Underwater Soft Robotics

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***Abstract*—The purpose of this paper is to provide a comprehensive literature review on underwater soft robotics. Soft robots provide multiple benefits to underwater locomotion by allowing for bio-inspired, flexible, and more organic movement compared to their rigid counterparts. Aquatic animals have been genetically evolving for a very long time and have the most efficient movements in the water. In this literature survey, three main locomotion strategies used by aquatic animals were identified, and ways to duplicate these motions were discussed. Overall, soft robotics displays a promising future for underwater locomotion.**

***Index Terms*—Underwater, Soft, Fishes, Eels, Jellyfish, Squids, Octopuses, Jet Propulsion, Undulation**

I. Introduction

Biological animals have been genetically evolving, making them the best at locomotion in their respective habitats. Robots are being created that duplicate these biological motions to more effectively traverse various terrains. Soft Robotics is a relatively new and rapidly evolving field that utilizes soft components, which allow the robots to bend more naturally, allowing them to effectively duplicate the same motions as their biological counterparts.

The ocean makes up 71% of the Earth's surface, and more than 80% of the ocean is undiscovered [2]. Aquatic robotic systems are increasingly becoming valuable tools for underwater exploration, research, and environmental monitoring. Fig. 1 shows some of the existing underwater robots, which have been divided into 2 categories: rigid and soft robots.

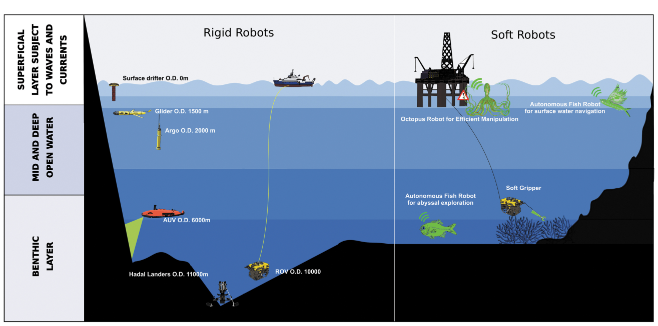

Fig. 1. Example of rigid and soft robots. [1]

Types of rigid robots include surface drifters, gliders, Argo floats, autonomous underwater vehicles (AUV), remotely operated vehicles (ROV), and Hadal Landers [1]. Underwater soft robots are more biomimetic, duplicating the motion of fish, octopus, etc. Currently, most of the robots used in marine applications are rigid [1]; however, there is an increase in research on soft underwater robots.

To better understand how soft robotics is being utilized for underwater applications, this literature survey focuses on bio-inspired underwater locomotion using soft robotics. This survey hopes to answer three main questions:

1) How is soft robotics used with underwater locomotion?
2) What are the advantages and disadvantages of using soft underwater robots?
3) What is the trend in underwater soft robotics?

In the following sections, the results of the literature review will be presented, which will discuss existing underwater locomotion projects that utilize soft robotic actuation. Then, the overarching trends and key takeaways from this research will be discussed.

II. Presentation of Survey Findings

Various research projects related to this topic were surveyed to understand soft robotic locomotion underwater. Interesting papers that used different movements and different ways to create these movements in the water. Based on initial research, most papers on underwater soft robots were inspired by aquatic animals and hence, this paper is broken down into different types of animal movements to traverse the underwater terrain:

1) Jet Propulsion
2) Undulation

A. Jet Propulsion

In nature, some aquatic animals move by rhythmically contracting and relaxing their muscles, causing them to push the water backward, which in turn forces them forward. These motions usually require rapid contractions and slow relaxation of the muscles. These types of motions can be seen in multiple animals, including jellyfish, squids, and octopuses.

1) Jellyfish: Jellyfish have an umbrella-shaped body with tentacles on their underside. They are known to be highly energy efficient, which has led to further research on them [3]. The pulsating bell shape is what causes these animals to swim. Researchers have developed various methods to replicate this motion, including electro-deformation actuation, magnetic field actuation, cardiomyocyte actuation, and visible-light actuation [3].

In electro-deformation actuation, Zhou et al. developed a jellyfish robot using a soft and smart modular structure (SMS), consisting of SMA (shape memory alloy) wires sandwiched between two PCBs and connected by a constant-length PVC plate that acts as a recovery layer [6]. The assembly is encased in PDMS to create a flexible yet durable structure, as shown in Fig. 2.

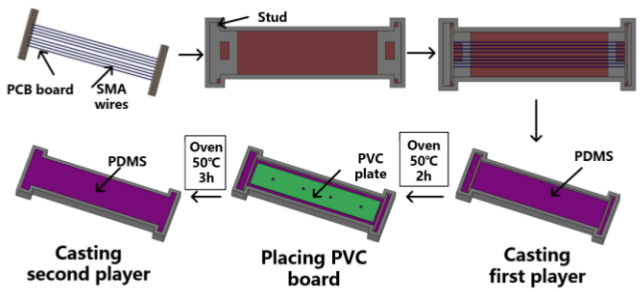

Fig. 2. SMS Fabrication. [6]

Six SMS modules arranged in a hexagonal pattern allow for forward motion, while four of these modules could be used for turning, as shown in Fig. 3 [6].

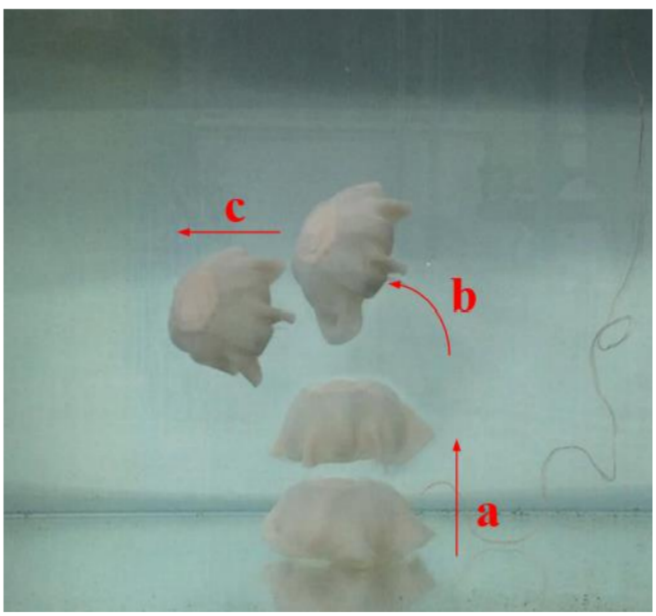

Fig. 3. Robotic jellyfish swimming straight and turning. [6]

For magnetic field actuation, Ren et al. fabricated a jellyfish robot using a magnetic composite elastic core made from soft silicone rubber mixed with neodymium-iron-boron (NdFeB) microparticles [4]. The lappets are driven by an oscillating external magnetic field that causes rhythmic contraction and relaxation, as shown in Fig. 4 [4].

For cardiomyocyte actuation, Nawroth et al. created a jellyfish by engineering a tissue composed of rat cardiac muscle cells (cardiomyocytes) cultured onto a PDMS scaffold, as shown in Fig. 5 [5]. When subjected to an external electric field, the cardiomyocytes contract rhythmically, causing the PDMS body to deform and generate forward propulsion [5].

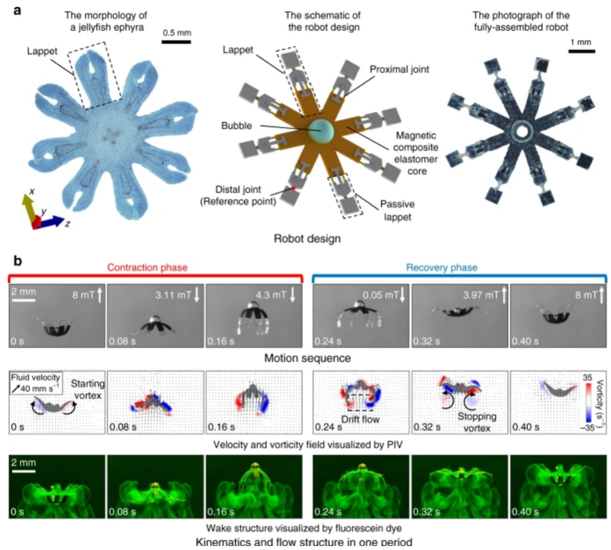

Fig. 4. Robotic jellyfish parts and detailed images of contraction and recovery phase. [4]

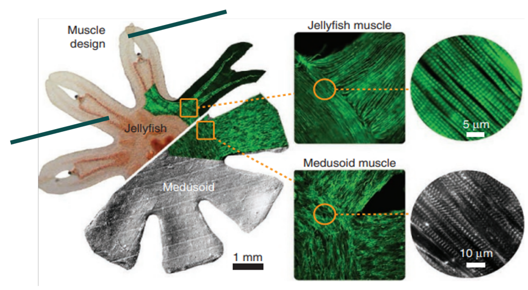

Fig. 5. Robotic jellyfish parts shown with comparison to real jellyfish. [5]

For visible-light actuation, Wei et al. fabricated a jellyfish robot that responds to visible light using a composite material made of a temperature-sensitive hydrogel-poly(N-isopropyl acrylamide) and carbon nanotubes (PNIPAM/CNTs) [3]. Upon exposure to light, the hydrogel bends due to a localized temperature increase, creating a contraction-relaxation cycle that propels the jellyfish forward, as shown in Fig. 6 [3].

Regardless of the fabrication method, the resulting movement generally mimics the natural pulsing motion of jellyfish. By contracting their bell-shaped bodies and expelling water, robotic jellyfish create thrusts to propel themselves forward. The contraction phase generates a high-speed jet of water backward, while the relaxation phase allows the bell to re-expand with minimal resistance, making the movement highly efficient. The fabricated robots are capable of swimming both straight and executing turning maneuvers by selectively activating different sections of their structure, demonstrating controlled and bio-inspired underwater locomotion.

2) Squids: Squids use jet propulsion by rapidly expelling water from their mantle cavity through a funnel-like siphon. They are known for their impressive acceleration and maneuverability in water [7]. The contraction of the mantle muscles forces water out, propelling the squid forward [8].

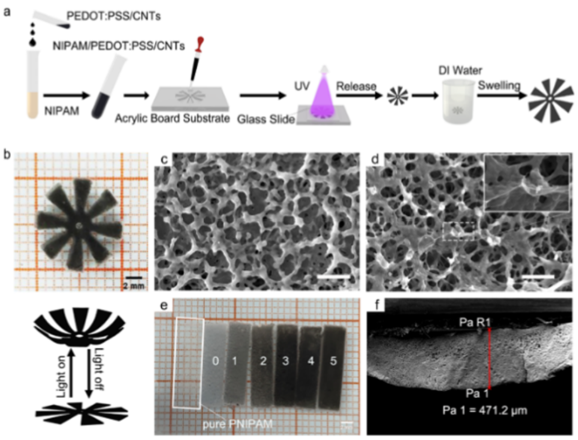

Fig. 6. Fabrication of Light-bending Jellyfish. [3]

The relaxation of mantle muscles causes negative pressure, causing the water to fill the mantle cavity [8]. There are two main untethered ways to replicate this motion: magnetic and origami.

For magnetic actuation, Jiang et al. created a squid robot that uses an electromagnetic-controlled soft diaphragm pump (ECSDP) to create high-pressure jet flow [7]. The ECSDP consists of a magnetic liquid metal (MLM) sphere, a soft body, two valves, and a working fluid called Novec 7000, as seen in Fig. 7 [7]. The MLM was created by mixing Gallium-based alloy with iron (Fe) particles in concentrated hydrochloric acid (HCl) as seen in Fig. 7 [7].

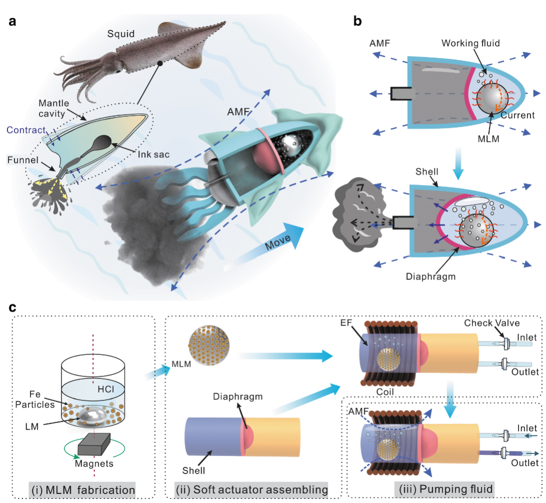

Fig. 7. Fabrication and workings of a robotic squid. [7]

When an external magnetic field is induced, the MLM phase shifts from solid to liquid, expanding in the process and causing a high pressure to be generated [7]. This causes the water to quickly flow out, creating a jet and allowing the robot to move, as seen in Fig. 8 [7]. When the magnetic field is removed, the MLM again turns back into a solid [7].

For origami actuation, Hu et al. created a squid robot that uses a compressible origami body to rhythmically create positive and negative pressures to propel itself forward [8]. It uses a gear, gear rack, and a motor to compress and decompress the origami section, creating cyclical jet propulsion similar to a real squid [8]. The squid robot can be seen in Fig. 9.

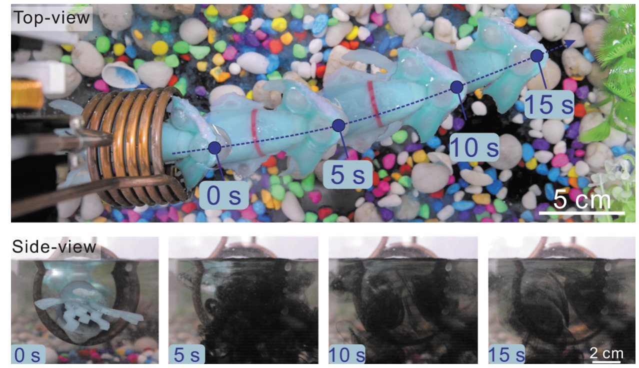

Fig. 8. Movement of a robotic squid under a magnetic field. [7]

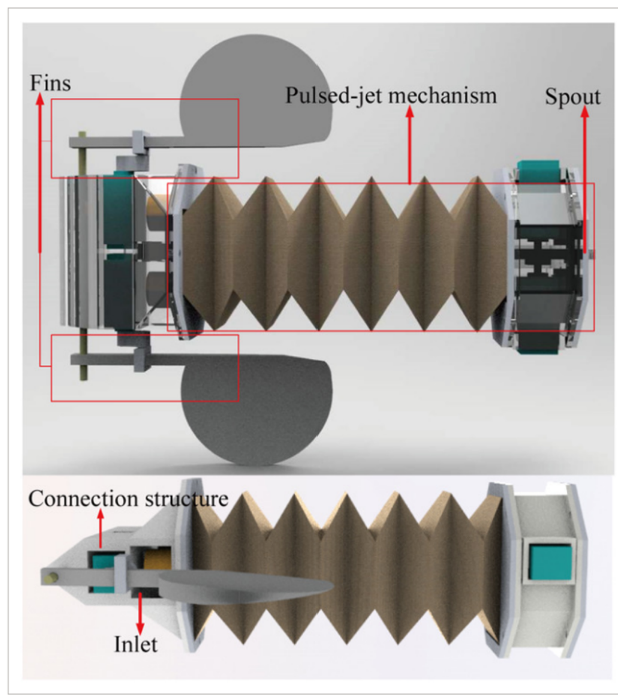

Fig. 9. An origami robotic squid. [8]

In addition to jet propulsion, this robot also uses actuated fins on its sides to enhance maneuverability. By adjusting the angle and movement of the fins, the robot can change its orientation [8].

3) Octopuses: Octopuses also use jet propulsion by forcefully expelling water through a siphon, but they are unique in their extreme flexibility and dexterity due to their entirely soft bodies, lacking any rigid skeleton. This gives them superior maneuverability and the ability to squeeze through small spaces. There are two main ways that octopuses locomote in the water: jet propulsion and crawling.

Arienti et al. created PoseiDRONE, a robotic octopus that was capable of jet propulsion and crawling through tendon-driven actuation [9]. For jet propulsion, the robot uses a motor and a crank to pull and release strings attached to the walls of a silicone chamber, causing the chamber to collapse and inflate alternately and allow short bursts of water to propel the robot forward [9]. For crawling, the robot uses six tentacles, each with its own mechanism to bend and change length [9]. The crawling takes place in sections: the contact phase, where the leg pushes the robot forward, and the aerial phase, where the leg returns to its original position [9]. By strategically moving the individual legs, the robot gets an omnidirectional movement [9]. The PoseiDRONE can be seen in Fig. 10.

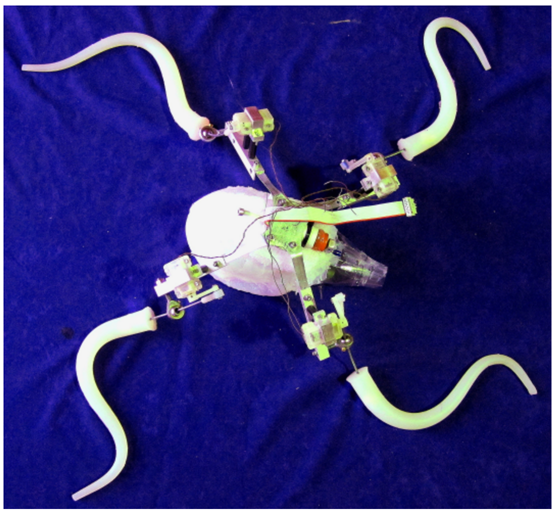

Fig. 10. PoseiDRONE Octopus robot with jet propulsion and crawling. [9]

B. Undulation

Undulatory locomotion uses wave-like movements of the body to generate thrust. This motion is commonly observed in fish and eels. However, other aquatic animals such as dolphins, whales, manatees, and crocodiles also use this traversal method. The main advantage of undulation is its efficiency in low-speed cruising and maneuverability in complex environments. Marine mammals such as dolphins, whales, and manatees have tails that thrust in an upward and downward motion, which not only helps them swim forward but also helps them change depth and surface for breathing. On the other hand, fish and eels have tails that have a sideways motion to swim more easily in the horizontal plane.

There are four different types of undulatory swimming modes: anguilliform, subcarangiform, carangiform, and thunniform [10], as seen in Fig. 11. In anguilliform, almost the entire body undulates and gives the most control and lowest speeds [10]. In subcarangiform, the rear half of the body undulates [10]. In carangiform, the rear third of the body undulates [10]. In thunniform, only the tail moves and gives the highest speeds and the lowest control [10].

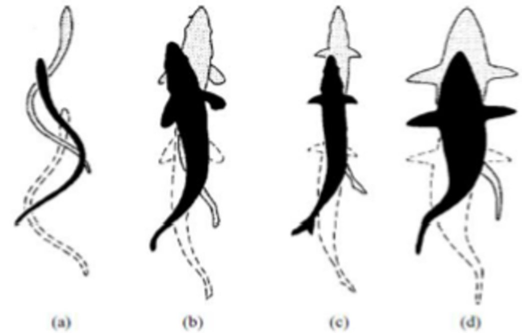

Fig. 11. Different types of Undulatory Swimming Modes. a) Anguilliform b) Subcarangiform c) Carangiform d) Thunniform. [10]

To replicate undulatory motion in soft robots, a variety of actuation methods have been explored. These actuation strategies aim to mimic the wave propagation observed in biological systems. Most research has been done on Tuna fish, which uses thunniform locomotion, swimming at high speeds; however, eels have recently started being researched more due to their high controllability. Some actuation methods include dielectric elastomer actuation (DEAs), fluid elastomer actuators (FEAs), magnetic actuation, and tendon-driven actuation.

Robotic fish using DEAs or FEAs work in a similar way. Two sets of DEAs/FEAs allow the tail to turn in either direction [11], [12]. When voltage (for DEAs) or fluid pressure (for FEAs) is applied, the activated actuator expands, increasing in length [11], [12]. Meanwhile, the non-actuated side remains contracted, causing the tail to bend toward the inactive side [11], [12], as seen in Fig. 12.

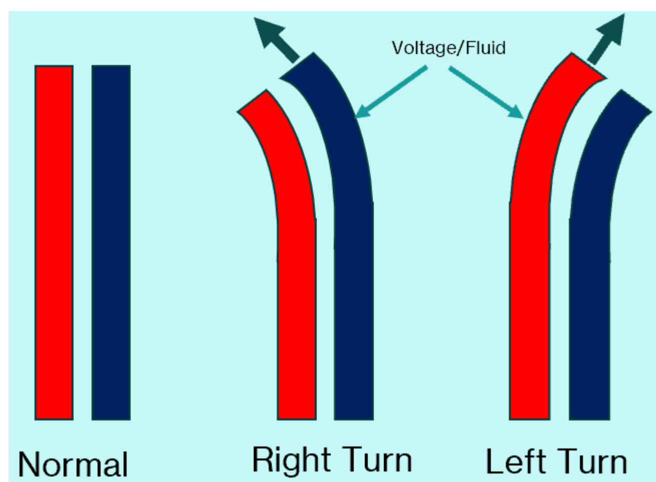

Fig. 12. Actuation of DEAs and FEAs.

Wang et al. developed a robotic fish that uses cylindrical DEAs for linear expansion [11], as shown in Fig. 13. The DEAs were fabricated by pre-stretching VHB film, applying carbon black grease to its surface, and then compressing a spring while winding the film around it to form a cylindrical structure [11].

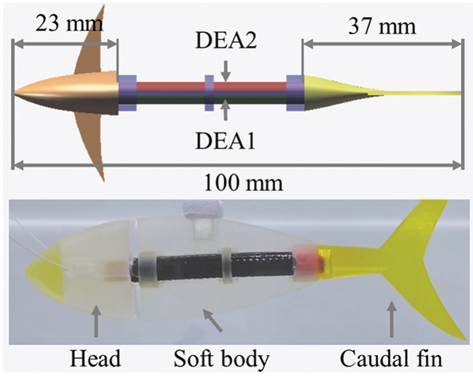

Fig. 13. Robotic fish using DEAs. [11]

Liu et al. developed Flexi-Tuna, a robotic fish that duplicated real fish muscles by using a silicone body with air channels that bend when air is pumped in, making the fish's tail swing back and forth. The soft body around these channels helps the robot move smoothly, as the real fish [12]. The Flexi-Tuna can be seen in Fig. 14.

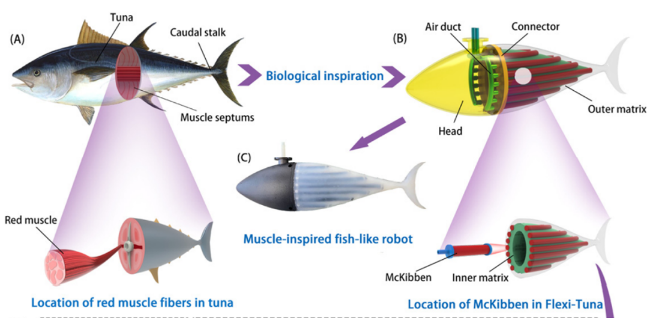

Fig. 14. Robotic fish using FEAs. [12]

For magnetic actuation, Wei et al. created MAGFLE, a robotic Tuna fish that has a permanent magnet fixed on the tail and solenoids on either side [13]. They applied out-of-phase AC currents in the solenoids so that when one solenoid attracted the magnet, the other repelled it [13]. As the current polarity reverses, the forces switch, causing the tail to oscillate back and forth and propel the robot through water [13]. The MAGFLE can be seen in Fig. 15.

For tendon-driven actuation, Hall et al. created a robotic eel that uses a TPU wave-spring body, servos, strings, and spools to convert the rotational movement of the servos into linear motion of the string [14]. The pulley system worked by tensing one side of the eel while relaxing the other side, causing the body to have a one-directional bend [14]. This design allows for highly controllable movements, closely resembling the natural undulatory motion of real eels [14]. The eel can be seen in Fig. 16.

To move to different depths, most fish use one of two main methods: fins and swim bladders.

1) Fins: All fishes, eels, and marine mammals have fins. There are five main types of fins: dorsal, pectoral, caudal,

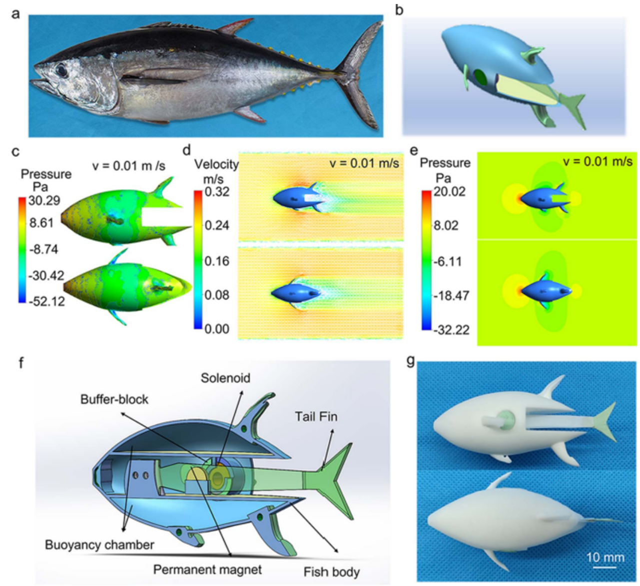

Fig. 15. Robotic fish using magnetic actuator. [13]

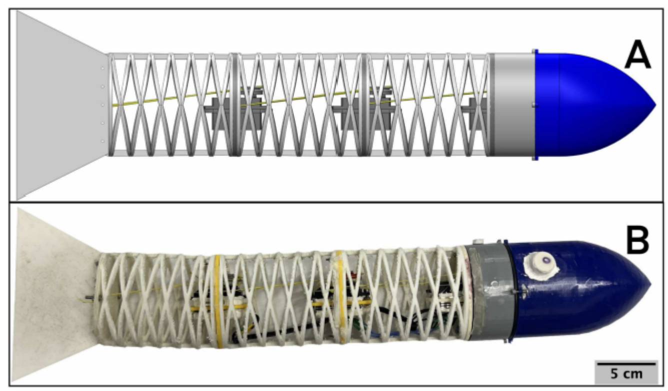

Fig. 16. Robotic eel using tendon-driven actuation. [14]

pelvic, and anal. Dorsal, pelvic, and anal fins are usually passive and help with stability and increase sideways surface area. Caudal fins, located at the tail of the fish, helps to propel the fish forward. Pectoral fins are used for stability, turning, and sometimes depth control.

Zhang et al. created robotic pectoral fins for depth control [15], as seen in Fig. 17. This robot uses two motors connected through a gear system, enabling the fins to articulate up and down. By adjusting the fin angles, the robot can glide to different depths within the water column [15].

2) Swim Bladders: Many fish possess a swim bladder, an internal gas-filled organ that allows them to maintain or adjust their buoyancy. By regulating the amount of gas in the bladder, fish can ascend or descend without needing to constantly expend energy swimming.

Inspired by this biological system, Makrodimitris et al. designed a robotic swim bladder to control depth for underwater robots [16]. They use a DC motor pump to change the volume inside a sealed bladder, thus adjusting the buoyancy

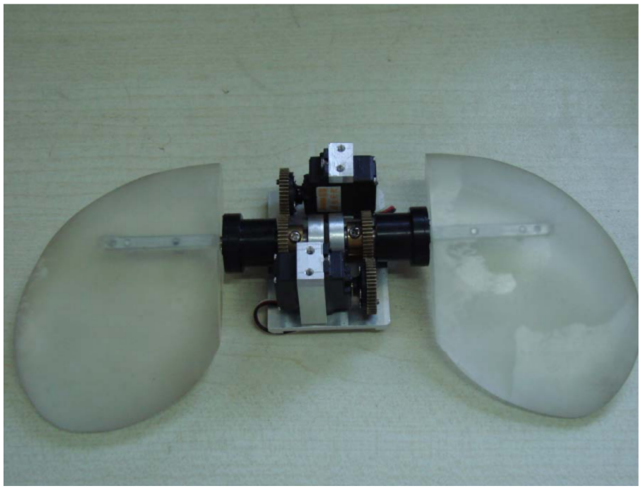

Fig. 17. Robotic Pectoral fins. [15]

dynamically [16], as seen in Fig. 18. This method allows the robot to glide vertically in the water without active propulsion [16].

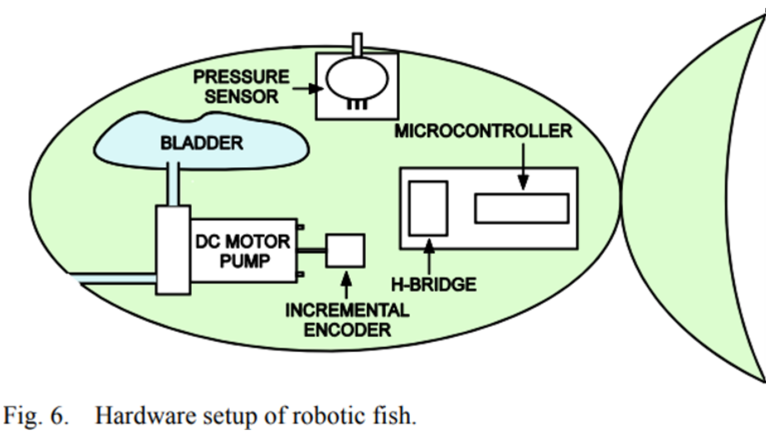

Fig. 18. A robotic fish using a bladder for buoyancy. [16]

III. Discussion

This section is going to cover four topics: gaps in the survey, applications of underwater soft robotics, and future trends in underwater soft robotics.

1) Gaps in the Survey: Throughout the survey of biomimetic underwater robots, several overarching trends and recurring issues were observed. A majority of the projects examined prioritized horizontal locomotion, allowing for two-dimensional movement.

One of the most evident trends is the limited adaptability of many underwater robotic systems. Most are optimized for swimming in open waters rather than navigating cluttered underwater structures such as coral reefs. There is a noticeable lack of designs that aim to replicate the versatility and flexibility of natural anguilliform locomotion, which could provide enhanced maneuverability in these complex environments.

A key challenge consistently seen in the literature survey is the lack of pressure testing in deep-water conditions. Many biomimetic robots are validated in shallow, controlled aquatic environments such as tanks or pools, which do not accurately replicate real-world pressures and environmental variability. This presents a significant gap in understanding how these robots would perform under actual oceanographic constraints, particularly in long-term or deep-sea exploration tasks.

Another issue is the overreliance on tethered systems for control and actuation. While suitable for controlled testing, these tethers significantly reduce the robot's autonomy. Only a few of studies explore the integration of compact, onboard actuation and control systems that would support fully untethered operation and allow for practical deployment in underwater environments.

2) Applications of Underwater Soft Robotics: Potential applications for soft underwater robots include environmental monitoring, biological research, infrastructure inspection, such as underwater pipes, and shipwreck exploration.

3) Current Trends: There has been an increase in soft underwater robots since the 2000s [17]. Researchers have been trying to replicate the speed and agility of animals in their robots, improving them and increasing their applications [17]. This can be seen in Fig. 19.

Fig. 19. A timeline of various soft underwater robots. [17]

4) Future Trends: There are several emerging trends that are shaping the future of underwater soft robotics. One notable development is the rise in research focused on anguilliform robots, which mimic the movement of eels and allow for more controllability, especially in confined or complex underwater environments. This would make them well-suited for tasks such as navigation through coral reefs, pipelines, or shipwrecks.

Another growing trend is the development of multimodal locomotion systems, as shown by robots like PoseiDRONE [9]. These designs aim to combine various movement strategies, such as swimming, crawling, and hovering to increase the usability of the robot in diverse underwater scenarios. Such robots could seamlessly transition between different environments, such as the seafloor and open water.

Untethered and fully autonomous systems are also being focused on. While many current underwater robots rely on external power, there is increasing interest in compact, onboard systems that enable long-range, tetherless operation. Achieving this would significantly enhance the mobility and scalability of underwater missions, especially for deep-sea or hazardous environments.

IV. Conclusion

Soft robotics presents a promising path forward in underwater locomotion by enabling the development of bio-inspired systems that closely mimic the efficient, adaptive, and flexible movements found in aquatic animals. This literature review explored various soft robotic implementations based on jet propulsion and undulation, each inspired by the mechanics of creatures such as jellyfish, squids, and eels. These studies demonstrated a wide range of actuation methods, including electro-deformation, magnetic fields, cardiomyocyte tissue, and smart materials responsive to light or temperature.

Compared to rigid robots, soft robots offer improved maneuverability, reduced environmental disturbance, and enhanced adaptability to complex and unstructured underwater environments. However, challenges remain in terms of durability, output precision, power efficiency, and integration of untethered systems.

Continued interdisciplinary research will be essential to overcome current limitations and allow for applications in marine exploration, environmental monitoring, and biomedical studies. As this field matures, soft robots may become indispensable tools for exploring the mysteries of the deep sea.

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