

Review

Variable-Stiffness Underwater Robotic Systems: A Review

Peiwen Lu ¹, Busheng Dong ¹, Xiang Gao ¹ , Fujian Zhang ¹, Yunyun Song ¹, Zhen Liu ² and Zhongqiang Zhang ^{1,*}

- ¹ Institute of Intelligent Flexible Mechatronics, Jiangsu University, Zhenjiang 212013, China; lpw1255961462@163.com (P.L.); dongbusheng2000@163.com (B.D.); 2112203012@stmail.ujs.edu.cn (X.G.); zhangfj@ujs.edu.cn (F.Z.); songyunyun@ujs.edu.cn (Y.S.)
- ² School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang 212003, China; liuzhen@just.edu.cn
- * Correspondence: zhangzq@ujs.edu.cn

Abstract

Oceans, which cover more than 70% of Earth's surface, are home to vast biological and mineral resources. Deep-sea exploration encounters significant challenges due to harsh environmental factors, including low temperatures, high pressure, and complex hydrodynamic forces. These constraints have led to the widespread use of underwater robots as essential tools for deep-sea resource exploration and exploitation. Conventional underwater robots, whether rigid with fixed stiffness or fully flexible, fail to achieve the propulsion efficiency observed in biological fish. To overcome this limitation, researchers have developed adjustable stiffness mechanisms for robotic fish designs. This innovation strikes a balance between structural rigidity for stability and flexible adaptability to dynamic environments. By dynamically adjusting localized stiffness, these bio-inspired robots can alter their mechanical properties in real time. This capability improves propulsion efficiency, energy utilization, and resilience to external disturbances during operation. This paper begins by reviewing the evolution of underwater robots, from fixed-stiffness systems to adjustable-stiffness designs. Next, existing methods for stiffness adjustment are categorized into two approaches: offline component replacement and online real-time adaptation. The principles, implementation strategies, and comparative advantages of each approach are then analyzed. Finally, we identify the current challenges in adjustable-stiffness underwater robotics and propose future directions, such as advancements in intelligent sensing, autonomous stiffness adaptation, and enhanced performance in extreme environments.

Keywords: underwater robot; soft–rigid hybrid robotics; variable stiffness; propulsion efficiency



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1. Introduction

Driven by economic and technological advancements, humanity's demand for natural resources has surged. As terrestrial resources diminish [1,2], attention has shifted to the oceans, which cover 70.8% of Earth's surface [3]. The seas harbor vast biological [4–10] and mineral reserves [11,12], with rare-earth metal deposits estimated to be five times greater than those on land. Additionally, marine biological resources hold immense untapped potential for the pharmaceutical and food industries [13–16], making oceanic exploration and exploitation critical for sustainable development. However, deep-sea exploration faces formidable challenges due to extreme conditions, including low temperatures, high pressure, and complex hydrodynamic forces. To date, only 5% of the ocean floor has been explored.

Advances in robotics have revolutionized underwater exploration technologies [17], offering robust tools for marine research [18,19]. State-of-the-art autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) are predominantly constructed from rigid materials. These systems rely on precise transmission mechanisms to control a limited number of degrees of freedom (DOF), enabling rotational or translational joint movements. Equipped with robotic arms, AUVs and ROVs—collectively termed unmanned underwater vehicles (UUVs)—perform specialized tasks such as pipeline inspection [20,21], sample collection [22–26], and environmental monitoring [27–32]. Despite their structural stability, rigid materials' high stiffness limits their adaptability. Traditional rigid robots risk harming marine life during contact and struggle to maneuver in confined underwater spaces due to inflexible transmission and control systems [33]. Breakthroughs in biomimetics [34–38], underwater testing platforms [39–43], and computational tools [44–48] have deepened insights into aquatic locomotion, spurring rapid innovation in underwater robotics [49–52]. To meet growing demands for adaptability, researchers have introduced flexible elements, leading to the emergence of soft underwater robots. The International Robot Federation defines soft robots as either devices made of compliant elastic materials or hybrid systems combining rigid components with soft robotic deformation capabilities. Soft robots, often inspired by marine organisms [53–56], utilize hyperelastic materials to achieve near-infinite degrees of freedom [57], overcoming the rigidity and limited flexibility of conventional designs. While rigid robots excel in structural robustness, soft robots adapt seamlessly to dynamic environments. Their flexible structures efficiently absorb and release mechanical energy, enabling bio-inspired soft robots to operate with significantly lower energy consumption per unit of thrust compared to rigid counterparts [58]. To merge the strengths of both approaches, scientists are developing hybrid rigid–soft robots. These systems integrate rigid frameworks for stability and precise motion control with flexible components that enable deformation and environmental adaptability [59]. Critically, this flexibility can be dynamically optimized through stiffness modulation—the real-time adjustment of material resistance to deformation—allowing the same structure to switch between high-compliance modes for safe interaction and high-rigidity states for high-speed movement. The hybrid design enhances operational safety by minimizing harm to delicate marine ecosystems while ensuring resilience to physical impacts [60]. While hybrid rigid–soft underwater robots have improved environmental adaptability through combined rigid and flexible components, their constant stiffness remains a fundamental limitation [59]. These systems cannot dynamically adjust mechanical properties to meet the changing demands of complex underwater tasks. Constant Stiffness configurations may compromise stability or increase energy consumption during unexpected hydrodynamic disturbances, restricting performance in scenarios requiring multimodal locomotion or dynamic environmental interaction. To address these limitations, researchers are developing robotic fish with variable stiffness mechanisms. Zuo et al. [60] demonstrated enhanced propulsion efficiency using a multi-link redundant mechanism to simulate tail stiffening. Behbahani and Tan [61] created electroactive fins with field-responsive stiffness via electrorheological fluids. Nakabayashi et al. [62] improved swimming performance by synchronizing stiffness adjustments with actuation frequencies using antagonistic elastic components. Jusufi et al. [63] optimized thrust through bilateral artificial muscle contraction in a soft robotic fish model. Li et al. [64] developed an online tail stiffness modulation system for thrust optimization, while Xu et al. [65] introduced a “negative work” stiffness-tuning principle to boost efficiency. Song et al. [66] enhanced flexibility without sacrificing rigidity through bio-inspired composite skins. Hybrid designs also improve operational safety. Flexible components absorb impact energy during collisions, protecting the robot and its

surroundings. Compliant grippers enable secure handling of fragile or irregular objects without damage [67–69].

In addition to variable stiffness mechanisms, factors such as navigation, control, sensing, and communication technologies are also crucial. These components must work in unison to enhance the performance and adaptability of underwater robots. For instance, advanced navigation systems [70–72] enable robots to accurately determine their position and navigate efficiently through challenging underwater environments. Control systems [73–76] ensure precise movement and task execution, while sensing technologies [77,78] provide real-time feedback on environmental conditions. Communication systems, particularly in deep-sea environments, are vital for transmitting data between the robot and operators. Traditional radio frequency communication methods are ineffective underwater due to substantial signal attenuation. Alternative solutions, including acoustic and fiber-optic communication, are essential for enhancing real-time control and ensuring effective data transfer from the robot to the surface. Real-time stiffness modulation, in conjunction with control algorithms, navigation, and communication systems, will be crucial. This integration will enable the creation of robotic fish that are both responsive and energy-efficient, capable of performing effectively in various underwater environments.

This review synthesizes the evolution and technological advancements in adjustable-stiffness underwater robotics. While prior studies have extensively explored actuation methods, materials, and biomimetic designs [79–81], research on stiffness modulation remains fragmented. The absence of a systematic framework hinders the broader application of stiffness-tuning technologies. Building on these insights, we first trace the transition from constant stiffness systems to actively variable designs. Next, we categorize stiffness-adjustment methods into offline component replacement and online real-time modulation. Finally, we identify key challenges and propose future directions, including intelligent sensing and adaptive control algorithms, to enhance environmental adaptability and propulsion efficiency.

2. Evolution of Underwater Robotic Systems

Since the 1950s, rigid underwater robots have become essential tools for marine exploration due to their reliability and engineering potential. Their structural evolution has progressed from rudimentary mechanical systems to sophisticated deep-sea platforms, driven by innovations in four key areas: materials, propulsion, pressure resistance, and intelligent control. The development of rigid underwater robots was closely tied to Cold War military needs. The 1953 U.S.-designed “POODLE” ROV pioneered modular architecture with its open steel frame and external propellers. Despite generating 50% hydrodynamic drag, this exposed structure allowed flexible integration of sensors and robotic arms within its framework. During the 1960s, France’s “SP-350” introduced spherical pressure-resistant hulls with 20 mm-thick steel walls, achieving 300 m depths. However, its 2.5-ton weight limited maneuverability. Early propulsion systems used single DC motor-driven propellers with rudder steering, achieving less than 0.3 energy efficiency and mere hours of operation. The 1980s oil and gas exploration boom accelerated robotic advancements. The 1985 U.S. “Jason” submersible featured a streamlined fiberglass hull reducing drag to 40% of earlier models, paired with four vector thrusters enabling precise six-degree-of-freedom motion control. The 1990s witnessed the rise in untethered autonomous underwater vehicles (AUVs). The 1994 “REMUS” series adopted torpedo-shaped hulls with an 8:1 length-to-diameter ratio, achieving 24 h endurance through lithium battery integration. A 1995 materials breakthrough occurred with Japan’s “Kaiko” submersible, which utilized ceramic composite pressure hulls. Despite maintaining a 350 mm wall thickness, its density decreased from 4.5 g/cm³ (titanium) to 2.8 g/cm³, enabling record dives to 11,000 m in the Mariana Trench.

Subsequent carbon fiber-reinforced epoxy composites reduced hull weight by 30% while increasing payload capacity to 200 kg.

In this section, we will introduce the development history of underwater robots and focus on different variable stiffness methods, as shown in Figure 1.

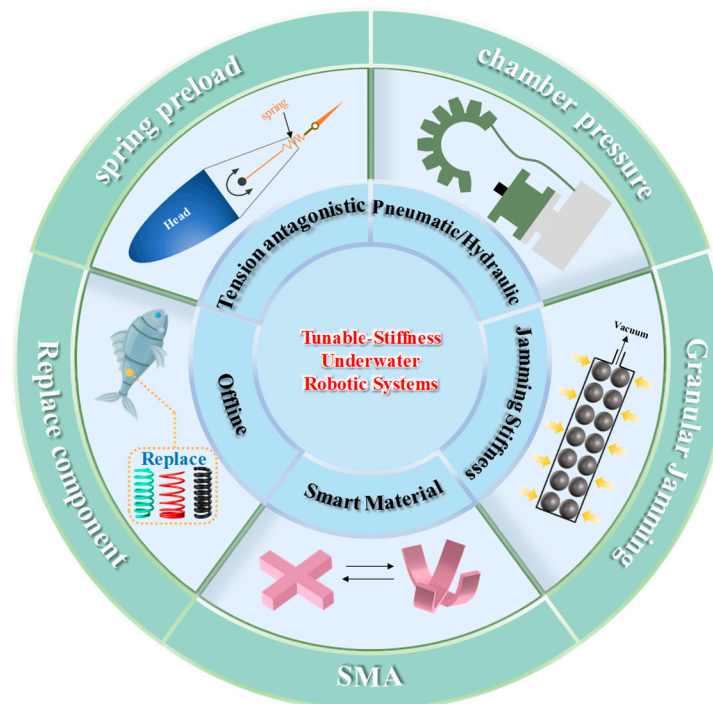


Figure 1. Methods for stiffness modulation in underwater robotic systems. The figure divides the variable stiffness method into five categories and lists their general areas of application. Early on, replacing components was commonly used to achieve offline stiffness. Tension-based antagonistic mechanisms, frequently utilizing springs. Pneumatic and hydraulic systems provide effective solutions for both flexible caudal fin actuation and stiffness variation. Jamming-based mechanisms typically offer simpler structures and demonstrate a broader operational stiffness range. Finally, intelligent materials represent an emerging technology within the domain of bio-inspired robotic fish. The yellow arrows indicate external loads applied to the system.

2.1. Rigid-Structured Underwater Robotic Systems

Rigid-structured underwater robots are characterized by a fixed geometric frame, which practically does not produce elastic deformation during operation. Their propulsion relies on mechanical joints and rigid materials, prioritizing high structural stability and precise kinematic control over environmental adaptability, as shown in Figure 2.

Since the mid-20th century, traditional propeller-driven submersibles have faced persistent challenges, including operational noise, restricted mobility, and environmental disruption, limiting advancements in underwater exploration. A breakthrough emerged in 1994 with MIT's RoboTuna [82], which redefined underwater propulsion through biomimicry. Its hinged vertebral structure and 6-DOF servo system replicated the undulating kinematics of bluefin tuna tails, achieving 27% higher propulsion efficiency and reducing wake turbulence to one-third of conventional propellers at equivalent power. This demonstrated the theoretical superiority of bio-inspired propulsion in flow control and energy conversion. Building on this success, MIT's 1998 RoboPike [83] integrated a tri-segment spine with bioelastic skin to regulate muscle contraction phase differences. Micro-vortex generators along the tail fin delayed boundary layer separation by 42%, reducing turbulent kinetic energy by 19%. The system achieved 85% propulsion efficiency at 1.5 body lengths per second, revealing critical interactions between bio-inspired parameter

optimization and active flow control. Concurrently, Japan's National Maritime Research Institute (NMRI) [84] validated biomimetic propulsion feasibility through their PPF series. The UPF-2001 prototype improved efficiency by 22% via parametric optimization of tail fin amplitude and attack angle coupling. In 2002, MIT and Woods Hole Oceanographic Institution [85] unveiled VCUUV, RoboTuna's final iteration. Its rigid forebody housed power and control systems, while a hydraulically actuated multi-joint tail enabled fish-like undulation, achieving 1.2 m/s speed and 75°/s turning rates. Tokyo Tech's two-joint robotic dolphin [86] featured a streamlined body with a servo-driven tail, achieving 0.2 m/s speed and pectoral-fin-free steering—a milestone in simplified biomimetic control. Post-2000s research diversified: Essex University's "fish-G9" [87–89] utilized multi-joint tails and adaptive algorithms for 3D maneuvers, while integrated sensors enabled autonomous navigation. Northwestern University's knifefish robot [90] demonstrated precision control via 32 independently actuated fins, achieving 0.2 m/s lateral drift. ETH Zurich's BoxyBot [91] pioneered amphibious locomotion using rotating fins, attaining 0.37 m/s swim speed and 0.12 m turning radius. National University of Defense Technology's RoboGnilos [92] advanced distributed propulsion with dynamically adjustable pectoral fins, enabling 3D maneuvers like pitch control and hovering through multi-fin coordination. Heo et al. [93] highlighted material impacts using piezoelectric tails, while Peking University's turtle robot [94] achieved 19.8 cm/s via paddle-like fins. Liang's SPC-III [95–97] combined speed (1.36 m/s) with endurance (20 h) through rigid parallel linkages. Recent advances target ultra-high-speed and cross-medium locomotion: iSplash-II [98] reached 11.6 body lengths/s (3.7 m/s) at 20 Hz tail oscillations, outperforming biological counterparts. Pliant Energy's Velox integrates undulatory, jet, and legged propulsion for seamless water–land–ice transitions.

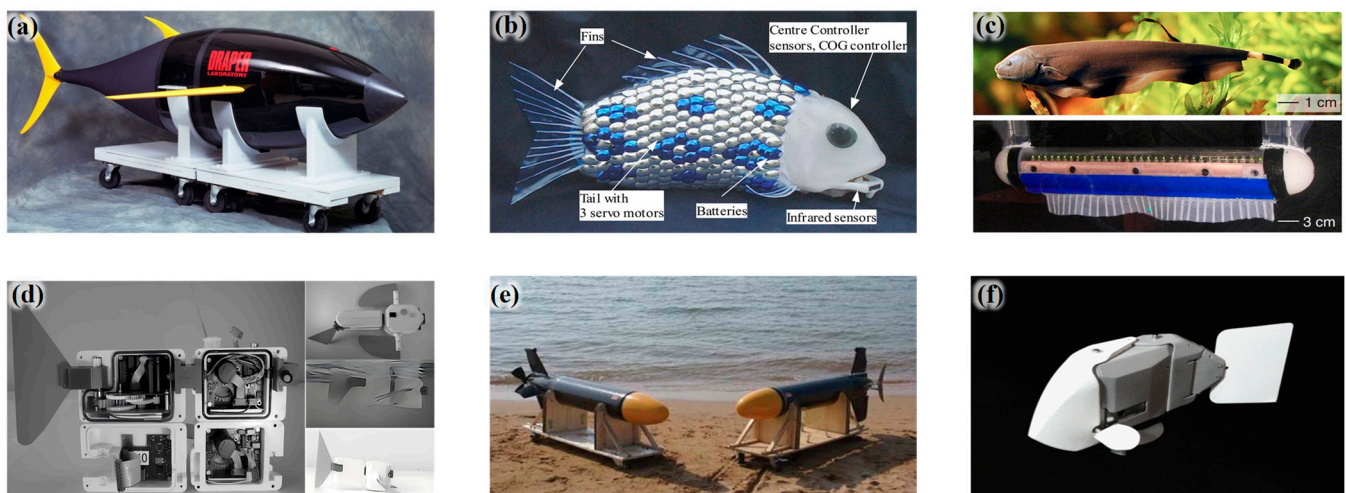


Figure 2. Evolution of rigid-structured underwater robotic systems. (a) VCUUV [85]; (b) fish-G9 [87–89]; (c) knifefish-like robot [90]; (d) BoxyBot [91]; (e) SPC-III [97]; (f) iSplash-II [98].

2.2. Flexible-Structured Underwater Robotic Systems

In contrast to rigid systems, flexible-structured robots utilize elastic materials (e.g., silicone, PVC, hydrogels) and soft actuators (e.g., SMA wires, dielectric elastomers) to enable continuous body deformation. This design mimics biological flexibility (e.g., fish undulation), enhancing adaptability to complex flows, as shown in Figure 3.

As rigid bio-inspired robots encounter limitations in environmental adaptability, researchers are increasingly focusing on integrating flexible structures with smart materials. In 2002, Otake et al. [99] pioneered a rigid-skeleton-free design using electroactive polymer gel (EAPG), which responds to electric fields. Their starfish-inspired robot achieved basic

motions like rolling and bending by leveraging ion migration triggered by spatial gradient electric fields, as illustrated in (Figure 3a). Suleman's team [100] developed a tuna-inspired hybrid prototype combining a glass fiber body with a neoprene tail fin. Driven by opposing shape-memory alloy (SMA) actuators, this system achieved wave-like propulsion. Despite SMA's limited 5% strain capacity, it demonstrated the feasibility of smart materials in energy transfer across rigid-flex interfaces. Wang et al. [101] refined this approach in a manta ray-inspired robot. By embedding SMA wires in a 0.25 mm elastic PVC substrate and using pulse-width modulation to actuate pectoral fins, they achieved a propulsion speed of 57 mm/s. The compact design (total length < 15 cm) serves as a practical model for confined underwater exploration. In 2010, Su Yudong's [102] team overcame actuation challenges by developing a crucian carp-inspired robot with an IPMC-PVC hybrid tail. Three synchronized ionic polymer-metal composite (IPMC) actuators enabled the 9.9 cm robot to swim at 24 mm/s. Remarkably, it achieved an 8 mm turning radius at 2 Hz actuation, highlighting the advantages of distributed flexible actuation for maneuverability. Yan et al. [103] optimized pectoral fin actuation by combining a rigid body with SMA-based flexible fins. Phase-change-induced bending enabled multi-mode locomotion, improving low-speed fluid adaptability by 40% compared to fully rigid systems, thereby validating the stability benefits of rigid-flex hybrid designs in complex flow fields. To address high-frequency propulsion demands, Clapham's team [104] developed the iSplash-MICRO. Its rigid modular skeleton, paired with a kinetically optimized flexible tail, achieved ultra-high-speed propulsion of 10.4 body lengths per second at 19 Hz oscillations. With a power consumption of 0.8 W (65% lower than conventional systems), it surpassed theoretical energy-efficiency limits for rigid-flex structures. Marchese et al. [105] achieved a breakthrough in 2014 with a carangiform robotic fish. Using multilayered silicone fluidic elastomers as artificial muscles, the design generated 10 Hz radial contraction waves via microchannel-controlled dielectric fluid pressure. This enabled a C-shaped escape maneuver with an angular acceleration of $5200^\circ/\text{s}^2$ and 68% energy efficiency, while fluid-structure topology optimization ensured submillimeter deformation accuracy. Huang et al. [106] pioneered miniaturized light-driven actuation in 2015. Their flagellum-inspired micro-robot used a light-sensitive liquid crystal polymer, eliminating traditional electronics. Alternating UV-visible light triggered periodic tail bending, enabling precise 142 $\mu\text{m}/\text{s}$ motion in low-Reynolds-number environments. This demonstrated the potential of contactless optical control for micro-robots in biomedical applications. Concurrently, Kazakidi et al. [107,108] designed an octopus-inspired tapered rigid-flex robotic arm. Suction-cup-like protrusions enhanced thrust by 2.3 times through flow field manipulation, while a "slow-recovery, fast-actuation" stroke pattern overcame rigid manipulators' limitations in unsteady hydrodynamic environments. Advancing stiffness-adaptive systems, Jin's team [109] created a modular starfish-inspired robot in 2016. Five PDMS-based arms embedded with SMA wires achieved coordinated motion via electrothermal activation, reaching 70 mm/s in semi-aquatic environments. This highlighted the role of variable rigidity in motion efficiency. Shintake et al. [110] developed a salmon-inspired robot using a four-layer silicone structure with embedded dielectric elastomer actuator (DEA) arrays. High-voltage electric fields induced thickness contraction to generate traveling-wave propulsion. Its 37.2 mm/s swimming speed closely matched biological Strouhal numbers ($St \sim 0.25$), demonstrating DEA's effectiveness in replicating natural aquatic locomotion. Christianson et al. [111] created a transparent eel-like robot using fluid-electrode dielectric elastomer actuators (FEDEA). Achieving 1.9 mm/s propulsion with 94% light transmittance, this design pioneered new approaches for covert underwater exploration. In 2019, the team advanced this concept with a jellyfish-inspired robot [112]. Using fluid-electrode dielectric elastomer actuators for radial oscillation, it mimicked pulsating propulsion to reach 3.2 mm/s at 0.2 Hz activation. Remarkably, its cost

of transport ($COT = 35$) surpassed rigid systems by two orders of magnitude, underscoring soft actuation's energy-saving advantages. Addressing terrain adaptability, Wu et al. [113] designed an octopus-inspired bipedal robot in 2021. A cable-driven system based on the spring-loaded inverted pendulum (SLIP) model enabled stable 6.48 cm/s walking using silicone arms, solving dynamic balance challenges in underwater soft robotics. Li et al. [114] reimagined deep-sea robotics in 2021 with a fully soft robotic snailfish. By replacing rigid pressure housings with silicone-encased DEA, it achieved 5.19 cm/s swimming at 10,900 m depth in the Mariana Trench, proving soft systems' viability in extreme environments. Pushing biomimetic efficiency limits, Matharu et al. [115] created the Jelly-Z in 2023. This moon jellyfish-inspired robot uses twisted coiled polymer (TCP) artificial muscles to pulse its silicone bell, achieving 7.3 mm/s motion at 168 g mass with energy efficiency comparable to biological counterparts. Wang et al. [116] developed a light-driven serpentine robot using temperature-sensitive hydrogel-carbon nanotube composites. Photothermal-induced shape changes enable both undulating and folding locomotion, allowing cable-free propulsion and obstacle navigation through alternating light exposure.

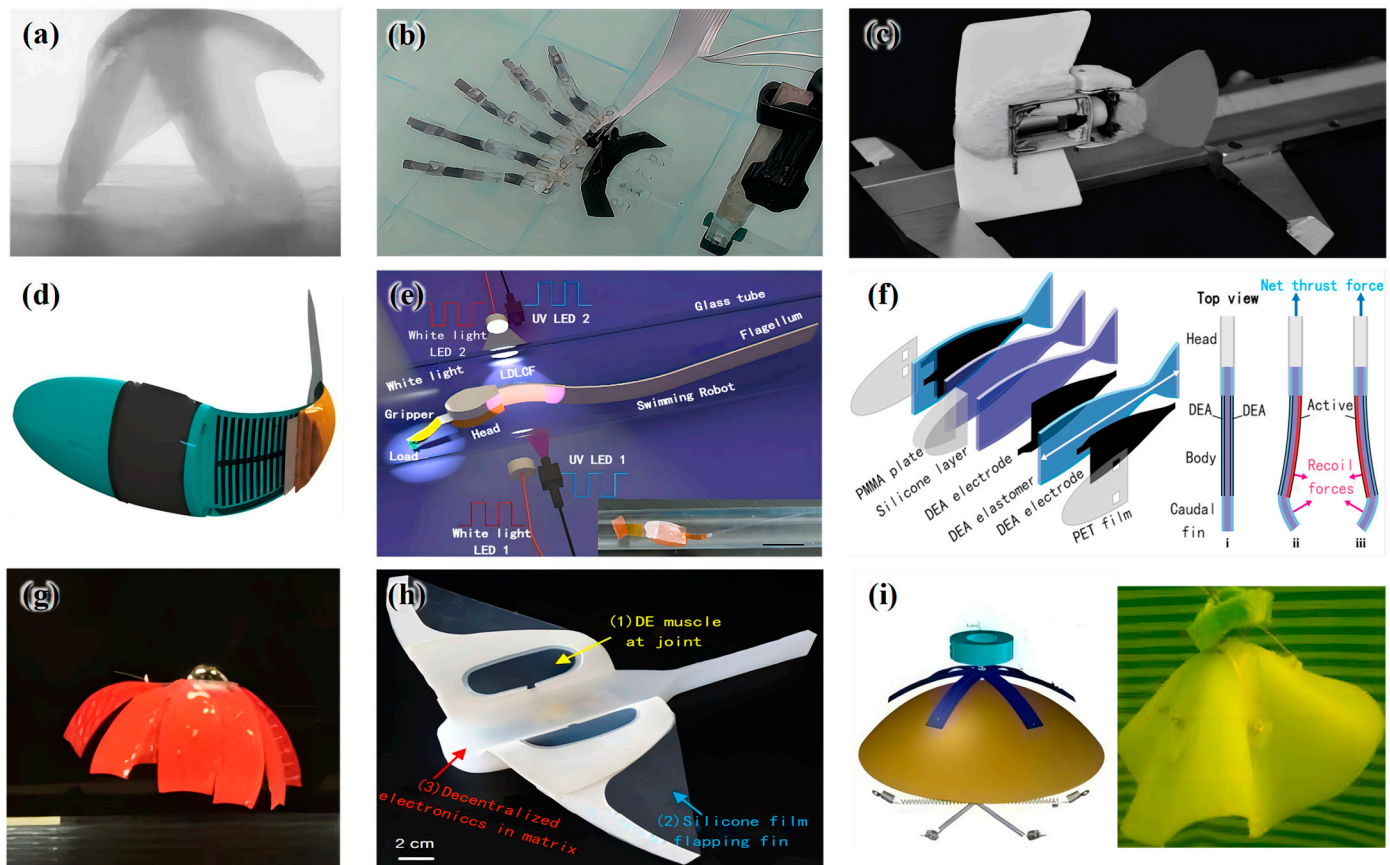


Figure 3. Evolution of flexible-structured underwater robotic systems. (a) Starfish-shaped gel robot [99]; (b) SMA-driven fins [103]; (c) iSplash-MICRO [104]; (d) pneumatic flexible robotic fish [105]; (e) light-driven robot [106]; (f) robotic fish based on DEAs [110]; (g) DEA-actuated jellyfish robot [112]; (h) self-powered soft robot [114]; (i) Jelly-Z [115].

2.3. Variable-Stiffness Underwater Robotic Systems

Variable-stiffness underwater robots are advanced marine systems capable of real-time structural rigidity adjustment, optimizing performance across varying conditions, as shown in Figure 4. Their adaptability enables seamless transitions between high stiffness (for high-speed movement) and low stiffness (for flexibility and impact absorption).

Neither rigid nor fully flexible underwater robots can match the propulsion efficiency of real fish, which dynamically adjust body stiffness through muscles, tendons, and biological tissues to optimize swimming performance [117–119]. To bridge this gap, researchers have introduced “adjustable stiffness” into underwater robotic design. In 1999, Nakashima et al. [120] pioneered adjustable stiffness in a dolphin-inspired robot. Their design featured three rigid modules (head, mid-body, tail) and a dual-joint propulsion system. By swapping torsion springs with varying stiffness coefficients, they achieved passive tail joint stiffness adjustment—a foundational step in bio-inspired robotic control. Experimental results demonstrated significant propulsion improvements through stiffness tuning. Optimal spring configurations enhanced wave propagation and energy transfer in the tail, boosting both speed and efficiency. Moderate stiffness settings proved ideal, balancing high propulsion efficiency (up to 27% increase) with motion stability. Building on this foundation, J.H. Long et al. [121] developed an evolutionary approach in 2006. Their bio-inspired closed-loop system simulated natural selection using three robotic “Tadro” models mimicking sea squirt larvae. By testing tails with varying stiffness levels, they systematically mapped how mechanical compliance influences propulsion efficiency in hydrodynamic environments. To balance real-time structural adaptation with propulsion efficiency, Masataka Nakabayashi et al. [122] designed a variable-stiffness robotic tail in 2009. Inspired by fish caudal fins, the system combined an aluminum body with a flexible PVC tail and adjustable support plates (0–20 mm range). Under static stiffness settings, an optimal plate length maximizes speed and efficiency. Dynamic adjustments during operation boosted peak speed by 47.2% and efficiency from 20.8% to 34.5%, demonstrating adaptive stiffness’s role in propulsion optimization. Rahim Mutlu et al. [123] introduced curvature-based stiffness control in 2010. By constraining actuator bending paths with curved surfaces (20–40 mm radii), they achieved dynamic stiffness modulation. At 40 mm radius, stiffness increased by 80% compared to unrestricted bending, while finite element simulations and experiments confirmed reduced displacement (at 1 V input) and enhanced force precision, proving constrained bending improves force–density trade-offs. In the same year, Tangorra et al. [124] developed a bionic pectoral fin based on a detailed analysis of the pectoral fins of the bluegill sunfish, and experimentally tested the swimming performance of seven bionic fins with different stiffness configurations under the conditions of 0.5 to 2.0 Hz beat frequency and 0 to 270 mm/s water velocity. The results indicated a clear positive correlation between propulsive force magnitude and the stiffness of the bionic fin. John H. et al. [125] developed the MARMT robot in 2011, mimicking a spiny dogfish’s vertebral column. A hydrogel-based spine embedded with modular rigid vertebrae (0–11 segments) allowed dual stiffness control: structural (more vertebrae increased rigidity) and activation-based (tailbeat frequency: 0.25–2 Hz). While added vertebrae enhanced stiffness by 62%, they reduced bending range by 28%, highlighting the inherent flexibility–stiffness compromise in bio-inspired propulsion systems. Park et al. [126] developed a bio-inspired underwater robot with variable stiffness, mimicking the tendon mechanics of marine organisms. The dolphin-tail-inspired structure combined alternating rigid plates and silicone segments. Two embedded steel cables, acting as artificial tendons, enabled real-time stiffness adjustment via servo-driven tensioning. This system achieved five discrete stiffness levels by modulating axial compression in the flexible segments. Yu Junzhi’s team [127] created a high-performance robotic dolphin in 2016. Mimicking spotted dolphins, their design utilized current-regulated torque control in the tail joint to achieve 2.85 body lengths per second (BL/s) at 4.65 Hz—tripling previous speed records. This adaptive compliance mechanism also enabled breaching maneuvers through optimized hydrodynamic coupling. The robot’s movement is controlled using PID feedback control for pitch, yaw, and depth, allowing for precise adjustments during high-speed swimming and leap execution. This

control system enables real-time responsiveness to water currents and dynamic movement, optimizing thrust and maneuverability in complex underwater conditions. Behbahani et al. [128] designed a flexible passive feathering joint for robotic fish pectoral fins. This mechanism enforces a predetermined power-stroke trajectory through mechanical limiting while enabling drag-reducing passive feathering on return strokes, enhancing propulsion efficiency under symmetric driving conditions. The joint was modeled as a torsion-spring-damping system to quantify parameter effects. Experimental tests with three FLX980 joints (JF1/JF2/JF3) showed that high-stiffness configurations optimize propulsive performance above 1.75 Hz, while flexible joints excel at lower frequencies. Chen and Jiang [129] pioneered a tensegrity-structured robotic fish in 2019. Seven rigid ABS segments connected by pre-tensioned cables created anisotropic joints—laterally stiff yet rotationally compliant. This biomimetic design replicated bass-like undulation through single-degree-of-freedom bending, mimicking natural spinal kinematics. Chen Di et al. [130] introduced a four-step stiffness control system in 2020. Their modular design employed torsion springs with varying stiffness coefficients (0.12–0.48 N·m/rad), allowing rapid manual adjustment of tail joint rigidity for optimized propulsion under discrete flow conditions.

To address redundant degrees of freedom in multi-jointed robotic fish, Liao Xiaocun et al. [131] proposed a wire-driven bi-elastic fishtail (WH-Rofi) in 2023. Utilizing spring steel's periodic elastic deformation to store energy, thereby enhancing propulsion efficiency. By optimizing stiffness parameters, their approach facilitates hydrodynamic adaptation, improving both swimming speed and energy efficiency. This system demonstrated a peak swimming speed of 0.92 m/s (1.87 BL/s), indicating significant improvements in dynamic performance. In 2025, Ding Fuhui et al. [132] further advanced this concept by introducing online stiffness adjustment in a tensegrity-based robotic fish, which allows real-time tuning of body stiffness to maximize swimming performance. Their system demonstrated that adjusting the stiffness distribution could lead to higher thrust and swimming speed, particularly at high-frequency actuation (2.5–6 Hz), providing valuable insights for control optimization in biomimetic designs. These dynamic control strategies, combined with stiffness modulation, offer substantial potential for improving maneuverability and energy efficiency in underwater robots. Recent research on bistable mechanisms highlights their effectiveness in achieving programmable and adaptable stiffness. For instance, Mohammadi et al. (2025) [133] developed 3D-printed bistable mechanisms for wearable devices designed to attenuate tremors, showing their potential in both vibration damping and customizable stiffness responses. Similarly, Zolfagharian et al. (2025) [134] explored the use of bistable mechanisms integrated into tuned mass damper (TMD) systems for vibration control, enhancing the flexibility of traditional methods by providing a passive solution to dynamic frequency changes. Both studies underscore the versatility and application potential of bistable mechanisms in engineering systems requiring adaptive vibration and stiffness modulation. The design and modeling of adaptive flexible structures with stiffness shifts have been significantly advanced by recent studies. Mohammadi et al. (2025) [135,136] introduced a framework using physics-enhanced neural networks (PENNN) and reduced-order models (ROM) to optimize flexible structures based on desired stiffness profiles, enabling rapid inverse design of mechanical metamaterials for variable-stiffness underwater robots. This method, incorporating genetic algorithms and machine learning, facilitates the creation of adaptive structures with nonlinear stiffness behaviors like buckling, essential for dynamic underwater conditions. These studies highlight cutting-edge techniques for enhancing the performance and adaptability of underwater robotic systems through advanced material design and fabrication methods.

In summary, the ability to adjust the stiffness of underwater robots not only optimizes propulsion but also directly contributes to their maneuverability, stability, and responsive-

ness to changing environmental conditions. For instance, real-time stiffness adjustments allow the robot to adapt to different flow regimes, enhancing its control over complex maneuvers and improving its ability to navigate in dynamic underwater environments. Furthermore, these stiffness changes can complement sensor systems by providing more accurate feedback for adaptive control algorithms, which could enable real-time adjustments to optimize both propulsion and stability in varying conditions. In this context, the combination of dynamic stiffness modulation with sophisticated navigation and communication systems could significantly elevate the autonomy and performance of variable-stiffness underwater robots, as they respond effectively to environmental and task-related challenges. This multi-faceted approach is essential for the development of fully functional, bio-inspired underwater robots capable of operating in diverse and unpredictable marine settings.

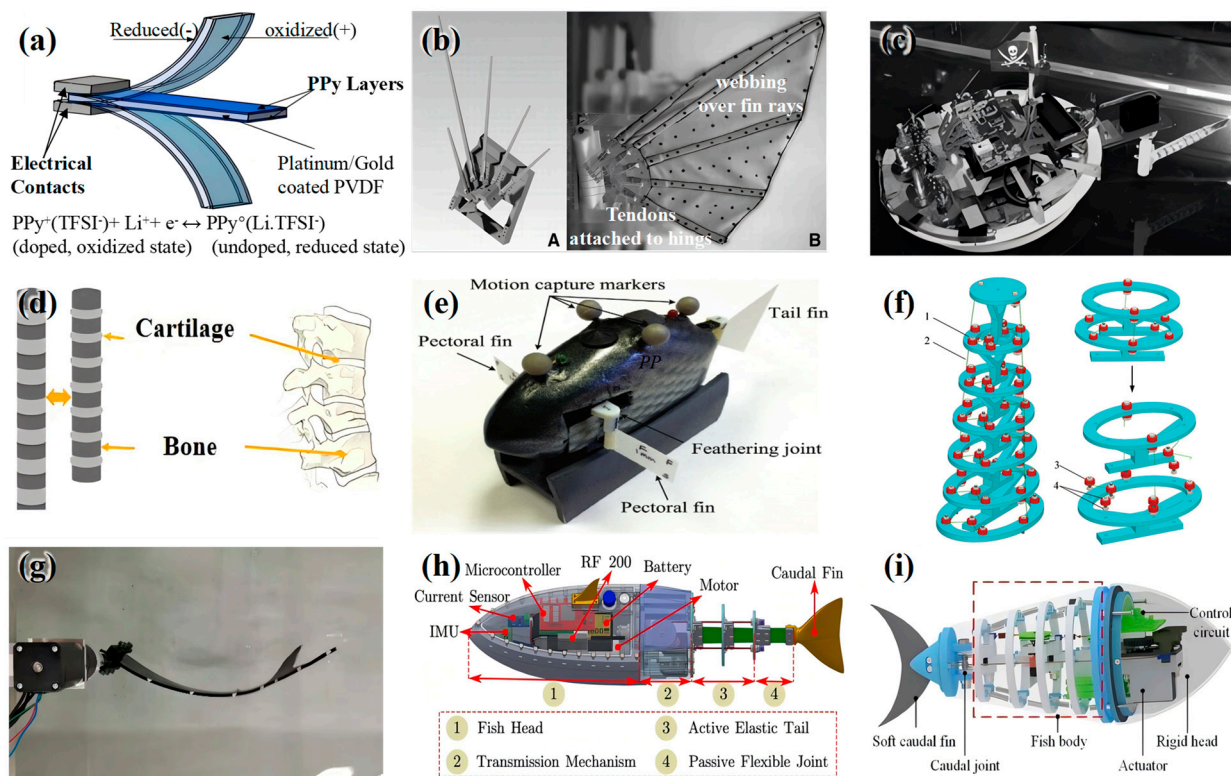


Figure 4. Historical development of variable-stiffness underwater robotic systems. (a) Five layers and bending mechanism of the trilayer polypyrrole polymer actuator [123]; (b) design of the biorobotic pectoral fin [124]; (c) extra vertebrae [125]; (d) artificial tendons [126], the arrows represent the transition from flexible (left side) to rigid (right side); (e) 3D-printed robotic fish prototype along with mounted fins [128]; (f) structure of the tensegrity joints: 1: rigid segments. 2: tension elements. 3: cable outlets. 4: bolts and nuts [129]; (g) variable stiffness tail fin made of layers of rubber sheets [130]; (h) overview of the WH-Rofi [131]; (i) overall structure of TenFiBot-HFS [132].

3. Methods for Stiffness Modulation in Underwater Robotic Systems

Adjustable stiffness underwater robotic fish can change the stiffness of their bodies in two primary ways. The first category involves smart materials-based stiffness modulation, where materials such as shape-memory alloys (SMAs) and electrorheological fluids are used to dynamically adjust stiffness in response to external stimuli. The second category encompasses mechanism-based architectures, which rely on physical mechanisms to achieve stiffness modulation. This category can be further divided into several methods: replacing modular passively adjustable stiffness elements [120,121], adjustable springs [122,137], pneumatic/hydraulic brakes [63,138,139], artificial tendons [126], and motor braking [127].

Each of these methods employs physical structures or mechanisms to enable adjustment of the fish body's stiffness, allowing it to adapt to various environmental conditions.

3.1. Offline Stiffness Modulation

Passive stiffness modulation allows underwater bio-inspired robots to adjust rigidity through structural or material modifications. Unlike active control, this method uses predetermined materials/components to achieve task-specific stiffness without real-time feedback. Common approaches include component replacement (motors/springs), joint adjustments, and material changes (hardness/thickness). Structural geometry modifications, such as varying vertebrae counts or spring stiffness, further enable stiffness adaptation.

Table 1 lists the history of underwater ROVs with adjustable stiffness of replacement elements, and describes the changed elements, the range of stiffness adjustments, and the impact on propulsion performance.

Table 1. Offline—adjustable stiffness underwater robot.

Year of Publication	Regulation Mode	Stiffness Control Range	Impact of Propulsion Performance
1999 [120]	Replace the springs	3.1 times	Swim speed increased by about 39%
2006 [121]	Replace the bionic tail chord	4.7 times	Swim speed increased by about 60%
2010 [123]	Add a limiter	2.2 times	Displacement decreased by about 62%
2011 [125]	Increase vertebrae	5.3 times	Swim speed increased by about 70%
2012 [140]	Replace the nylon inserts	1.9 times	Thrust increased by about 96%
2018 [64]	MACCEPA	16 times	Swim speed increased by about 5.8 times
2019 [129]	Preset spring tightness	~	Swim speed increased by about 59%
2020 [130]	Replace the springs	~	Energy efficiency improved by about 89%
2021 [141]	Replace the spring blades	91 times	Swim speed increased by about 1.7 times
2022 [142]	Replace the spring steel	78.8 times	Swim speed increased by about 3.3 times
2022 [143]	Replace the tail fin assembly	35.1 times	Swim speed increased by about 87%

3.2. Tension Against Stiffness Modulation

Active stiffness modulation in underwater robots typically employs physical tension or counteractive forces to adjust body rigidity dynamically during operation. This real-time adaptability enables optimized performance across varying hydrodynamic conditions [144]. A seminal study by Prof. Dan Quinn's team [118] demonstrated that muscle tension should scale proportionally to the square of swimming speed for maximal efficiency. Their tuna-inspired robotic platform (Figure 5a) achieved doubled propulsion efficiency through adaptive stiffness control at biologically relevant frequencies and velocities. Building on this principle, Masataka Nakabayashi et al. [122] pioneered early real-time stiffness modulation in 2009. Their prototype (Figure 5b) utilized motor-driven sliding plates to dynamically alter spring engagement lengths during motion, creating tension-counteraction effects. Quantitative analysis (Table 2) revealed significant correlations between adjustable stiffness parameters and swimming performance metrics, establishing foundational insights for subsequent bio-inspired propulsion systems.

In 2011, Marc Ziegler et al. [137] introduced a multi-joint compliant caudal fin platform (Figure 5c), marking the first implementation of real-time stiffness modulation across multiple joints in underwater robotics. Their design leveraged the MACCEPA principle (Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator) to achieve variable rotational stiffness. Each passive joint integrates pulleys, cables, springs, and servos, with servo motors dynamically adjusting spring preload angles to tune joint stiffness during operation. This system enabled optimization of propulsion performance by tailoring stiffness distribution along the posterior body under varying swimming frequencies and amplitudes. Experimental results demonstrated a fivefold stiffness variation range (from softest to hardest), independent joint stiffness programming, and heterogeneous

stiffness distribution capabilities, culminating in a 25–40% increase in maximum thrust. Building on this, Park et al. [126] developed a bio-inspired vertebral tensioning system (Figure 5d) that mimicked artificial tendons to modulate caudal peduncle bending stiffness actively through axial compression. Their design achieved a stiffness range of 48.0 N/m to 155.9 N/m, with frequency-dependent experiments showing that optimal stiffness configurations could enhance propulsion force by $38 \pm 7\%$. These findings validated the biological principle of frequency-dependent optimal stiffness in undulatory locomotion.

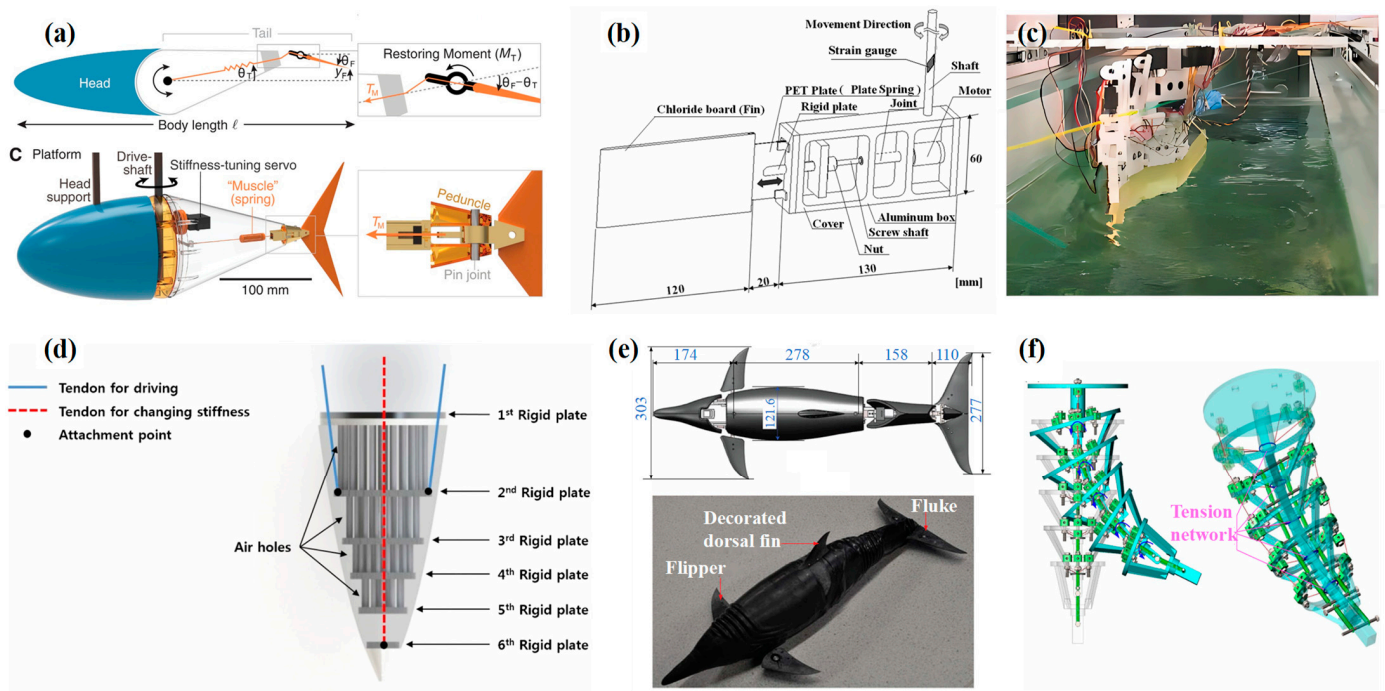


Figure 5. Underwater robot with a tension—counteracting adjustable stiffness structure. (a) Motor-pull [118]; (b) mobile rigid plate [122]; (c) multi-joint [137]; (d) bionic vertebra [126]; (e) equivalent spring-loaded [127]; (f) tension structural [145].

Table 2. Change in propulsion performance [122].

Maximum Pitch Angle	Fixed-Stiffness Velocity	Dynamic Stiffness Velocity	Fixed-Stiffness Propulsive Efficiency	Dynamic Stiffness Propulsive Efficiency	Velocity Improvement Magnitude	Efficiency Improvement Magnitude
30°	134 mm/s	146 mm/s	26.2%	26.9%	9.1%	2.7%
37.5°	131 mm/s	142 mm/s	29.2%	30.8%	8.4%	5.5%
45°	86.3 mm/s	127 mm/s	20.8%	34.5%	47.2%	65.9%

To achieve real-time controllability and high-frequency response, Yu Junzhi's team at Peking University [127] developed a continuous joint stiffness regulation system using an equivalent spring model controlled by current feedback (Figure 5e). This system achieved adjustable stiffness coefficients from 0.05 to 0.25 N/m. Experimental results demonstrated that increased stiffness enhanced propulsion angles and attack angles at constant frequencies, thereby improving thrust generation. At maximum stiffness with 4.65 Hz oscillation frequency, the robotic fish attained swimming speeds exceeding 2.7 times those of comparable prototypes, while successfully executing a five-phase water-breaching maneuver.

Inspired by natural fish musculature stiffness modulation during free swimming, Chen Bingxing and Jiang Hongzhou et al. [145] proposed TenFiBot in 2021—a tensegrity-

structured biomimetic robot integrating a Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator (MACCEPA) with tensegrity architecture (Figure 5f). This configuration achieved 14-fold stiffness variation, demonstrating notable propulsion performance variations under different stiffness distributions and driving frequencies. The prototype attained peak swimming speeds of 0.87 body lengths per second (BL/s), with Strouhal numbers consistently within the biologically optimal range of 0.35–0.5.

3.3. Pneumatic/Hydraulic Stiffness Modulation

Pneumatic/hydraulic stiffness modulation employs pressure-controlled chambers (gas/liquid-filled) to achieve real-time structural stiffness adjustment. These systems typically utilize elastic cavities, biomimetic muscles, or soft-material encapsulation. Increasing internal pressure enhances structural compactness and deformation resistance, while pressure reduction induces compliant, deformable states, enabling dynamic stiffness adaptation through precise pressure regulation, as shown in Figure 6. Building on previous pneumatic actuator designs, Ardian Jusufi et al. [63] developed a flexible biomimetic fish in 2017 featuring bilateral soft pneumatic actuators. The robot integrates an elastic central “spine” (flexible stainless steel shim) with segmented pneumatic actuators along both sides. By adjusting the phase difference in actuator contraction and pneumatic input timing, they achieved real-time body stiffness modulation from 18 N/m to 29 N/m. Experimental results demonstrated that optimized stiffness adjustments enhanced energy conversion efficiency across driving frequencies, improving swimming performance. Building upon Jusufi’s robotic fish design, Zane Wolf et al. [138] developed three pneumatic variants with distinct central spine stiffness profiles using plastic backbones of varying flexural rigidity. Through active modulation of pneumatic actuators’ maximum/minimum pressure thresholds, they systematically investigated the coupling effects between undulation frequency, spine stiffness, and active stiffness control. Experimental analysis revealed significant stiffness–frequency interactions: rigid spines generated maximum thrust at higher frequencies (0.75–1.0 Hz) but incurred elevated lateral forces and torque that compromised swimming efficiency. Conversely, flexible spines achieved enhanced thrust at low frequency (0.25 Hz) through amplified undulation amplitudes under high pressure, while medium-stiffness spines exhibited peak thrust performance at 0.5 Hz. To quantify body deformation during undulation, Wright et al. [139] implemented soft curvature sensors in 2019 for real-time strain measurement, coupled with a feedback-controlled stiffness regulation system. By coordinating bilateral actuator contractions, they achieved dynamic stiffness modulation throughout the swimming cycle. Optimal performance occurred at 4% cycle-synchronized bilateral contraction, yielding maximum propulsion force. The robotic fish attained a 13 cm/s swimming speed (0.8 BL/s) at 0.55 Hz driving frequency, with the caudal fin achieving a peak undulation amplitude of 1.4 body lengths.

To address pneumatic stiffness modulation limitations (buoyancy variations and external air supply requirements), Insung Ju and Dongwon Yun [146] developed a hydraulically variable caudal fin system in 2023. Their biomimetic prototype employs peristaltic pumps to regulate water volume within flexible tail chambers, achieving bending stiffness modulation from 0.0016 to 0.0534 N/m². Through stiffness–frequency synchronization, the robotic fish attained a peak swimming velocity of 38.9 cm/s (0.63 BL/s) at 1.25 Hz drive frequency, achieving a 118% average speed increase and up to 260% peak enhancement compared to fixed-stiffness configurations.

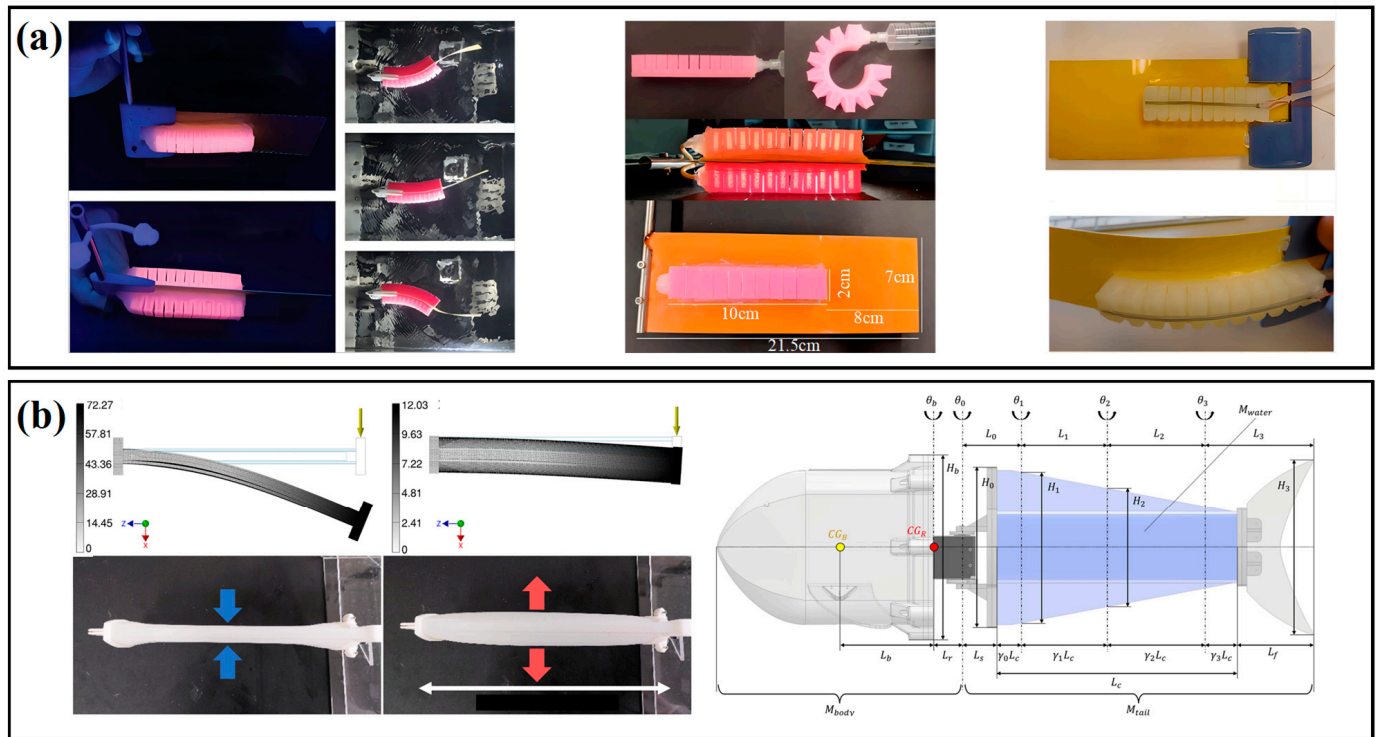


Figure 6. Underwater robot with an air-pressure/hydraulic-pressure adjustable stiffness structure. (a) Pressure Regulation [63,138,139]; (b) hydraulic adjustment [146], the yellow arrows represent external loads, while the blue and red arrows indicate the deformation trends.

3.4. Smart Material Stiffness Modulation

Smart material-based stiffness modulation utilizes responsive materials (e.g., shape memory alloys [SMAs], electrorheological [ER], and magnetorheological [MR] fluids) to achieve dynamic structural rigidity adjustment under external stimuli (temperature, electric/magnetic fields), as shown in Figure 7. This technology exhibits millisecond-level response times [147–153]. Demonstrating this principle, Behbahani and Tan [61] developed an ER fluid-regulated flexible caudal fin in 2017. Their design encapsulated ER fluid within a multilayered flexible structure, where applied electric fields ($0\text{--}1.5 \times 10^6 \text{ V/m}$) modulated the fluid's shear modulus to control fin bending stiffness. Hydrodynamic characterization revealed a 40% increase in natural frequency (3.64 Hz to 5.12 Hz) and 130% damping ratio enhancement (0.18 to 0.42) under maximal field excitation. To address challenges in electrorheological fluid encapsulation and high power requirements, Liu Sijia et al. [154] from Jilin University developed a shape memory alloy (SMA)-based stiffness modulation system. By regulating SMA wire heating currents (0–2 A), they achieved 57.4% stiffness enhancement from 0.2242 to 0.3528 N/mm. Under 50 kPa hydrodynamic pressure at 5 Hz actuation frequency, experimental results demonstrated 35.5% velocity improvement (0.06749 to 0.09148 m/s) with current modulation from 0 to 1.5 A. Concurrently, the Strouhal number decreased by 21.9% (0.37772 to 0.29493), indicating enhanced propulsion efficiency without significant energy consumption increases.

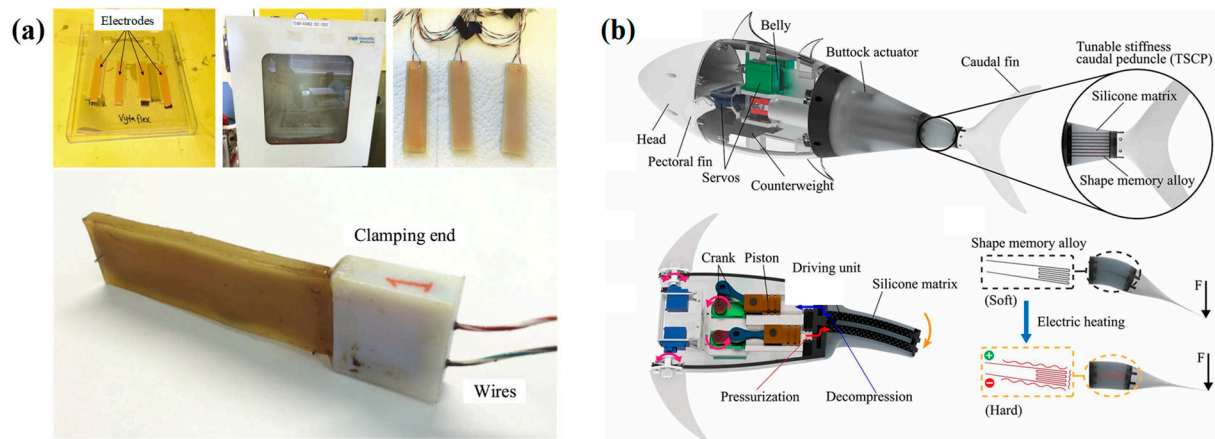


Figure 7. Underwater robot with a stiffness-adjusting structure using intelligent materials. (a) Electro-rheological fluids variable stiffness [61], (b) SMA variable stiffness [154].

3.5. Jamming Stiffness Modulation

Particle jamming-based stiffness modulation operates by restricting internal particle movement to transform compliant structures into rigid configurations through external compression. This phase transition mechanism enables substantial stiffness enhancement, as shown in Figure 8. Pioneering this approach, Chunhui Zhu et al. [155] developed a biomimetic caudal fin in 2022 using elastomeric spheres in a silicone matrix. Stepper motor-driven axial compression deformed the regularly arranged spheres, achieving 26.46% maximum bending stiffness increase through controlled geometric constraint. Addressing limited tunability in homogeneous jamming systems, Zhang Yu et al. [156] introduced a dual-chamber pneumatic actuator with hybrid particle chains in 2024. Mimicking dolphin tail musculoskeletal systems, this design combines cable-driven axial tension with rigid-flexible particle chain interactions to achieve a remarkable 57-fold bending stiffness enhancement (2 N/m to 114.1 N/m). Hydrodynamic testing demonstrated over 300% thrust improvement at maximum stiffness configuration. Building on jamming-based innovations, Zicun Hong et al. [157] developed a laminate interference architecture for robotic fish caudal stiffness modulation. Their vacuum pressure regulation system enables rapid, continuous stiffness adjustment (3 N/m to 30 N/m, 10-fold enhancement) without geometric alteration. Hydrodynamic evaluations demonstrated over two-fold thrust enhancement (144.5 mN at 0 kPa to 292.3 mN at −20 kPa vacuum) through this non-geometric-altering stiffness control paradigm.

3.6. Performance Comparison of Stiffness Modulation Techniques in Underwater Robotics

Table 3 compares the advantages, disadvantages, and stiffness modulation ranges of various emerging methods. Offline Stiffness Modulation allows for a wide range of stiffness adjustments but lacks real-time control. Online stiffness adjustment through physical tension or counteractive forces provides continuous modulation but is prone to mechanical fatigue over time. Pneumatic/Hydraulic Stiffness uses flexible chambers to achieve stiffness modulation, offering soft deformable properties, though it requires an external power supply and must consider material pressure limits. Smart Materials modulate stiffness with minimal energy consumption but typically have a narrow modulation range. Jamming Stiffness Modulation achieves significant stiffness changes using granular or layered structures, but it often requires an external pump for operation, adding complexity.

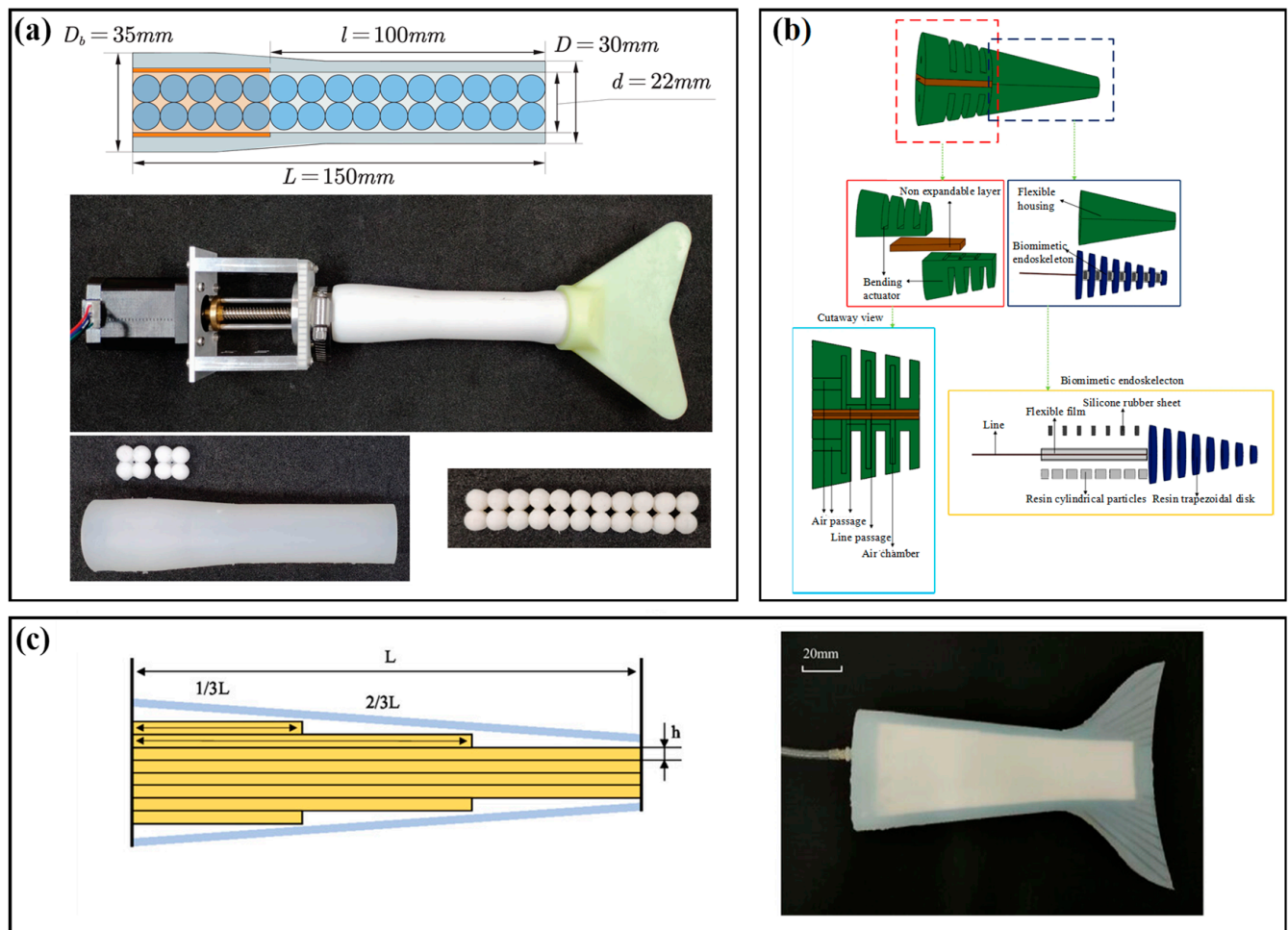


Figure 8. Underwater robot with a jamming-adjusted stiffness structure. (a) Globular elastic filler [155]; (b) rigid-flexible mixed granules [156]; (c) layer interference [157].

Table 3. Comparison of stiffness modulation methods.

Stiffness Modulation Method	Advantages	Disadvantages	Range of Stiffness Modulation
Offline Stiffness Modulation	Simplicity and reliability	Lack of real-time adaptability	Varies significantly depending on the components replaced, up to 91 times
Tension Against Stiffness	Continuous stiffness adjustment	Less precise at high frequencies Mechanical wear over time	About 3 to 5 times
Pneumatic/Hydraulic Stiffness	High environmental adaptability Rapid response time	Requires external power supply	Pneumatic: about 2 times Hydraulic: up to 30 times
Smart Material Stiffness Modulation	Lightweight and compact High energy efficiency	Limited stiffness range	Relatively narrow, between 1.5 and 3 times
Jamming Stiffness Modulation	High-stiffness range	Susceptibility to mechanical wear	Significant increase, up to 56 times

In summary, each stiffness modulation technique offers unique advantages and limitations, and their suitability depends on the specific requirements of the underwater robotic system, including adaptability, efficiency, and operational constraints.

4. Critical Challenges and Integrated Solutions for Stiffness Modulation in Underwater Robotic Systems

4.1. Challenges in Adjustable Stiffness

The realization of adjustable stiffness technology in underwater vehicles can significantly improve their propulsion efficiency, flexibility, and environmental adaptability. However, in addition to the challenges in stiffness modulation, the integration of dynamic aspects such as navigation, control, sensing, and communication in underwater robotic systems presents additional obstacles. These dynamic systems must be synchronized with stiffness adjustments to ensure optimal performance under varying environmental conditions, but there are still many challenges in practical design and application.

(1) Current stiffness modulation mechanisms in underwater robotics (e.g., particle jamming, hydraulic injection, vacuum laminate interference) exhibit critical response latency (100 ms to multi-second range) that impedes real-time synchronization during high-speed maneuvering or emergent tasks. This temporal mismatch between stiffness adjustment and dynamic demands frequently induces locomotion instability and suboptimal propulsion efficiency, despite their broad stiffness tunability.

(2) Prevailing open-loop control paradigms [158,159] predominantly rely on pre-calibrated parameters without integrated sensing of actual stiffness states or hydrodynamic feedback. This empirical tuning approach demonstrates limited adaptability in dynamically changing environments due to the absence of closed-loop compensation for nonlinear fluid–structure interactions.

(3) High-pressure operational challenges manifest as structural collapse in vacuum-based systems (negative pressure maintenance failure) and pneumatic chamber deformation under extreme hydrostatic loads. Such poor environmental adaptability currently restricts the deployability of variable-stiffness mechanisms in deep-sea exploration (>1000 m depth) and harsh marine applications.

(4) Stiffness and control integration. One of the main challenges in integrating stiffness modulation with control systems is that changes in stiffness often affect the underwater robot's speed and posture. This can complicate control, as the robot's movement may become less predictable. The dynamic adjustment of stiffness can introduce additional complexity in maintaining stable control during tasks that require precise movement, such as obstacle avoidance and course corrections.

(5) Sensor feedback and environmental interaction. Underwater robots require a robust sensing system that can continuously monitor environmental variables and provide feedback for dynamic stiffness adjustment. However, current sensor systems often struggle with providing real-time feedback on fluid–structure interactions, leading to delays in the adaptation of stiffness.

4.2. Innovative Solutions for Stiffness Control and Environmental Adaptability

To overcome the challenges of slow stiffness control, lack of environmental perception and adaptive adjustment, and poor adaptability to extreme environments such as the deep sea, underwater robots' ability to adaptively adjust their stiffness in response to complex environments and varying working conditions can be significantly improved. This can be achieved through the use of advanced adjustable stiffness mechanisms, machine learning, and the integration of flexible sensors, ultimately enabling optimal propulsion performance across all operating conditions and environments.

(1) To address the challenge of slow stiffness response rates that hinder robotic systems from meeting real-time stiffness adjustment requirements during unexpected tasks, novel stiffness modulation technologies can be implemented in underwater robots. These

include rapid-response electrostatic layer densification [160–164] and electrostatic adhesion mechanisms [165–168], which enable swift stiffness adaptation.

(2) Conventional stiffness adjustment methods in underwater robotics primarily rely on fixed parameters or manual calibration, demonstrating limited adaptability to dynamic aquatic environments. A multimodal sensing array [169–172] comprising stress–strain sensors [173–175], inertial measurement units, hydrodynamic sensors, and vision systems [176–178] enables real-time monitoring of robotic deformation, propulsion forces, and environmental flow characteristics [127,145]. Through extensive experimental validation of optimal stiffness configurations, we systematically collect operational data while developing a deep reinforcement learning-based decision model [174,179,180]. This model undergoes progressive training [181] to enable autonomous offline stiffness regulation in robotic fish systems ultimately.

(3) To enhance extreme-environment adaptability in underwater robotic stiffness regulation, bio-inspired structural optimization and material substitution strategies have been proposed [182–184]. Specifically, hydraulic water-infused stiffness modulation systems [146] demonstrate superior pressure resistance compared to conventional pneumatic approaches, effectively mitigating instability risks in high-pressure environments. Furthermore, non-metallic flexible architectures show exceptional promise, notably the dielectric elastomer actuator (DEA) system developed by Li et al. [114], which was successfully deployed in Mariana Trench conditions. Complementary approaches, including solid infill patterns, nested support frameworks, and pressure-compensated chambers, further enhance the pressure tolerance and operational stability of stiffness modulation systems in extreme marine environments.

(4) Four-Dimensional Printing for Stiffness Modulation: Recent advancements in 4D printing have shown great promise for creating adaptive structures in underwater robotics. Multimaterial 4D printing using shape-memory polymers (SMPs) and elastomers allows for dynamic stiffness adjustments in response to external stimuli, offering energy-efficient and flexible solutions for soft robotic components. Studies, such as those by Zolfagharian et al. [185–187], demonstrate the potential of tunable bending models and composite foam metamaterial springs, providing effective means to enhance the performance and robustness of stiffness modulation systems in dynamic marine environments.

(5) Integrated Control Systems: By combining real-time stiffness adjustment with advanced navigation algorithms and trajectory optimization techniques, the robot can more effectively respond to environmental changes. The use of model predictive control (MPC) or adaptive control algorithms ensures that stiffness adjustments align with the robot's movement, allowing for smoother and more stable navigation during dynamic tasks.

5. Conclusions

The systematic evolution of underwater robots from rigid structures to actively controllable stiffness comprises three distinct phases: The early stage featured rigid-frame propeller systems like POODLE, constrained by high hydrodynamic resistance and limited environmental adaptability. The intermediate phase introduced compliant actuation through responsive materials such as electroactive polymers (EAPs) and shape memory alloys (SMAs). Currently, the field has progressed to real-time dynamic stiffness modulation through multi-physical field coupling. This paper systematically categorizes stiffness modulation strategies into offline component replacement and online adjustment techniques. The latter encompasses tendon-cable systems, pneumatic/hydraulic pressurization, smart materials (SMAs, electrorheological fluids), and jamming interference mechanisms (particle chains, spherical shells, laminate interference). These approaches predominantly employ flexible or hybrid flexible–rigid architectures, achieving broad stiffness variation

ranges and enhanced propulsion efficiency through distinct modulation principles. Shape memory alloys (SMAs) and electrorheological (ER) materials demonstrate rapid response times and high integration density, making them particularly suitable for micro-scale underwater systems. Hydraulic architectures offer broad adjustment ranges and exceptional environmental adaptability. Jamming mechanisms enable continuous stiffness modulation without profile alteration, while elastic spinal structures permit real-time stiffness switching while maintaining optimal hydrodynamic profiles. However, each approach presents distinct limitations: Smart materials exhibit high energy consumption, complex control requirements, and limited operational cycles. Jamming mechanisms suffer from response hysteresis and inadequate feedback control. Pneumatic systems require an external gas supply, while hydraulic configurations face challenges in pressure containment and sealing integrity. While these advances in stiffness modulation technologies are crucial, it is also important to recognize the need for integrating dynamic control systems in future underwater robots. This includes advancements in autonomous navigation, sensor networks, and communication systems to enhance real-time interaction with environmental conditions and improve overall system performance. Future developments in underwater robotic stiffness systems will likely integrate three critical advancements: (1) embedded intelligent sensing networks for real-time environmental interaction, (2) self-optimizing stiffness adaptation algorithms with energy efficiency constraints (<5 J/cycle), and (3) biohybrid architectures combining biological principles, advanced materials, and adaptive control systems. These innovations will pave the way for fully autonomous underwater robots capable of real-time decision-making, seamless interaction with dynamic environments, and unprecedented operational depths (>6000 m), providing critical solutions for deep-sea exploration and other challenging marine applications.

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