PID alongside Kalman filtering in addition to visual servo. Potential MATLAB simulations and experiments have shown some outcome, however, the issues of recognizing objects and or forms and measuring of distances still remained a daunting task for future work with reinforcement learning by gait control [14]. This work describes the fabrication and characterization of the freshly developed ampicillin-selective electrodes based Mn (III) TPPI ionophore in PVC and sol-gel matrices. These electrodes when coupled to pharmaceutical analysis they depict a similar precision as that of HPLC however they are easier to use, expensive reagents are minimized, and are cheaper when used with SIA system [15].

2. Structure Design of Robotics Fish

2.1. Oscillating Mechanism Proposed for Robotic Fish Propulsion

This mechanism, which is simply voltage applied, is an actuator or single-layer PVC gel with contraction-displacement motion as shown in (**Figure 1**). Voltage application will simply push up the gel to the anodes to create the displacement. Instead of traditionally, we use 2 closely placed actuators linked together by lever arm for more effective execution of the principle. Coupling actuators exploit the synchronization principle to make mechanical motion take place in a desired fashion [12]. It provides the ability to carry out controllable alterations in the tail direction or any other appendages required in the animatronic system and hence achieve the desired movements. PVC gel actuators in this oscillating mechanism were used in this reciprocating motion, as they have the advantage of being able to perform more efficiently, flexibly, and easily controllable. For instance, the simplicity and robustness of the design make it applicable to many kinds of robot assemblies, chiefly in underwater constructions where traditional actuators may fail to work. Supposing this oscillating model is implemented into robotics, it may contribute greatly to progress in robotics, and provide a successful route to the development of more agile and flexible robotic platforms by providing an efficient approach for both control and movement within robots.

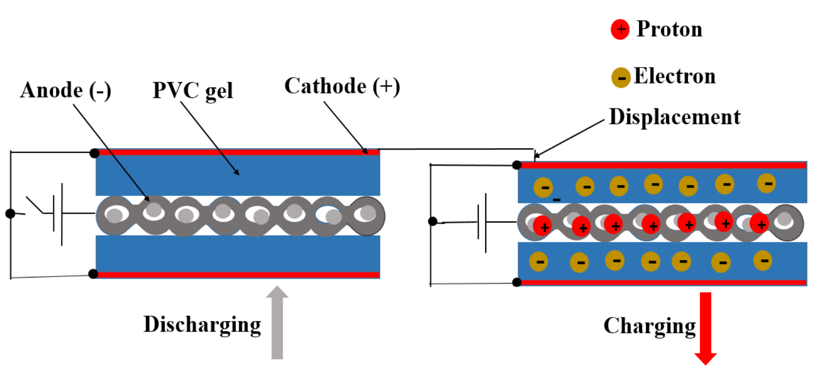

Figure 1. PVC gel actuator schematic with contraction deformation [12].

2.2. Active Fishtail Design Utilizing PVC Gel Actuators for Oscillation

This paper elaborates the synthesis and use of dibutyl adipate (DBA) as the plasticizer within PVC gel concerning its employment in the motion structure of a bionic robot fish. It starts with the preparation of PVC gel that requires dissolving of PVC powder and DBA in Tetrahydrofuran (THF). This mixture advantageously utilizes DBA where it was observed to increase the dielectric constant this is crucial in the actuation of the robot fish using the PVC gel. For the preparation of the gel, the reaction medium used shall be a THF-DBA system, where THF is the main solvent and DBA acts as the cross-linking agent. One amount of the PVC powder is added slowly to this mixture and it is then heated for a few minutes to form a viscous gel. The crucial step involves mixing PVC and DBA in a 4:1 ratio, followed by stirring the resulting suspension for 24 more hours at 40˚C, during which the PVC powder dissolves completely. This all helps to produce a distinct PVC solution, a crucial part of the motor function of the robot fish. The construction of the robot fish can be described up of several stages: first, two plastic covers are put together; second, PVC gel is prepared and injected into the body of the fish; third, a moving mechanism is installed. After the assembly is done, the company then powers the PVC gel actuators by electricity and this allows the movement of the robot fish. The engagement of these actuators is of high importance, as it is through it that converting electrical energy into mechanical one is enabled, thus making the fish move.

Thus, the paper focuses on the fact that DBA is helpful to refine specific characteristics of the formed PVC gel, including the dielectric properties, which are critical to actuation. With regards to dielectric properties which determine the materials response to an electric stimulus, directly impacts the speed and functionality of the robot fish. By optimizing these properties, it guarantees that the DBA-enhanced PVC gel maximizes the capacities of the actuators as expected. Moreover, the paper describes the importance of the actual mixing process that has been described in more detailed above. The inclusion of PVC powder in a gradual process and the stirring at the given temperature are important mechanisms in making the gel proportional and efficient. The 24 h stirring for the samples at 40˚C is critical to dissolving the PVC to the occurrence of a clear solution that is also uniform. Such homogeneity is crucial to the performance of the actuators, as it ensures that they provide optimal performance in distinct settings.

The assembly process is also stressed as in the end for creating the robot fish, the clear PVC solution gains some components to compose the base of its motion. To allow for this, the assembly of the process is very precise to make sure that the actuators are in the right places and can function correctly once a flow of electricity is passed through them. These components are the essential elements that show how a robot fish should work and how well it will function when used in the intended application [12] [16].

The soft actuator is a PVC gel. It produces linear displacement. It's contracting under DC voltage, returning to its original shape without voltage, with the contraction rate increasing with voltage until saturation. A novel swinging mechanism using PVC gel actuators has been proposed to simulate the contraction of fish muscles for bends in their tail. The mechanism is composed of joints, PVC gel actuators, hinges, and press buttons (**Figure 2**). The two PVC gel actuators are placed at the joint where they rotate to enable bidirectional motion. In this manner, the actuators which are used to give the driving signals in turns create the swinging motion; the swing angle is in direct relation with the voltage. Thus, this mechanism copies the path of fish movements to improve the power and direction in the water environment (**Figure 3**).

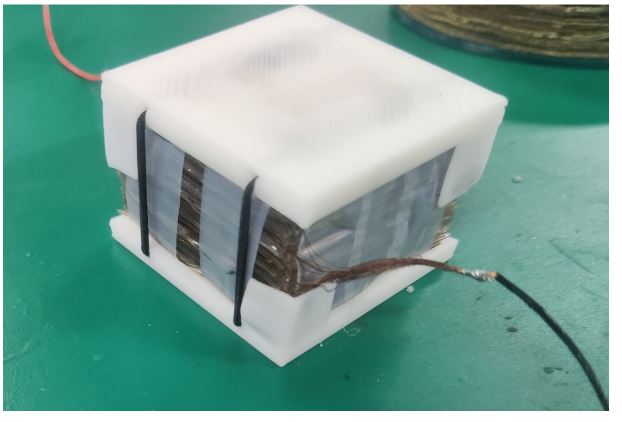

Figure 2. PVC gel actuator assembly.

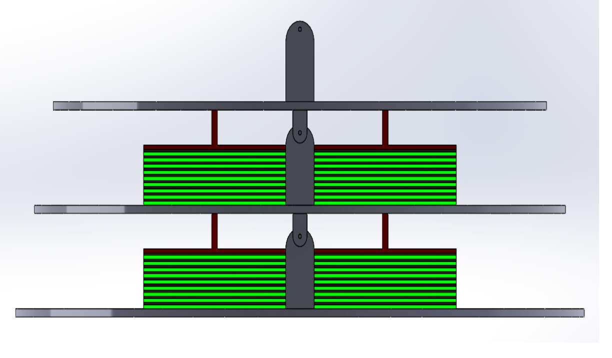

Figure 3. Two PVC gel actuators were employed.

Actuators are to be positioned at junctions between joints. Precompression plates must be spread during assembly. The two actuators' driving signals are adjusted to be oscillating. The stored charge in the right actuator will produce the joint rotation through the right-handed screw sense with the clockwise precompression torque generation. It results in the swing angle proportional to the voltage. When the operation actuator on the left is set in place, so does the show. The main function of this act is based on the timing control of the two parallel signals which produce ongoing the two waveforms either the charging or the reverse-waveform signals by the switching action. Perpetual right and left-hand side twisting movements are easily possible with either regular or alternating actuator operation. Units connected in series (**Figure 4**) create a parallel-series system, except signals are passed from left to right and from right to left.

The bionic robot fish design involves placing actuators at the junctions between joints, with precompression plates spread during assembly (**Figure 4**), titled "The oscillating mechanism utilizes two PVC gel actuators for controlled movement," includes two different subfigures, labeled as **Figure 4(a)** and **Figure 4(b)** for clarity.

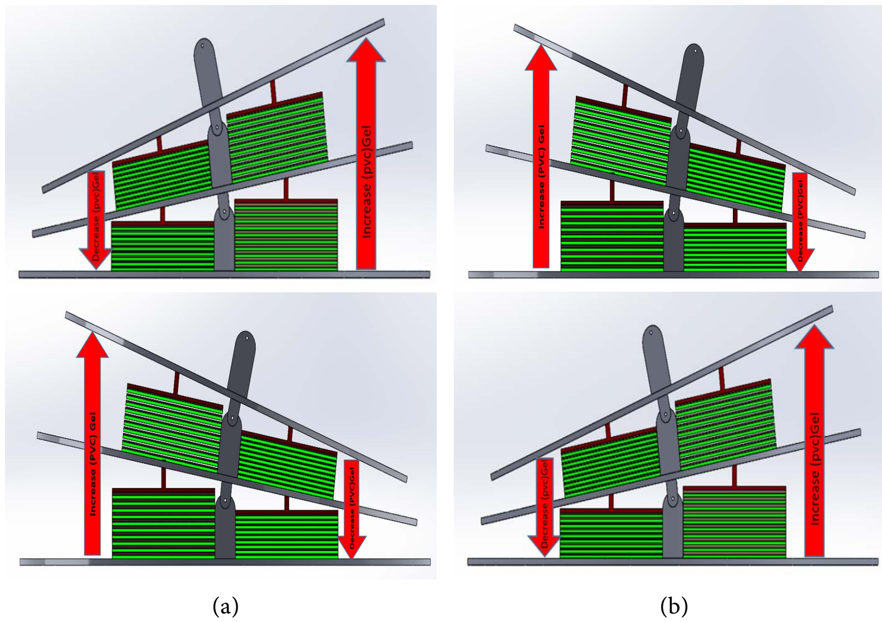

Figure 4. The oscillating mechanism utilizes two PVC gel actuators for controlled movement.

Figure 4(a): Illustrates the configuration where the two actuators are positioned, showing how the driving signals are adjusted to oscillate. The stored charge in the right actuator generates joint rotation through the right-handed screw sense with a clockwise precompression torque, resulting in a swing angle proportional to the voltage. This subfigure highlights the specific arrangement and activation of the right-side actuator.

Figure 4(b): depicts the operation when the left-side actuator is activated. The same principles apply, with the left actuator producing the necessary movements through its oscillating driving signals. This results in left-hand side twisting movements, mirroring the function of the right actuator shown in (**Figure 4(a)**).

The main function of these actuators is based on the timing control of the two parallel signals, producing ongoing waveforms through switching actions that alternate between charging and reverse-waveform signals. This setup allows for continuous right and left-hand twisting movements with either regular or alternating actuator operation. When units are connected in series, as shown in the combined representation of (Figure 4(a) and Figure 4(b)), they create a parallel-series system. In this system, signals are passed Bidirectionally from left to right and right to left, enabling synchronized and efficient movement of the bionic robot fish.

2.3. Model of a Robotic Fish Utilizing Soft Actuators for Propulsion

The proposed "swinging" mechanism we are talking about here, uses two PVC pills to move the base for rotation at an angle of 55.52˚. The system is based on new standards, it's fast and streamlined, therefore it's significantly better than the mechanisms which resemble the movements of fish. Just like the majority of them, it has something unique to offer the industry namely the low friction torque. The associated machinery will be running flawlessly and performing its functions at optimum.

This mechanism of other fish systems is quite simple and therefore it can be intuitively managed and preferred. This appeals not only to recreational divers but also to those who seek practical benefits when using it. This actuation mechanism features the use of PVC gel as a key feature. Among these actuators is the component that pushes the upper and lower bodies to generate wave-like movements. PVC gel actuators are praised for their flexibility, fast reaction time, and longer duration, which reveals that this type of actuator is best for dynamic systems. In this case, the application of these actuators isn't just about making the mechanism function better but also adding versatility to its designs (Figure 5).

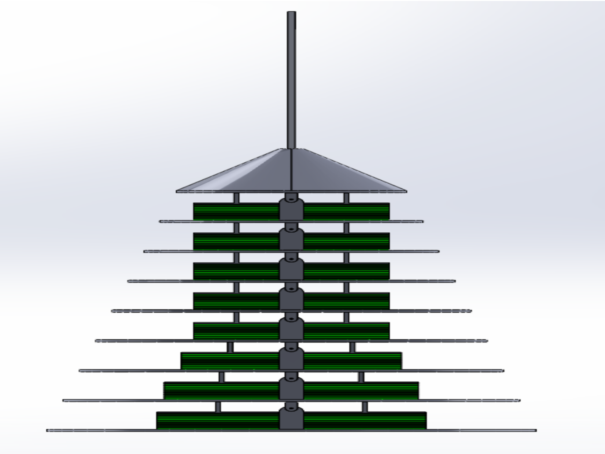

Figure 5. Active fishtail functionality.

This performance of the system with a 55.52˚ danging precision is a proud victory in the engineering sphere. This accuracy in movement offers new solutions to a variety of processes in different fields, like robotics or automation in production. Beyond that fast working mechanism, this tool also enables a faster working process for assigned tasks that are precise and precise. It, therefore, applies to jobs that require instant work. The difference that this mechanism presents is contrary to the popular approach of fish-shaped systems (Figure 6).

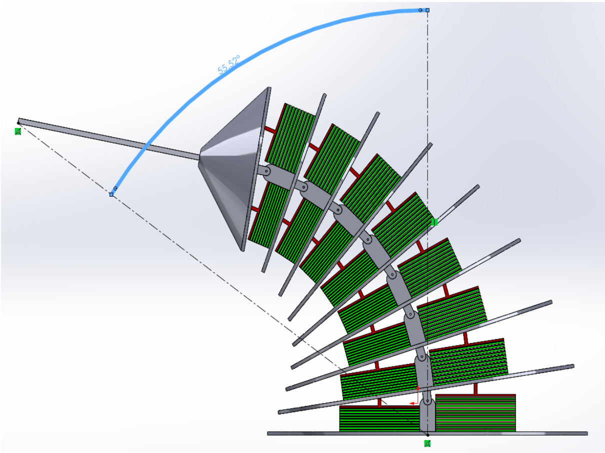

Figure 6. Depicts the precise rotation of the left side of the active body by 55.52˚.

Whereas the majority of underwater technologies connect its movement and swimming patterns with those of fish, this system moves in a unique, one-way manner. The intention here is to effect a break away from a norm in an endeavor to devise a mechanism that incorporates efficiency as well as distinction as its mode of operation. This stabilizing method is not only technically feasible but also very affordable to implement. This is made possible by the system's ability to tap into the potential energy of the wind and its inherent low friction; this translates to an inexpensive cost of electricity. One of the components in a system of the world will be the feature of energy efficiently that is more and more encouraged so that it has a great financial value for the operation (Figure 7).

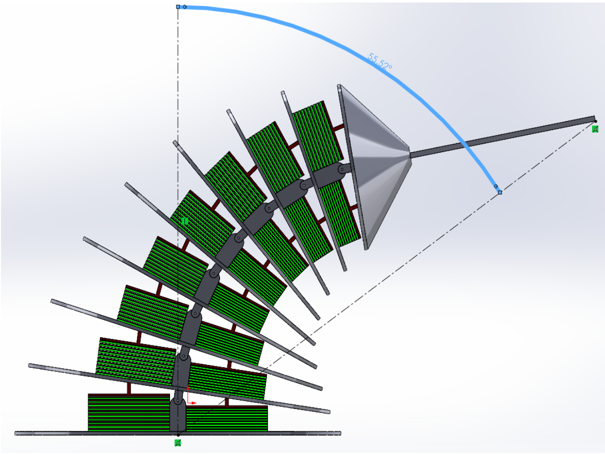

Figure 7. Depicts the precise rotation of the Right side of the active body by 55.52˚.

This is due to the cost-effectiveness of the technology, which often makes it feasible for use in a wide range of applications, and probably in situations where energy savings is an important goal. Finally, I can say that mechanical assembling that has been accomplished using two PVC gel actuators precisely reminds me of a huge growth in technical creativity. Its dual-helix shape, turn-over-time is faster than the conventional up-and-down structure, and working efficacy which is user-friendly make it different from the conventional systems (**Figure 8**).

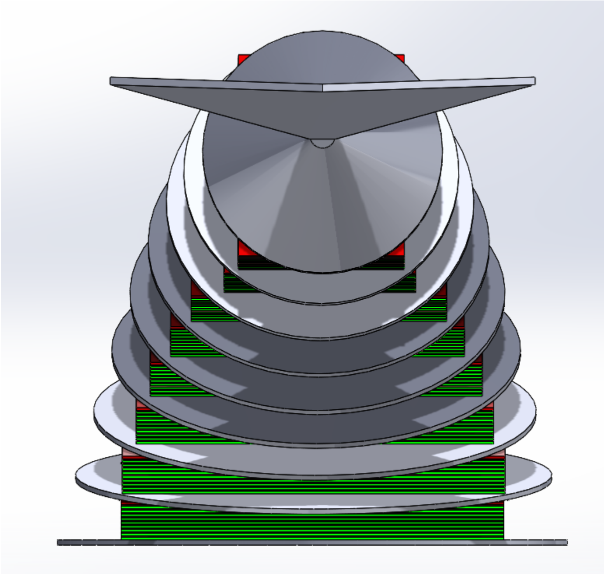

Figure 8. Back left side view.

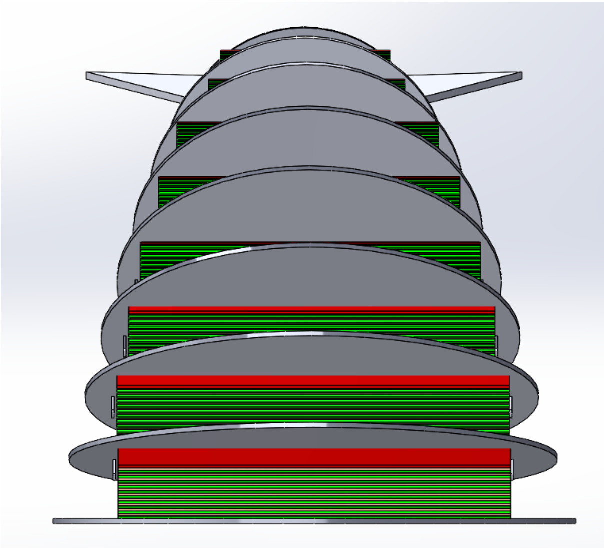

Figure 9. Back right side view.

The usage of PVC has boosted its performance and capabilities to adapt to diverse applications. The accuracy of revolving motion is what drives the versatility of such an operation, and the economy of use is what makes it practical in real-world scenarios. The mechanism of oscillation signifies by its example how a brilliantly conceived system of a dynamic nature could bring together effectiveness, practicality, and economy with ease. This economic aspect is a practical choice for different application areas accentuates its usefulness, especially in those cases where minimizing operating costs is the chief priority. To draw the curtain, however, the Bilyeley manufacture of two PVC gel actuators that stands for engineering brilliance is the highest level. This is not only a characteristic of the MBring system but also a special feature of the design of the MBring system, which has won over other fish-like systems using its ease of rotation and fast working efficiency. Using PVC gel actuators is its key feature for proper working and adapting. High accuracy of rotation enables multiple practical application fields and low cost is one more factor of making it handy for transportation. It is the gyratory mechanism that has emerged as the inventive line in the world of dynamic systems due to the harmony of efficacy, accuracy, and economy (**Figure 9**).

2.4. Robotic Fish Design and Structure

The working model bio-inspired robots of the design unit are based on parameters like body size (distribution of body size) and also on swimming patterns (pattern of undulation). For such bio-mimicry, the proportions of the robots are looked at and are designed as per the proportions of their natural models fish [17]. The design of this robotic fish was made in such a way that it imitates the swimming action of fish that belong to sub-carangiform swimmers and hence ensures its resemblance with the biotic ones (**Figure 10**). In this distribution, predators having sub-carangiform swimmer proportions, with undulations covering about half the total length, have the dominant executor role.

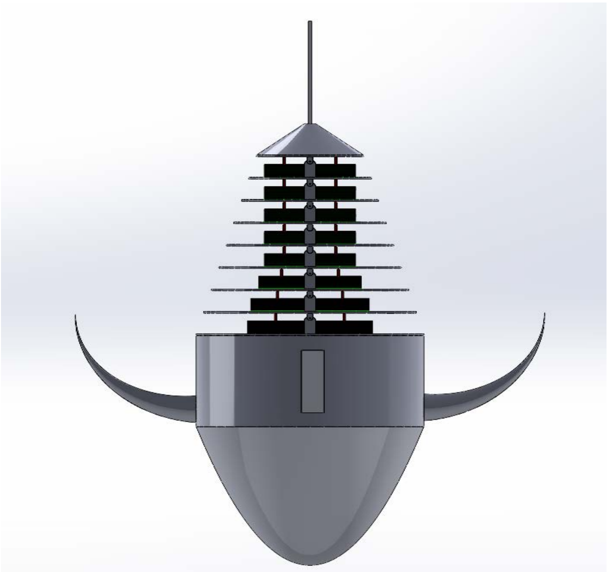

Figure 10. Design of robotic fish.

The fish's body was listed into four parts along the length of its fish and (**Table 1**). Streamlining of the hull design is made by design engineers to decrease drag area and hence enhance propulsion efficiency (**Figure 11**). Twin pectoral fins are installed to increase stability and prevent unwanted flipping. Pushing forward of the tail being a determining motive, is carried out by eight pieces of PVC gel actuators, which are located symmetrically to cater for the balance. Actuators (**Figure 9**) which have a green cuboid shape will be strategically sized for the simultaneous activities of force output and fish streamline appearance. Adding on, the caudal fin design which design was inspired by the real world emarginated fin of sub-carangiform swimmers, therefore, the model is known globally for its biomimicry. In summary, the design of the robot fish model is focused on efficiency in terms of swimming that sub-carangiform swimmers can achieve while combining the stability and flexibility for movement underwater.

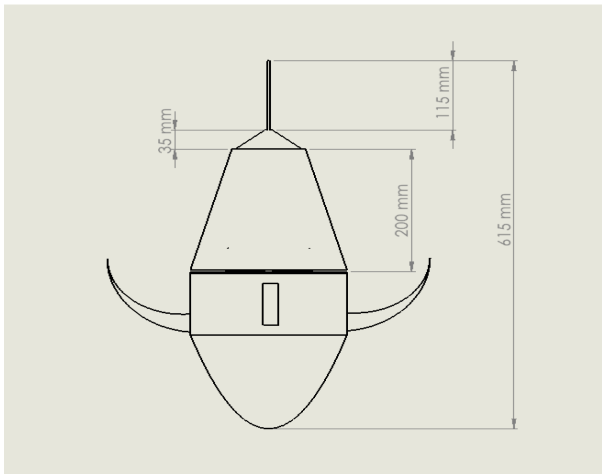

Figure 11. 2D Design of robotic fish.

Table 1. Showcases robot fish size data.

Length of the item	Summary of Characteristics
Total length specified	615 mm
Active body length	200 mm
Peduncle length	35 mm
Caudal fin length	115 mm

3. Circuit Board Design Overview

The tail of a real fish is designed with a two-mode control system that provides an independent pattern generator. MPU shows PWM outputs via its ports. Such signals are specified with two shapes: one whose signal is the reversal of the other. Such a technique provides the possibility of patterned fish-tail motion, which means it can happen in time and space simultaneously. The circuit board provides the robots' oscillation and swimming synchronizing the PWM (pulse width modulation) signals with implicit waves. This design allows us to make the fishtail perform those convert swimming movements that can easily be similar to the moves made by the natural live fish. Furthermore, the ranking-control design of the system provides an additional advantage by contributing to the device's variability in its maneuvers, hence enabling it to mimic these with accuracy and speed. As a whole, it is the circuit board design in place that has efficiently upgraded the functionality of the robotic fish as it is now capable of swimming automatically in an original position in water environments. Circuit design provides the fishtail with fine motion control by applying two-mellenium mode layout with carefully chosen distances between the shafts. The next heavy input signal within the actuator is contraction where the swinging of the fishtail takes place into one side or the other. On opposite side, the low-energy coil turns on when there is a high-level switching state, and the signal flows into a fishtail pushing it to the other side of the platform too. Through this switch response, the action of the fishtail becomes synchronized with the metalion's swim.

These features can be used in the code by the users to set and display frequency and speed for the actuators, which will help to drive the oscillations properly and the fish motion, while being precise, as well. In different situations for different tasks, users can tune these factors to present the fish behavior that corresponds to their swimming behavior. Apart from that, the design of robot fish circuit boards by physicochemical principles ensures that they are properly and profitably used in waters, through which they operate without any complication.

4. The Assembly Process of the Robot Fish

The robot fish assembly, in general-purpose terms, comprises several important steps that build up the functional and working robot fish. First of all, there will be a set of items used for the assembly of the system, for example, body frame, propulsion system, control systems, and any other extra features like sensors or cameras (**Figure 12**). Generally, constructing the body frame is the first step of the assembly process, as it is the spinal cord of the robot fish. This frame is usually constructed of plastics, or other synthetic materials, which are light, but at the same time strong enough to deal with water while making a unit buoyant and stable.

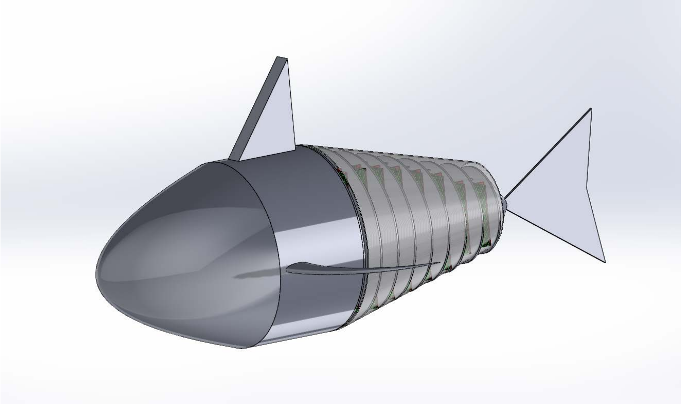

Figure 12. Illustrates the assembly process of the robotic fish.

So-called actuators are placed in certain areas of the body frame to imitate the movement of a real fish's tail, then, allow the robot fish to propel itself through the water. Besides, since other features or add-ons such as cameras that enable underwater visioning to avoid obstacles are still being assembled during manufacturing, they are put in the robot fish as well. These processes are done systematically with controls between components to give them the desired operation. Assembling the man-made fish is the most complicated stage of this project, which includes putting the small pieces of the robot fish together to build a submarine robot.

5. Advantages of the Designed Robot Fish

The designed robot fish, utilizing PVC gel actuators in its oscillating mechanism, offers several distinct advantages compared to other types of robots: The designed robot fish, utilizing PVC gel actuators in its oscillating mechanism, offers several distinct advantages compared to other types of robots:

1) Bio-Inspired Design: It also resembles the real movements and flexibility of fish using biomimicking technology which has a bionic fishtail and numerous soft structures. This planar technique reduces the complexity of the robot movements and makes it easier to maneuver the robot in underwater as opposed to the normal bulky type robots.

2) Soft Actuators: The freedom and flexibility offered by the use of the PVC gel actuators is particularly helpful in enhancing the mobility of the robot fish in underwater terrains with numerous bends and twists. Soft actuators are useful in application scenarios where there is a likelihood of operations with fragile marine organisms or structures, thus reducing the probability of the operations harming the organisms or structures.

3) Efficiency in Propulsion: PVC gel actuators also make the oscillating mechanism to move and create efficient propulsion. The actuators' capacity to create back and forth vibrations and focused motion enhances the maneuverability of the robot fish and the energy efficiency of the locomotion; in some respects, they are likely to be more effective than popular rigid propellers in terms of adaptability and rates of speed.

4) Reduced Weight and Size: This is particularly important considering that other conventional underwater robots might use more heave metal and larger mechanical parts than the robot fish with PVC gel actuators although this is sheer speculation. This reduction in weight and size can be highly beneficial since it enhances maneuverability and ease of deployment in underwater military applications such as exploration and surveillance.

5) Quiet Operation: Soft actuators in general create less acoustic so noise in comparison to conventional rigid actuators which is sometimes an advantage in low visibility underwater operations. Lower noise levels mean that there is little interference with the activities of water dwelling animals and the robot fish is then well suited for spying or data collection assignments.

6) Adaptability and Versatility: Soft robotic design HERE is superior to rigid

design as it adapts easily to several underwater tasks and challenges. The concept of the robot fish shows that it can be maneuvered through small channels, can interact softly with objects in the marine environment, and perform tasks that require accurate, sensitive movements, which can be seen as valuable for various tasks in marine environment.

The therapeutic outcomes of the designed robot fish are attributed to the soft bio-inspired approach to the robot's body, the optimization of the propulsion system, integration of compact and lightweight structures, low-noise modus operandi, and versatility in adjusting to various marine environments. These characteristics make it suitable for operations in underwater search, monitoring and studying environments where the use of arbitrary strong robotic structures can be a challenge.

6. Conclusion

Finally, a robot fish prototype of size 200 mm was exclusively designed for demonstration. Its body is driven by eight skeletal actuators of PVC gel, an action that forces the caudal fin to act. As a whole, each set has matching elements, resulting in a total of 16 actuators integrated into the fish's skeleton. The structural design angle of 55.52˚ was chosen to optimize the fish's movement dynamics. By taking advantage of the precise engineering and rich design, the robotic fish successfully proved it is fast and efficient. The arm and wing structures of the robotic fish are actively synchronized through the placement and synchronization of the PVC gel actuators to help generate propulsion efficiently just like fish while swimming underwater. The adoption of soft actuators, e.g., the use of PVC gel actuator, comes in handy as the actuator is flexible and highly responsive. This is required in simulation swimming to produce the natural movements. Both the right and the left actuators are arranged in symmetric manner to make the lines of movement uniform and in sequence, being the secret to efficient robot fish movement. Additionally, the mechanical structures of Robo Fish are designed to allow them to work with speed and accuracy. The optimized angle of 55.52˚ constant velocity allows quick movements that are penalized with instability and go out of control. It will be impossible for the robot fish to operate with high-speed swimming through the water and task completion, but with this design feature, they can move swiftly and efficiently. Finally, it can be noted that the successful deployment and implementation of such bionic robot fish display the talents that soft robotics are endowed with to develop agile and versatile underwater vehicles. Instead of the current bionic robot fish, successive models are likely to merge the innovative design principles with advanced materials, and the actuators. Consequently, the next iterations may even further enhance their performances and capabilities, and ultimately open up new applications for underwater robotics.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Raj, A. and Thakur, A. (2016) Fish-inspired Robots: Design, Sensing, Actuation, and Autonomy—A Review of Research. *Bioinspiration & Biomimetics*, **11**, Article ID: 031001. https://doi.org/10.1088/1748-3190/11/3/031001

[2] Xie, F., Zuo, Q., Chen, Q., Fang, H., He, K., Du, R., *et al.* (2021) Designs of the Biomimetic Robotic Fishes Performing Body and/or Caudal Fin (BCF) Swimming Locomotion: A Review. *Journal of Intelligent & Robotic Systems*, **102**, Article No. 3. https://doi.org/10.1007/s10846-021-01379-1

[3] Duraisamy, P., Kumar Sidharthan, R. and Nagarajan Santhanakrishnan, M. (2019) Design, Modeling, and Control of Biomimetic Fish Robot: A Review. *Journal of Bionic Engineering*, **16**, 967-993. https://doi.org/10.1007/s42235-019-0111-7

[4] Triantafyllou, M.S. and Triantafyllou, G.S. (1995) An Efficient Swimming Machine. *Scientific American*, **272**, 64-70. https://doi.org/10.1038/scientificamerican0395-64

[5] Youssef, S.M., Soliman, M., Saleh, M.A., Mousa, M.A., Elsamanty, M. and Radwan, A.G. (2022) Underwater Soft Robotics: A Review of Bioinspiration in Design, Actuation, Modeling, and Control. *Micromachines*, **13**, Article 110. https://doi.org/10.3390/mi13010110

[6] Zhong, Y., Li, Z. and Du, R. (2017) A Novel Robot Fish with Wire-Driven Active Body and Compliant Tail. *IEEE/ASME Transactions on Mechatronics*, **22**, 1633-1643. https://doi.org/10.1109/tmech.2017.2712820

[7] Katzschmann, R.K., DelPreto, J., MacCurdy, R. and Rus, D. (2018) Exploration of Underwater Life with an Acoustically Controlled Soft Robotic Fish. *Science Robotics*, **3**, eaar3449. https://doi.org/10.1126/scirobotics.aar3449

[8] Chen, Z. (2017) A Review on Robotic Fish Enabled by Ionic Polymer-Metal Composite Artificial Muscles. *Robotics and Biomimetics*, **4**, Article No. 24. https://doi.org/10.1186/s40638-017-0081-3

[9] Li, G., Chen, X., Zhou, F., Liang, Y., Xiao, Y., Cao, X., *et al.* (2021) Self-powered Soft Robot in the Mariana Trench. *Nature*, **591**, 66-71. https://doi.org/10.1038/s41586-020-03153-z

[10] Le, C.H., Nguyen, Q.S. and Park, H.C. (2012) A SMA-Based Actuation System for a Fish Robot. *Smart Structures and Systems*, **10**, 501-515. https://doi.org/10.12989/sss.2012.10.6.501

[11] Gao, F., Wang, Z., Wang, Y., Wang, Y. and Li, J. (2014) A Prototype of a Biomimetic Mantle Jet Propeller Inspired by Cuttlefish Actuated by SMA Wires and a Theoretical Model for Its Jet Thrust. *Journal of Bionic Engineering*, **11**, 412-422. https://doi.org/10.1016/s1672-6529(14)60054-8

[12] Dong, C., Zhu, Z., Li, Z., Shi, X., Cheng, S. and Fan, P. (2022) Design of Fishtail Structure Based on Oscillating Mechanisms Using PVC Gel Actuators. *Sensors and Actuators A*: *Physical*, **341**, Article ID: 113588. https://doi.org/10.1016/j.sna.2022.113588

[13] Ruyhan, A.A.H.N. and Melon, M.M.H. (2024) Optimization of Brake Pedal Mass and Safety Factor Using Topology Optimization *Techniques. International Research Journal of Engineering and Technology* (*IRJET*), **11**, 478-497.

[14] Lyu, T. (2022) A Control Method for SMA Robotic Actuators. *Journal of Computer and Communications*, **10**, 103-112. https://doi.org/10.4236/jcc.2022.105007

[15] Zárate, N., Araujo, A.N., Montenegro, M.C.B.S.M. and Pérez-Olmos, R. (2011) Sequential Injection Analysis of Ampicillin in Pharmaceuticals by Using Potentiometric Detectors Based on PVC and Sol-Gel Membranes. *American Journal of Ana-*

lytical Chemistry, **2**, 491-499. https://doi.org/10.4236/ajac.2011.24059

[16] Li, Y., Guo, M. and Li, Y. (2019) Recent Advances in Plasticized PVC Gels for Soft Actuators and Devices: A Review. *Journal of Materials Chemistry C*, **7**, 12991-13009. https://doi.org/10.1039/c9tc04366g

[17] Scaradozzi, D., Palmieri, G., Costa, D. and Pinelli, A. (2017) BCF Swimming Locomotion for Autonomous Underwater Robots: A Review and a Novel Solution to Improve Control and Efficiency. *Ocean Engineering*, **130**, 437-453. https://doi.org/10.1016/j.oceaneng.2016.11.055