Design Strategies for Flexible Skeletons of Underwater Bionic Robots

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Abstract. Underwater bionic robots, by mimicking the efficient promotion mechanism of aquatic animals, have significantly overcome the mobility and noise limitations of the traditional rigid submersibles, which demonstrate unique value in resource exploration and ecological monitoring. As the core carrier for realizing the bionic implementation, the flexible skeleton not only determines the efficiency of the transmission between deformation and driving force but also directly relates to the degree of integration of structure, perception, and actuation. This paper focuses on flexible skeletons, first systematically outlining two major technical routes: purely soft continuous skeletons and hinge-hybrid joint skeletons. Based on this, it proposes a third, entirely new technical route: an integrated smart material skeleton. Subsequently, popular examples were selected and analyzed in accordance with the above routes and methods to evaluate their performance. Ultimately, the key challenges currently faced in terms of collaboration, environmental tolerance, and large-scale manufacturing are summarized. Furthermore, targeted improvement strategies are proposed, including multi-material hybrid printing, gradient stiffness topology, and distributed intelligent material-driven systems, with a vision for the next generation of flexible skeletons where structure is the actuation mechanism and the skeleton is the sensing mechanism.

Keywords: Flexible skeleton; purely soft skeleton; hinge-hybrid joint skeleton; integrated smart material skeleton

1 Introduction

Research on underwater bionic robots originated from the urgent need for efficient, highly maneuverable, and low-disturbance underwater platforms in fields such as marine resource exploration, ecological environment monitoring, and national defense security. Inspired by the movement mechanisms of aquatic organisms in nature, bionics offers a novel approach to overcoming the limitations of traditional propeller-based propulsion systems in terms of efficiency, noise, and maneuverability [1-3]. Compared to traditional underwater robots composed of rigid structures and joints, flexible soft robots demonstrate significant advantages through their continuously variable forms. The undulating or flapping propulsion generated by their flexible bodies more closely mimics the essence of biological movement, offering high

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energy efficiency and enabling rapid acceleration, agile maneuvering, and near-silent cruising [4,5]. Its soft characteristics significantly reduce disturbance to sensitive underwater ecosystems while enhancing safety and passive adaptability during interactions with the external environment [6]. In this bionic system, the flexible skeleton occupies a central position. Serving as the robot's core force transmission and load-bearing structure, it directly determines the morphological characteristics of motion, propulsion efficiency, and environmental adaptability.

This paper focuses on the flexible skeleton—a core component of underwater bionic robots. By systematically categorizing and summarizing three major technical approaches—pure soft continuous skeletons, flexible hinge hybrid skeletons, and smart material integrated skeletons—and combining comparative analyses of bionic jellyfish and bionic fish cases, it aims to provide theoretical references for the design innovation and performance optimization of flexible skeletons, thereby outlining their future technological development pathways.

2 Three Technical Links of the Flexible Skeleton

2.1 Purely Soft Continuous Skeleton

The purely soft continuous skeleton integrates “load-bearing, force transmission, and deformation” within a seamless polymer body, completely eliminating joints, hinges, and rigid linkages.

Hareesh Godaba et al. developed a soft jellyfish robot actuated by a dielectric elastomer actuator. Its core structure comprises a 3D-printed ABS bell-shaped shell, an internal PVC air chamber, and three slender ABS beams. The actuator was fabricated from VHB elastomer film, which was uniformly pre-stretched in all directions, secured over the air chamber opening, and subsequently inflated to form an electrically controllable artificial muscle. When high voltage is applied, the film area expands, increasing the volume of the air chamber and simultaneously generating two driving forces: thrust produced by the jet flow and buoyancy changes resulting from variations in displacement. The bionic robotic design enables efficient vertical movement in water, demonstrating rapid responsiveness and high payload capacity, thereby validating the feasibility of dielectric elastomer actuators for soft underwater robotic applications [7].

Caleb Christianson and his colleagues investigated and developed a bio-inspired soft jellyfish robot. Its key innovation lies in the adoption of a fluid electrode dielectric elastomer actuator, which enabled a completely soft-bodied structure devoid of rigid components. The robot's "skeleton" is composed of eight symmetrically arranged bending actuators. Each actuator features a four-layer laminated design: an active dielectric elastomer layer, an internal fluid electrode, a passive dielectric elastomer layer, and a flexible backing that serves as a strain-limiting layer. Through a unique fabrication process, the inherent curvature of the backing layer itself is utilized to impart a slight pre-strain to the actuator, thereby eliminating the need for the rigid frames traditionally required for dielectric elastomer materials. Experimental results demonstrate that this design successfully achieved cordless swimming, with an average speed of 3.2 mm/s. This outcome confirms that the proposed actuation and fabrication strategy, based on fluid electrodes and a rigid-free skeleton, represents a viable pathway for realizing soft-bodied underwater robots with low power consumption and silent operation [8].

2.2 Hinge-hybrid Joint Skeleton

Articulated hinge-hybrid joint skeletons have seen the most rapid progress and come closest to practical application in underwater bionic robotics over the past five years. By alternately arranging “rigid links + flexible joints,” they replace large deformations of purely soft structures with predictable elastic deformation, balancing support, force transmission, and controllability.

Kunhui Luo et al. presented a biomimetic jellyfish robot employing a link-bar structural mechanism, with a focus on the design, optimization, and fabrication of its skeletal framework. By integrating multibody dynamics simulations (ADAMS) with optimization tools (ISIGHT), a multi-objective optimization process was conducted on the linkage geometry—including key point coordinates and link lengths—to maximize the tentacle oscillation amplitude while minimizing power consumption. The optimized design achieved a tentacle oscillation angle of 42.44°. For the structural fabrication, 3D printing was utilized to produce custom enclosures and support components, incorporating integrated linear guides to improve motion stability. The effects of tentacle geometry—including length, width, shape, and thickness—on propulsion performance were investigated via computational fluid dynamics (CFD) analysis. This process identified the optimal tentacle parameters as a total length of 320 mm and a thickness of 1.5 mm when fabricated from TPU material. Experimental results validated a maximum acceleration of 1.86 m/s^2 and an instantaneous thrust of approximately 4.66 N [9].

Chenyuan Dong et al. developed a bionic robotic fish tail actuated by PVC gel, focusing on the design and fabrication of a multi-jointed skeletal structure. The skeleton consists of six 3D-printed rigid links interconnected by hinged pins, forming a biomimetic spine with six degrees of freedom. Arrays of layered PVC gel actuators, serving as artificial muscles, are symmetrically arranged on both sides of the spine. Their alternating actuation induces bilateral bending in the hinge joints, thereby mimicking the body waveform characteristic of fish swimming. During the design and manufacturing phase, the target curvature and rotation angle for each joint were determined based on the fish body wave equation, and custom-sized actuators were fabricated accordingly. Preload plates and pin assemblies were employed to ensure firm contact and apply precompression between the actuators and joints, resulting in a stable "muscle-skeleton" hinge system. Experimental validation on land demonstrated that the resonant hinged tail skeleton achieves a maximum swing amplitude of 70 mm at 2 Hz. In underwater tests, it maintained a swing amplitude of 26 mm and generated a maximum oscillation force of 1.17 N at an operating frequency of 1.5 Hz [10].

2.3 Integrated Smart Material Skeleton

Integrated smart material Skeleton (Structure-Actuation-Sensing Integrated Skeleton) refers to the direct incorporation of stimulus-responsive smart materials into load-bearing components. This enables them to simultaneously handle mechanical loads while performing actuation and sensing functions, thereby eliminating the need for traditional separate “motor-transmission-sensor” assemblies.

In 2021, researchers from the Max Planck Institute for Intelligent Systems and others achieved the first complete integration of “actuator-sensor-structure” triple functions within a single flexible skeleton: a 0.5 mm plastic sheet serves as the longitudinal load-bearing substrate, symmetrically coated on both sides with silicone fast-PneuNet pneumatic muscles, while the outer wall is fully embedded with an eGaIn microchannel strain sensor layer. By antagonistically inflating and deflating to dynamically adjust local stiffness while simultaneously outputting real-time bending feedback from a liquid metal layer, it achieved closed-loop swimming control without rigid joints, providing a complete paradigm for integrated intelligent material underwater bionic skeletons [11].

This study presents a sophisticated integrated structural and actuation system for a smart material-based robot, achieved through the lamination of a dielectric elastomer actuator (DEA) with a PET rigid frame in a skeleton design and fabrication process. Specifically, a pre-stretched DEA film is employed as the active actuation layer, directly sandwiched between a customized PET main frame and reinforcement frame. This design allows the film to function both as a bending deformation source and as the flexible joint structure at the core of the robotic limb. The 3D-printed hemispherical body and PET foot serve as auxiliary rigid skeletons, collectively forming the complete robotic body integrated with the actuator. This integrated design effectively eliminates the boundaries between independent motors, transmission mechanisms, and skeletons that are typically found in traditional robots, seamlessly merging the driving function of the smart material DEA with the mechanical structure of the robot. Research findings, validated through hydrodynamic modeling and computational fluid dynamics (CFD) simulation optimization, reveal that this integrated skeleton achieves peak propulsion efficiency of 27.6% at a foot vertex angle of 120°. This demonstrates the performance advantages of the structural framework and highlights the potential for further enhancing the overall efficiency of smart material-driven systems through geometric optimization.

Despite the innovative potential of integrated exoskeletons, they currently face several significant challenges that impede their widespread application. In terms of driving performance, the materials used often exhibit a fundamental trade-off between limited output force and slow response times, which severely restricts their ability to support high-speed, highly maneuverable movements. Regarding energy efficiency, the low energy density of these materials and their high-energy-consumption drive modes significantly limit the endurance of robots, making prolonged operations impractical.

In system integration, mismatches between soft and hard components, as well as issues related to environmental aging, directly impact the overall system reliability and lifespan. At the modeling and control level, the strong nonlinearity of the materials and the immaturity of perception-feedback systems result in insufficient control precision, which limits the autonomy of these robots in complex environments.

These bottlenecks collectively hinder the transition of this technology from laboratory research to practical deep-sea applications. Therefore, while the integrated smart material flexible skeleton represents a novel paradigm for miniaturized, tetherless underwater robots, it is still necessary to complement it with fluid-driven systems and rigid frameworks for missions that require heavy loads, high speeds, or long durations.

2.4 Comparison of Technical Approaches

In the field of soft robotics structural design, the choice of skeleton solution directly determines the system's motion flexibility, mechanical strength, manufacturing complexity, and integration level. The radar chart shown in Fig.1 quantitatively compares three mainstream skeleton solutions across four dimensions: “flexibility,” “strength,” “manufacturing ease,” and “response speed.” It is evident that pure soft continuous skeletons exhibit optimal flexibility, enabling substantial deformation and smooth motion transitions, making them inherently suited for complex environments. However, lacking rigid support, they possess the lowest load-bearing capacity and are prone to fatigue damage under repeated loading. Although their fabrication requires only one-step molding or printing, it demands highly homogeneous materials, making consistency in mass production difficult to guarantee. The hinged hybrid rigid-flexible skeleton, featuring segmented connections between discrete hinges and elastomers, significantly outperforms in strength. It can withstand higher external loads while maintaining dimensional accuracy. However, the introduction of rigid structures inevitably sacrifices some flexibility. Stress concentrations may occur under extreme bending or twisting conditions, and issues like sealing, lubrication, and wear increase system complexity.

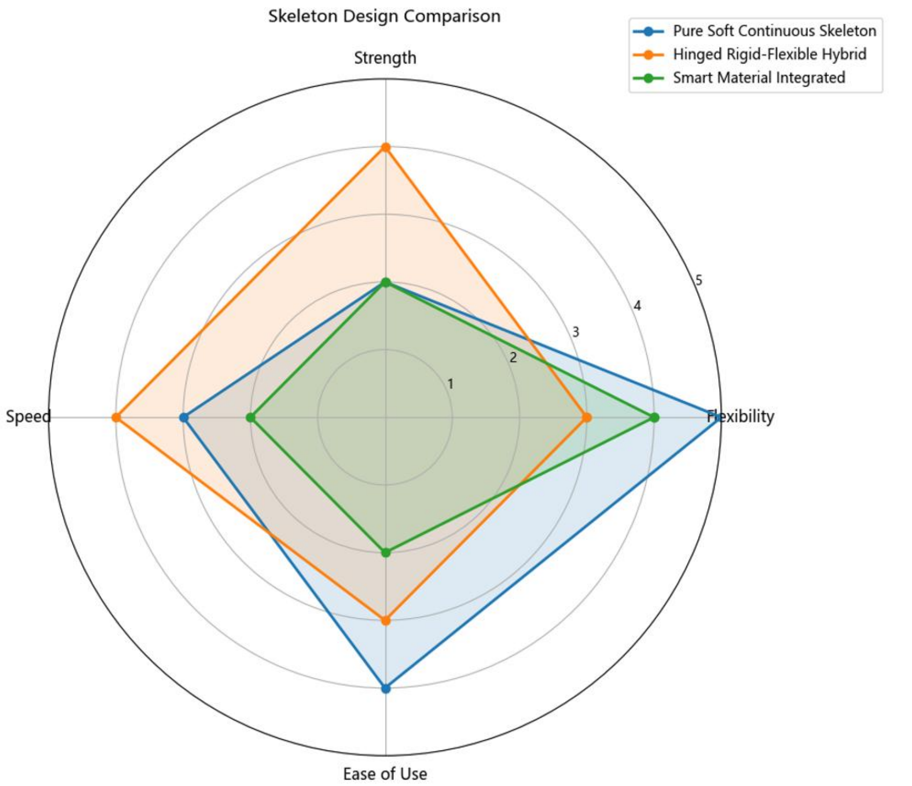

Fig. 1. Performance Comparison of Framework Solutions

In contrast, the smart material integrated skeleton did not achieve a single leading score across all four metrics: its strength is constrained by the mechanical properties of currently achievable materials; while its flexibility surpasses that of hinge-based solutions, it falls slightly short of purely soft continuous structures due to challenges in embedding the drive-sensing layer; the manufacturing process requires simultaneous consideration of material synthesis, multi-layer interface bonding, and electrical interconnections, significantly increasing complexity and resulting in the lowest scores for “ease” and “speed.” However, its greatest advantage lies in the deep integration of function and structure: drive, sensing, energy harvesting, and thermal control networks can be formed in a single step, eliminating the traditional sequential assembly of “mechanics first, electronics later.” This theoretically reduces system mass and volume while completely eliminating cable drag and interface failure risks. With breakthroughs in programmable liquid crystal elastomers, two-dimensional material-reinforced hydrogels, and micro/nano 3D printing, integrated smart material skeletons hold promise for synergistic optimization of composition, structure, and performance. This approach simultaneously enhances strength and flexibility while maintaining high integration, thereby addressing bottlenecks like lightweighting, miniaturization, and cable-free operation in a single step. Such skeletons are poised to become the core carriers for next generation soft robots.

3 Morpho-Functional Validation: Classic Examples

3.1 Bionic Jellyfish Robot

Within the skeletal design framework of biomimetic jellyfish robots, “continuum” and “articulated” approaches have evolved into two complementary paradigms: The former treats the bell-shaped canopy as a single elastic membrane. Through the synergistic layering of radial fibers and circumferential membranes, it transforms “contraction-expansion” motion into continuous surface deformation—where fibers endure tension and the matrix undergoes shear. In this design, the skeleton serves as the muscle, and the muscle acts as the shell. This seamless integration eliminates rigid points and assembly gaps, thereby achieving ecologically friendly and low-disturbance performance. In contrast, another approach deconstructs the canopy into radial petal units, with flexible hinges embedded at their bases or peripheries. This design allows rigid petals to rapidly close within limited angles, replicating the rapid flagellating motion of jellyfish through a “hinge-linkage” mechanism. This approach retains the high thrust advantage of traditional linkages while creating cavities for embedding circuits and sensors, thereby enhancing the overall functionality and integration of the system.

Continuous Skeleton Case. Pawandeep Singh Matharu and colleagues investigated a soft robotic jellyfish named Jelly-Z, whose core innovation lies in employing a purely soft continuous skeleton structure to achieve movement patterns mimicking real organisms. The robot's main body is molded from silicone (Ecoflex 00-10) into a flexible bell-shaped structure. Its propulsion utilizes novel spiral-wound polymer muscles (TCPFL), which contract via the Joule heating effect. These muscles are directly embedded along the silicone bell's periphery as actuators. Extremely thin 0.2mm spring steel plates are also implanted internally to assist TCPFL in achieving rebound extension, thereby optimizing propulsion performance. Experimental results demonstrate that Jelly-Z achieves vertical underwater swimming at a maximum speed of 7.3 mm/s, while offering quiet operation and concealed actuation. This design integrates propulsion, support, and locomotion into a unified structure, eliminating the need for conventional motors or rigid transmission components. It forms a complete, self-contracting and expanding continuous soft skeletal system [12].

Hinge-Type Skeleton Case. Kunhui Luo et al. designed a biomimetic jellyfish robot based on a linkage-hinge structure. Its skeletal core consists of a multi-link mechanism. A crank-rocker mechanism driven by a worm gear reduction motor causes the drive plate to flap up and down, generating propulsive force. Power is transmitted from the drive plate to the outer edge of the robot's "head" through a series of articulated connecting rods. This ultimately drives the tentacle structure, hinged to the head, to perform periodic opening and closing oscillations, mimicking the movement patterns of real organisms. To address the challenges of complex support structures and high manufacturing difficulty for the robot's non-standard shell, the team employed 3D printing technology using high-performance TPU material, effectively meeting structural strength and durability requirements. Experimental results demonstrate the biomimetic jellyfish achieves a maximum acceleration of 1.86 mm/s^2 and instantaneous thrust of 4.66 N. The institute's hybrid rigid-flexible skeleton design balances the robot's motion requirements with structural flexibility while maintaining structural simplicity [13].

3.2 Bionic Fish Robot

The current design of bionic fish robot skeletons is advancing along two parallel paths. The articulated approach centers on a multi-jointed metal or rigid plastic spine, with each segment independently equipped with motors, shape memory alloys, or soft actuators. This enables segment-by-segment deformation, generating traveling waves within milliseconds while delivering both high thrust and rapid steering capabilities. The other continuum approach abandons rigid joints, utilizing a single superelastic nylon or silicone spine embedded with filamentary shape memory alloys or biomimetic tendons on both sides. Through distributed contraction and pulling, it achieves smooth S-shaped deformation. This skeleton operates with fluidity and silence, exhibiting superior safety and environmental compatibility in complex aquatic environments.

Continuous Skeleton Case. Research by Keisuke Igushi et al. proposes a bionic fish robot based on direct continuum actuation. Its skeletal core consists of a flexible pure soft body, internally embedded with a thin carbon fiber-reinforced polymer sheet. This structure is then molded with silicone rubber material, forming a bionic fish body that combines flexibility with structural strength. This skeleton is directly driven by a high-torque brushless DC motor, eliminating traditional transmission components like linkages. This design transforms the skeleton into an integrated flexible oscillator. It not only exhibits high mechanical robustness to withstand external impacts but also achieves efficient fish-like undulating motion through fluid-structure interaction with surrounding water. This interaction excites resonant modes during direct motor oscillation. Experiments demonstrate the robotic fish achieves a maximum speed of 2.6 m/s, with peak thrust occurring during sinusoidal waveforms [14].

Hinge-Type Skeleton Case. Qinyuan Ren et al. investigated a bionic fish robot based on a multi-jointed hinge skeleton. The skeleton consists of rigid linkages and rotational joints, driven by servo motors to coordinate the oscillatory motion of multiple tail segments. This mechanism mimics fundamental swimming patterns of jackfish, including cruising and C-shaped sharp turns. The study focuses on extracting joint motion trajectories from real carp swimming videos as training samples through biomimetic learning methods. A generalized internal model (GIM) simulating a central pattern generator is employed for learning and motion generation. This GIM model, utilizing an internal oscillator and artificial neural network, can learn and reproduce coordinated body undulations while exhibiting both temporal and spatial scaling properties. Experimental results demonstrate that adjusting temporal parameters and spatial amplitude parameters effectively generates realistic fish swimming patterns while enabling smooth control over swimming speed and turning angles [15].

4 Technical Challenges and Future Development

4.1 Current Technical Challenges

Flexible robots currently face multiple technical bottlenecks in practical applications. At the material level, existing systems struggle to achieve both high elastic modulus and high toughness within the same substrate, let alone simultaneously meet requirements for fatigue resistance, corrosion resistance, and mass-production feasibility. This results in rapid structural degradation after repeated large deformations, limiting reliable service life. In modeling and control dimensions, flexible bodies exhibit strong geometric nonlinearity, with coupled fields evolving dynamically in real time. Traditional rigid-body assumptions fail, necessitating higher-order nonlinear partial differential equations and distributed parameter system identification. This causes computational complexity to increase exponentially, making millisecond-level real-time feedback unfeasible. In the energy and actuation domain, mainstream soft actuators rely on low-energy-density materials or fluid transmission, resulting in specific power far below that of biological muscles. Actuation pressure and strain rate mutually constrain each other, while insufficient force density prevents robots from carrying loads exceeding their own weight. Operational endurance is also limited by the volume and mass of energy storage units. Regarding system integration, sensing, actuation, energy storage, and computing modules still employ a separated architecture. The mechanical-electrical interfaces between flexible segments and rigid electronic islands introduce additional redundancy, resulting in bulky systems with reduced payload ratios. This makes it difficult to achieve high functional integration within confined spaces. These bottlenecks form a coupled “material-structure-control-energy” closed-loop constraint, severely hindering the transition of flexible robots from laboratory prototypes to large-scale applications.

4.2 Future Development

The development of flexible skeletons for underwater bionic robots will transcend current mainstream passive flexible or rigid hinge designs, evolving toward higher-order forms that integrate smart materials. The core improvements lie in: First, the deep integration of materials and actuation. Future skeletons will no longer be isolated force-transferring or load-bearing structures but will be composed of more advanced smart materials. This achieves a fundamental shift from “actuator-driven skeletons” to “skeletons as actuators”, significantly simplifying structures while enhancing energy efficiency and motion realism. Second, controllable stiffness and dynamic adaptability are achieved through biomimetic principles designing gradient stiffness or developing variable-stiffness materials—such as composites based on low-melting-point alloys and magnetorheological elastomers. This enables the skeleton to maintain rigidity during high-speed traversal to minimize energy loss while locally softening during sharp turns or narrow-gap traversal to enhance maneuverability and safety. Finally, embedded sensing and closed-loop control involve integrating flexible sensors—such as liquid metal circuits and optical fibers—directly into the skeleton. These sensors continuously monitor deformation, stress, and surrounding flow pressures, forming an integrated “perception-decision-actuation” intelligent closed-loop system. This enables the robot to sense water current changes and autonomously adjust its swimming posture like a living organism, ultimately achieving efficient, adaptive, and long-endurance operations in complex dynamic environments.

5 Conclusion

Three distinct and complementary design approaches have emerged for flexible skeletons in underwater bionic robots: purely soft continuous skeletons excelling in passive compliance, flexible hinge skeletons balancing load capacity and controllability, and smart material integrated skeletons pursuing ultimate structural-functional integration. Each exhibits distinct advantages and limitations, demonstrating varying potential in natural motion biomimicry, drive efficiency and structural strength, as well as system integration and response speed. Analysis of representative cases like biomimetic jellyfish and fish reveals that current research has achieved remarkable motion performance. However, common challenges persist, including insufficient energy density, ineffective formation of drive-sensing-control closed loops, and limited adaptive capabilities in complex flow fields. Looking ahead, future advancements in this field will transcend mere optimization of existing models, advancing toward a paradigm of deep integration centered on “smart material integration”. Future flexible skeletons will evolve beyond simple load-bearing or transmission structures into “intelligent skeletal systems” featuring dynamically adjustable stiffness, embedded sensing capabilities, and autonomous decision-making. This evolution will ultimately propel underwater biomimetic robots from basic motion mimicry toward true environmental adaptability and autonomous intelligence.

References

[1]. Jaya, A.S., Kartidjo, M.W.: Thrust and efficiency enhancement scheme of the fin propulsion of the biomimetic autonomous underwater vehicle model in low-speed flow regime. Ocean Engineering 243, 110090 (2022)

[2]. Marcin, M., Adam, S., Jerzy, Z., et al.: Fish-like shaped robot for underwater surveillance and reconnaissance–Hull design and study of drag and noise. Ocean Engineering 217, 107889 (2020)

[3]. Hou, Z., Luo, Y., Bao, T., et al.: Propulsion performance of a cownose ray inspired robotic fish flapping pectoral fins near the ground. Ocean Engineering 311, 119008 (2024)

[4]. Marchese, A.D., Onal, C.D.: Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators. Soft Robotics (2014)

[5]. Kyle, D.J.T., Oikonomou, A., Hill, E., et al.: Fabrication and modelling of fractal, biomimetic, micro and nano-topographical surfaces. Bioinspiration & Biomimetics 11(4), 046009 (2016)

[6]. Lu, P., Dong, B., Gao, X., et al.: Variable-Stiffness Underwater Robotic Systems: A Review. Journal of Marine Science and Engineering 13(9), 1805 (2025)

[7]. Godaba, H., Li, J., Wang, Y., et al.: A soft jellyfish robot driven by a dielectric elastomer actuator. IEEE Robotics and Automation Letters 1(2), 624–631 (2016)

[8]. Christianson, C., Bayag, C., Li, G., et al.: Jellyfish-inspired soft robot driven by fluid electrode dielectric organic robotic actuators. Frontiers in Robotics and AI 6, 126 (2019)

[9]. Luo, K., Yan, L., Zhu, Z., et al.: Design and optimization of a bionic jellyfish robot for enhanced underwater propulsion efficiency. Ocean Engineering 340, 122414 (2025)

[10]. Dong, C., Zhu, Z., Li, Z., et al.: Design of fishtail structure based on oscillating mechanisms using PVC gel actuators. Sensors and Actuators A: Physical 341, 113588 (2022)

[11]. Lin, Y.H., Siddall, R., Schwab, F., et al.: Modeling and control of a soft robotic fish with integrated soft sensing. Advanced Intelligent Systems 5(4), 2000244 (2023)
[12]. Matharu, P.S., Gong, P., Guntaka, K.P.R., et al.: Jelly-Z: swimming performance and analysis of twisted and coiled polymer (TCP) actuated jellyfish soft robot. Scientific Reports 13(1), 11086 (2023)
[13]. Luo, K., Yan, L., Zhu, Z., et al.: Design and optimization of a bionic jellyfish robot for enhanced underwater propulsion efficiency. Ocean Engineering 340, 122414 (2025)
[14]. Iguchi, K., Shimooka, T., Uchikai, S., et al.: Agile robotic fish based on direct drive of continuum body. npj Robotics 2(1), 7 (2024)
[15]. Ren, Q., Xu, J., Fan, L., et al.: A GIM-based biomimetic learning approach for motion generation of a multi-joint robotic fish. Journal of Bionic Engineering 10(4), 423–433 (2013)