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Bioinspired shape memory alloy-driven underwater soft robot enabled by pectoral–caudal-fin coordination and passive liquid thermal management

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S1 Design of the pectoral fin and caudal fin

S1.1 Design of the Pectoral Fin

During the fabrication and modeling of the pectoral fin actuator, a simplified constitutive description is adopted to qualitatively represent the bending behavior of the acrylic substrate under flapping deformation. The corresponding strain energy density function is expressed as

$$W = C(I_1 - 3), \tag{S1}$$

where C is a material constant and I_1 denotes the first invariant of the deformation tensor. It should be emphasized that the above Neo-Hookean formulation is introduced as a simplified, first-order constitutive description to explain how SMA contraction is converted into pectoral-fin bending. In the present study, this model is used for mechanistic interpretation and qualitative design guidance only, rather than for quantitative prediction of bending angle or hydrodynamic force. This limitation arises because the effective constitutive parameters of the 0.3 mm PMMA sheet were not independently identified, and thickness effects, rate dependence, and temperature dependence were not explicitly modeled. For an incompressible material under two-dimensional deformation conditions, I_1 can be written as

$$I_1 = \lambda_1^2 + \lambda_2^2 + \frac{1}{\lambda_1^2\lambda_2^2}, \tag{S2}$$

with λ_1 and λ_2 representing the principal stretch ratios. According to the definition of stress in hyperelastic materials, the stress tensor ε_{ij} of the acrylic pectoral fin during motion is

obtained by taking the partial derivative of the strain energy function W with respect to the strain tensor ε_{ij}, yielding

$$\sigma_{ij} = \frac{\partial W}{\partial \varepsilon_{ij}}. \tag{S3}$$

S1.2 Design of the Caudal Fin

Upon electrical activation, the SMA springs contract and induce bending of the elastomer toward the activated side, while the antagonistic SMA springs on the opposite side provide tensile resistance. In air, the system remains in a statically deformed configuration under the combined action of contraction and antagonistic tensile forces. The resulting deformation can be approximated by a pure bending model. Since the SMA springs are fixed only at their two ends, the direction of the axial force varies with deformation; however, it always points toward the fixed ends, leading to a bending moment that changes continuously during motion.

To provide qualitative design guidance for the BCF actuator, the tail deformation is described using a simplified pure-bending model. Under the bending assumption, the neutral layer of the elastomer undergoes no longitudinal displacement, and the curvature radius ρ can be approximated as

$$\rho = \frac{EI}{M}, \tag{S4}$$

where E is the elastic modulus of the elastomer, I is the second moment of area, and M is the bending moment generated by the antagonistic SMA springs.

Considering the force balance between the contraction-side SMA springs and the antagonistic tensile springs, the bending moment can be expressed as

$$M = (F_A \cos\alpha - F_B)\left(\frac{d_c}{2} + d\right), \tag{S5}$$

where F_A and F_B denote the contraction force and the antagonistic tensile force of the SMA springs, respectively, d_c is the elastomer thickness, d is the distance between the SMA spring and the neutral layer, and α is the angle between the SMA force direction and the neutral layer. For a rectangular elastomer cross-section, the second moment of area is given by

$$I = \frac{W d_c^3}{12}, \tag{S6}$$

where W is the elastomer width. The SMA forces are related to the corresponding stresses by

$$F_A = n\sigma_A \frac{\pi d^2}{4}, F_B = n\sigma_B \frac{\pi d^2}{4}, \tag{S7}$$

where n is the number of SMA springs, σ_A is the contraction stress, and σ_B is the tensile stress at ambient temperature. The antagonistic tensile stress is approximated by Hooke's law,

$$\sigma_B = \varepsilon_B E_M, \tag{S8}$$

where ε_B and E_M denote the tensile strain and elastic modulus of the SMA material, respectively.

Based on geometric compatibility, the SMA contraction strain ε_A is related to the curvature and bending angle of the caudal fin. With the effective tail length $L = \rho\theta$ and the geometric definition of α, a direct relationship between the SMA strain and the caudal-fin bending angle θ can be established. Likewise, the pure-bending model of the caudal fin is a simplified quasi-static representation intended to capture the dominant relationship between antagonistic SMA actuation and tail curvature. The model does not include time-varying SMA force evolution, geometric nonlinearity, neutral-axis migration, or hydrodynamic damping. Therefore, it is used here to identify the dominant structural factors governing deformation trends, but not as a fully predictive model for swimming performance or formal design optimization.

S2 Detailed Fabrication and Assembly Procedures of the PCF Robot

S2.1 Detailed fabrication of the bellows-like membrane

The bellows-like membrane used in this study served as the primary compliant waterproof barrier between the internal actuation cavity and the surrounding aquatic environment. The fabrication overview is shown in Fig. 1a of the main text. The membrane mold was first designed in UG/NX and fabricated by fused deposition modeling using PLA filament. After mold preparation, the two components of the AB adhesive were weighed at a 1:1 mass ratio and mixed thoroughly for 2–5 min. The mixture was then vacuum-degassed to remove entrapped air bubbles before casting. The degassed adhesive was applied onto the mold in a top-down manner and deposited in multiple successive layers. To ensure sufficient thickness and mechanical robustness, each new layer was applied only after the previous layer had reached a semi-cured state. The interval between adjacent coating steps was maintained at 2–5 h at an ambient temperature of approximately 25 °C. According to the local deformation requirement, a three-layer coating was used for the pectoral-fin region, whereas a five-layer coating was used for the caudal-fin region. After complete curing, excess material was removed and the membrane was trimmed to the target dimensions. This multilayer casting route was adopted to improve thickness uniformity, interlayer integrity, and fatigue resistance during repeated underwater deformation. Although no independent standardized fatigue-limit test was conducted for the multilayer AB adhesive membrane, pre-experiments showed no membrane rupture or leakage during repeated underwater operation, indicating adequate mechanical

durability for the tested operating conditions.

S2.2 Detailed fabrication and waterproof packaging of the biomimetic pectoral fin

The detailed fabrication process of the biomimetic pectoral fin is summarized in Fig. 1b of the main text. A 0.3 mm thick PMMA sheet was used as the structural substrate and was precision-cut according to the target pectoral-fin profile, with a dimensional accuracy within ±0.1 mm. The 0.3 mm PMMA sheet was selected for the pectoral-fin substrate because it provides a favorable balance between structural stiffness and bending compliance, while also offering good dimensional stability, optical transparency, ease of fabrication, and water resistance. The reduced thickness is critical for enabling biologically inspired flapping deformation under the limited output force of the SMA actuator. For the caudal fin, the 20 Shore A AB adhesive was selected as a compliant elastomer to provide the large reversible deformation and elastic recovery required for antagonistic SMA-spring actuation. In this work, literature- or datasheet-based material properties are used only as engineering reference ranges for design interpretation, rather than as experimentally identified constitutive parameters. The SMA positioning fixtures were modeled in UG/NX and fabricated by FDM-based 3D printing using PLA. To avoid mutual interference among adjacent SMA wires while preserving distributed actuation along the fin surface, the fixtures were designed with nonuniform limiting-hole spacing. Pretreated large-strain SMA wires were stretched to their maximum recoverable strain, approximately 8%, and sequentially threaded through the limiting holes to form a four-channel fin-ray-inspired actuation configuration. Electrical connections were established at both ends of the SMA wires, and the assembled actuator pair was symmetrically mounted on both sides of the PMMA substrate using M2 screws. Sufficient reserved space was maintained for subsequent integration with the robot body and for wire routing.

To ensure reliable underwater operation, the pectoral-fin actuator was encapsulated using a multilayer waterproof sealing strategy. A bellows-like membrane with a thickness of 0.5 mm was first fitted over the actuator assembly, and Kafuter K-704N silicone sealant was applied at the membrane openings while leaving one opening available for coolant injection. After room-temperature curing for 2–5 h, the cooling medium was introduced until approximately 90% of the internal cavity volume was filled. The remaining opening was then secondarily sealed using K-704N. After complete curing, Kafuter K-705 transparent silicone sealant was further applied at the sealing interfaces to enhance waterproof reliability. During the final sealing stage, the assembly was suspended horizontally to prevent undesirable adhesion between the sealant and the membrane surface. This packaging procedure allowed the pectoral-fin actuator to function simultaneously as a compliant flapping unit and as a sealed liquid-cooled module.

S2.3 Detailed fabrication of the caudal actuator and passive liquid-cooling cavity

The fabrication route of the biomimetic caudal actuator is shown in Fig. 2a and Fig. 2b of the

main text. The elastomeric tail components were produced by casting AB adhesive into dedicated molds while integrating multifunctional connectors that served both as SMA mounting interfaces and as mechanical links between neighboring elastomer segments. The molds and connectors were first modeled in UG/NX and then fabricated by FDM-based 3D printing. During casting, the connectors were positioned at both ends of the mold; one end was sealed with waterproof tape, whereas the other end was reserved for adhesive injection. After vacuum degassing, the AB adhesive mixture was poured into the mold, and mechanical vibration was applied to improve filling completeness. The mold was then placed in a salt-bath environment and cured at 25 °C for more than 5 h before demolding. After curing, the connectors were assembled by shaft–hole alignment and fixed using stainless-steel pins. To mitigate local thermal effects generated by SMA actuation, red copper bushings were embedded into the connector holes, after which pretreated SMA springs were threaded through the copper bushings and electrically connected at both ends.

The caudal fin itself was fabricated as a rigid passive hydrodynamic component. Its geometry was modeled in UG/NX, processed in slicing software, and fabricated by FDM 3D printing using PLA. The printed caudal fin was connected to the actuation chain via a dedicated fin connector and mounted at the distal end of the elastomeric tail through pin fixation. The sealing interface between the caudal section and the rigid body adopted a composite structural design. Specifically, a compliant sealing element cast from 20 Shore A AB adhesive was combined with rigid printed connecting elements, so that both sealing reliability and torsion-resistant structural connection could be achieved. Mechanical fixation to the body was realized using M3 stainless-steel screws, while the connection between elastomer and rigid components was reinforced using semi-cylindrical pins.

For external encapsulation of the caudal actuator, a bellows-like membrane produced through four to six repeated coating cycles was fitted over the elastomeric body. K-705 adhesive was applied to bond the membrane to both the waterproof sealing end and the caudal-fin connector. At the distal end, a high-strength structural adhesive was additionally used, followed by another K-705 coating to improve sealing continuity. To reduce thermal accumulation of the SMA springs and improve actuation repeatability, the caudal cavity was then filled with an appropriate amount of cooling medium. During this process, the entire caudal assembly was suspended with the sealing end facing upward, and the coolant was injected through a reserved opening until the elastomeric body was fully submerged. The injection opening was subsequently sealed with K-705. Through this procedure, the caudal actuator realized mechanical bending, waterproof encapsulation, and passive liquid-assisted thermal management in a single integrated structure.

S2.4 Fabrication of rigid components

The rigid body module served multiple functions, including housing of the control system,

accommodation of the ultrasonic sensing unit, and provision of mounting interfaces for the bilateral pectoral-fin actuators and the caudal section. To satisfy these requirements, the body geometry was designed with an optimized pectoral-fin mounting region at the head–body transition and a reinforced rigid connection interface at the body–tail junction. The body module was modeled in UG/NX and fabricated as a monolithic transparent PLA structure by 3D printing. In addition, a dedicated enclosure for control-system integration was designed separately and connected to the main body in a modular manner. This rigid-component design enabled geometric consistency, facilitated maintenance, and provided a stable support platform for the rigid–soft integrated robot architecture.

S2.5 Detailed assembly procedure and structural parameters

The final PCF robot was assembled according to a modular design philosophy, as shown in Fig. 2c of the main text. Individual functional modules were mechanically integrated using M2 screws to ensure repeatable assembly and replacement. During assembly, dual fixation was adopted at both the ultrasonic-sensor location and the bilateral pectoral-fin interfaces. Kafuter K-704N silicone sealant was applied not only to reinforce the mechanical joints but also to improve waterproof sealing and vibration resistance. The final robot had an overall length of 386 ± 0.5 mm, including a 201 mm body module, a 130 mm biomimetic caudal section, and a 55 mm caudal fin. Its total width was 218 ± 0.5 mm, with the main body accounting for 58 mm and each pectoral fin extending to a lateral span of 80 mm. The total mass of the assembled robot was 721 ± 5 g, of which 436 g corresponded to the body module with integrated electronics, 74 g to the bilateral pectoral fins, and 211 g to the caudal section. These structural parameters are reported here to support reproducibility and to clarify the mass and geometric distribution underlying the locomotion experiments described in the main text.

S2.6 Relationship between structural fabrication and thermal-management implementation

The passive liquid-thermal-management strategy of the robot was realized structurally rather than through the addition of an external cooling device. Specifically, the bellows-like membrane and associated sealing interfaces created enclosed cavities around both the pectoral and caudal SMA actuators, thereby allowing the coolant to remain in direct thermal contact with the active SMA elements. This architecture was selected to preserve system compactness and to avoid the added mass, volume, and control complexity associated with forced cooling. The pectoral-fin module retained the coolant within a partially filled internal cavity, whereas the caudal module employed a fully immersed configuration for the elastomer-embedded SMA springs. The thermal performance of this structurally integrated cooling scheme was subsequently evaluated experimentally in Fig. 2 of the main text.

S3 Quantitative Comparison for the Biomimetic Pectoral Fin

The optimal driving current of 2.4 A was initially identified from actuator characterization in air. To further assess whether this threshold remains applicable during underwater locomotion, additional analysis and validation were conducted from three perspectives: thermodynamic principle, component-level underwater actuation, and system-level underwater locomotion.

From the thermodynamic perspective, SMA actuation is fundamentally governed by a **temperature-driven phase transformation** rather than by current itself. The input current serves only as a means of generating Joule heat, whereas the decisive factor for actuation is whether the SMA temperature can reach the austenite-finish temperature during the heating interval. During the short transient heating stage (within 0.4 s), most of the electrical energy is used to raise the temperature of the SMA itself, and the influence of heat dissipation is relatively limited. Therefore, although heat loss is stronger underwater than in air, the same current level can still enable the SMA to approach or slightly exceed the effective phase-transition threshold within the pulse-heating duration.

It should also be emphasized that, in the present design, the SMA actuator is **not directly exposed to the surrounding water** but is instead immersed in a **sealed vegetable-oil cavity**. This liquid-filled cavity provides a thermal-buffering effect, which slows heat transfer from the SMA to the external aquatic environment and helps preserve the effectiveness of the 2.4 A excitation current during underwater operation.

To experimentally verify this point, underwater tests were carried out at both the component and system levels. The results are summarized in **错误!未找到引用源。 - 错误!未找到引用源。**.

As shown in **错误!未找到引用源。**, under 2.4 A excitation, the biomimetic pectoral fin maintained stable periodic motion underwater. Although the maximum flapping angle decreased slightly from 15° in air to 14° underwater, the actuator still retained 93.3% of its in-air amplitude, demonstrating that the 2.4 A threshold remains effective for underwater pectoral-fin actuation.

As shown in **错误!未找到引用源。**, compared with the complete fish tail tested in air, the underwater fish tail exhibited a certain reduction in swing amplitude. Nevertheless, the underwater deflection angle still reached approximately 74–75% of the maximum reference value and, more importantly, maintained stable reciprocating motion. This result directly confirms that the 2.4 A current remains sufficient to drive effective oscillatory deformation of the SMA-actuated caudal fin underwater.

As shown in **错误!未找到引用源。**, the complete PCF robot achieved stable underwater locomotion under 2.4 A excitation at 1 Hz. The robot reached a maximum speed of 45.67 mm/s

under tail-fin-only actuation and 51.33 mm/s under coordinated pectoral–caudal fin actuation. This system-level result provides direct evidence that, if 2.4 A were insufficient for underwater SMA actuation, such autonomous and stable swimming performance would not be achievable.

In summary, although some performance degradation exists underwater due to enhanced heat dissipation and increased hydrodynamic damping, the 2.4 A current threshold remains applicable in underwater locomotion. Specifically, the maximum tail swing angle decreased from 44° in air to 41° underwater, while the response time increased from 0.3–0.4 s to 0.5 s. Despite these reductions, the actuator still preserved effective reciprocating motion and enabled stable underwater swimming of the complete robot. Therefore, the applicability of the 2.4 A threshold underwater is supported jointly by the thermodynamic mechanism, the sealed liquid-cooling design, component-level underwater actuation experiments, and full-robot locomotion tests.

S4 Determination of Key Actuation Parameters for the SMA-Driven PCF Robot

This supplementary material provides the experimental and analytical basis for the selection of the key actuation parameters used in the manuscript, including the driving current, cooling time, and heating sequences for straight-line cruising, turning, and coordinated maneuvers.

S4.1 Determination of the Driving Current

The driving current was determined through systematic actuator characterization. The SMA actuator response was evaluated under different current inputs, namely 1.2 A, 1.6 A, 2.0 A, 2.4 A, 2.7 A, and 3.0 A. The results showed that increasing the current led to increases in both deformation amplitude and response speed. However, when the excitation current exceeded 2.4 A, the improvement in actuation performance became marginal. In particular, for the pectoral fin actuator, the maximum deflection angle no longer exhibited an obvious increase once the current exceeded 2.4 A. Similarly, for the caudal fin actuator, although the maximum swing angle continued to increase slightly beyond 2.4 A, the angular velocity did not improve significantly. Therefore, 2.4 A was identified as the optimal driving current, representing the effective saturation point at which the actuator achieved the best overall balance between output performance and thermal efficiency.

S4.2 Basis for Selecting the Cooling Time

The cooling time was selected based on both thermal analysis and fatigue experiments. Since SMA actuation is governed by thermally induced phase transformation, the cooling interval must be sufficient to allow the material to recover toward the martensitic state and thereby maintain repeatable cyclic actuation.

According to the thermal equilibrium analysis, under vegetable-oil-assisted cooling, the SMA temperature approached equilibrium with the cooling medium within approximately 0.15 s after the heating current was turned off, reaching about 32.7 °C. This result established the thermodynamic lower-bound reference for cooling-time selection. To further determine the practical cooling time, a set of comparative experiments was conducted at a fixed driving current of 2.4 A and a heating time of 0.4 s, with cooling times of 0.05 s, 0.1 s, 0.2 s, 0.3 s, and 0.5 s. The results are summarized as follows:

- At 0.05 s, severe thermal accumulation occurred, the steady-state temperature rose to 68 °C, and the oscillation amplitude decayed rapidly, with a decay rate of 47% by the 10th cycle.
- At 0.1 s, the steady-state temperature converged to 41 °C, and the amplitude decay rate was reduced to 8%, indicating stable cyclic operation.
- At 0.2 s, 0.3 s, and 0.5 s, the amplitude decay rates were 7%, 6%, and 5%, respectively, showing only marginal improvement in thermal stability, while the lower actuation frequency significantly reduced propulsion efficiency.

Based on these results, a cooling time of 0.1 s was selected as the optimal compromise between thermal recovery and actuation frequency. Although the SMA temperature at this condition remained slightly above the martensitic finish temperature, it was sufficient to ensure effective recovery for subsequent actuation. Moreover, under this condition, the actuator maintained stable operation for more than 200 cycles over 4 min, with an amplitude decay of less than 10%, confirming its long-term feasibility.

S4.3 Determination of the Heating Time for Straight-Line Cruising

The heating duration for straight-line cruising was determined through swimming-performance optimization experiments. Under the fixed driving current of 2.4 A and the fixed cooling time of 0.1 s, heating durations of 0.2 s, 0.4 s, 0.6 s, 0.8 s, 1.0 s, and 1.2 s were systematically compared.

The measured swimming speeds showed that a heating time of 0.4 s produced the highest average cruising speed. Specifically, the caudal-fin-driven mode achieved a peak speed of 45.67 mm/s, while the pectoral-fin-driven mode achieved 11.25 mm/s. When the heating duration was shorter than 0.4 s, the SMA phase transformation was incomplete, resulting in insufficient bending amplitude and reduced thrust generation. In contrast, when the heating duration exceeded 0.4 s, although the single-stroke deformation increased, the overall actuation period became longer and the oscillation frequency decreased, which in turn reduced the average swimming speed. Therefore, 0.4 s was selected as the optimal heating duration for straight-line cruising, corresponding to a stable output frequency of approximately 1 Hz.

S4.4 Determination of the Heating Time for Turning Maneuvers

The heating duration for turning was determined through maneuverability optimization experiments. Under the same driving current of 2.4 A and cooling time of 0.1 s, the robot turning performance was evaluated using different heating durations.

The experimental results showed that turning performance improved as the heating time increased from 0.2 s to 0.8 s. At 0.8 s, the robot achieved the minimum turning radius of 19 cm and the maximum angular velocity of 8.86°/s. This is because turning requires a sustained unilateral yaw moment, and a heating duration of 0.8 s allowed the caudal fin to reach and maintain a pronounced unilateral C-shaped deformation. When the heating duration exceeded 0.8 s, overheating led to performance deterioration, causing the turning radius to increase and the angular velocity to decrease. Therefore, 0.8 s was selected as the optimal heating duration for turning maneuvers.

S4.5 Heating Sequence for Coordinated Maneuvers

Based on the optimized parameters obtained from the single-mode experiments, the coordinated actuation sequence of the pectoral and caudal fins was designed for enhanced turning performance. During coordinated turning, the ipsilateral pectoral fin was activated synchronously with the caudal fin over the full 0.8 s heating duration, followed by a 0.1 s cooling interval. For example, during right turning, the corresponding relay sequence activated the right-side turning mode in both the pectoral and caudal fins during the first heating interval, after which the opposite side was activated in the subsequent interval.

This synchronized heating strategy reduced the turning radius from 19 cm to 15 cm, corresponding to an improvement of 21.1%, and increased the angular velocity from 8.86°/s to 10.2°/s, corresponding to an improvement of 11.9%. These results demonstrate that multimodal coordinated actuation provides superior maneuverability compared with single-fin turning.

S4.6 Summary of Parameter Selection

The final actuation parameters were selected according to the following logic:

- The driving current was fixed at 2.4 A because it corresponded to the effective saturation point of actuator output.
- The cooling time was fixed at 0.1 s because it minimized thermal accumulation while preserving a sufficiently high actuation frequency.
- The heating time for straight-line cruising was set to 0.4 s because it produced the maximum average swimming speed.
- The heating time for turning was set to 0.8 s because it yielded the minimum turning

radius and maximum angular velocity.

- The coordinated heating sequence was designed by synchronizing the ipsilateral pectoral and caudal fins, which further improved turning performance.

Table S1 Performance Comparison Between the Proposed PCF Robot and Representative SMA-Driven Underwater Robots

Study	Actuation Method	Body Length (mm)	Speed (mm/s)	Turning Radius	Angular Velocity	Locomotion Modes	Coordinated Control
This work (basic locomotion mode)	SMA spring (caudal) and large-strain SMA (pectoral)	386	45.67	0.39 BL	10.2°/s	5	✓
This work (multi-mode locomotion)	Same as above	386	51.33	0.39 BL	10.2°/s	5	✓
Lattice-enhanced SMA jellyfish (Li et al., 2025)	Lattice-enhanced SMA	–	–	–	–	–	×
SMA biomimetic jellyfish (Luo et al., 2024)	SMA spring	118	39	0.88 BL	14°/s	3	×
SMA biomimetic jellyfish (Yang et al., 2023b)	SMA artificial muscle	–	126.1	319.5 mm	–	Multiple	×
KryptoJelly (Almubarak et al., 2020)	SMA wire	170	60	–	–	2–3	×
SMA wire-driven micro robotic fish (Wang et al., 2008)	SMA wire	Not specified	112	136 mm	–	2	×

Table S2 Performance Comparison of Underwater Soft Robots Based on Different Actuation Technologies

Actuation Type	Study	Speed (BL/s)	Turning Radius	Advantages	Limitations
SMA	This work	0.118–0.133	0.39 BL	Compact, low voltage, optimal turning radius	Relatively low speed, frequency-limited
SMA	SMA biomimetic jellyfish (Luo et al., 2024)	0.33	0.88 BL	Higher speed	Large turning radius
DEA	DEA soft robotic fish (Shintake et al., 2018)	0.76	–	High speed, high efficiency	Requires kilovolt-level high voltage
IPMC	IPMC robotic fish (Safari et al., 2022)	0.43	–	Low voltage, flexible	Low output force
Pneumatic	Pneumatic soft jellyfish (Joshi et al., 2019)	0.38	–	Large output force	Depends on external air supply
Motor-driven	Biomimetic tuna (Huang et al., 2024)	1.31	–	High speed	Rigid structure, noise

Table S3 Comparison of Swimming Speed Between the Proposed PCF Robot and Representative SMA-Driven Robots

Study	Speed (BL/s)	Comparison with PCF Robot
SMA biomimetic jellyfish (Luo et al., 2024)	0.33	Approximately 2.8 times that of this work
SMA wire-driven fish (Wang et al., 2008)	~0.5–0.6*	Approximately 4–5 times that of this work
Lattice-enhanced SMA jellyfish (Li et al., 2025)	111% improvement*	Significant relative enhancement
KryptoJelly (Almubarak et al., 2020)	0.30	Approximately 2.5 times that of this work
This work (multi-mode locomotion)	0.133	Baseline

Table S4 Comparison of Maneuverability Between the Proposed PCF Robot and Representative SMA-Driven Robots

Study	Turning Radius	Angular Velocity	Comparison with PCF Robot
SMA biomimetic jellyfish (Luo et al., 2024)	0.88 BL	14°/s	Radius is 126% larger than that of this work
SMA biomimetic jellyfish (Yang et al., 2023b)	319.5 mm	–	Radius is 113% larger than that of this work
SMA wire-driven fish (Wang et al., 2008)	136 mm	–	Radius is 33% larger than that of this work
This work (multi-mode locomotion)	0.39 BL (15 cm)	10.2°/s	Baseline

Table S5 Comparison of Locomotion Mode Diversity Between the Proposed PCF Robot and Representative SMA-Driven Robots

Study	Number of Locomotion Modes	Pectoral–Caudal Coordination	Autonomous Obstacle Avoidance
This work	5	✓	✓
SMA biomimetic jellyfish (Luo et al., 2024)	2–3	×	×
SMA wire-driven fish (Wang et al., 2008)	2	×	×
KryptoJelly (Almubarak et al., 2020)	2–3	×	×
Lattice-enhanced SMA jellyfish (Li et al., 2025)	Not specified	×	×

Table S6 Comparison of Standardized Performance Met-rics of Robots

Study	Actuation Method	Speed (BL/s)	Re	Turning Radius (BL)
This work	SMA (spring and large-strain deformation)	0.133 (multi-mode locomotion)	1.76×10^4	0.39–0.49
SoRoFAAM-1 (Tsimbo et al., 2023)	SMA artificial muscle	~0.38*	$\sim 1.5 \times 10^4$	–
SMA-driven biomimetic jellyfish (Yang et al., 2023a)	SMA spring	0.33	$\sim 4 \times 10^3$	0.88

Study	Actuation Method	Speed (BL/s)	Re	Turning Radius (BL)
DEA soft robotic fish (Wang et al., 2024)	DEA	0.76	~3×10^4	–
IPMC robotic fish (Hubbard et al., 2013)	IPMC	0.43	~1.7×10^4	–

Table S7 Comparison of obstacle-avoidance capability with related underwater soft robots

Study	Obstacle Avoidance	Sensor Configuration	Decision Strategy	Limitation
This work	Yes (physical validation)	Single ultrasonic sensor	Left-turn priority	May fail when the left side is also blocked
SMA biomimetic jellyfish (Yang et al., 2023b)	No	–	–	–
SoRoFAAM-1 (Tsimbo et al., 2023)	No	–	–	–
SMA wire-driven fish (Wang et al., 2008)	No	–	–	–
IPMC-driven robotic fish (Hubbard et al., 2013)	Yes (simulation only)	–	Collision-cone method	Simulation only

Table S8 Comparison of the Proposed PCF Robot with Representative SMA-Driven and Other Smart-Material-Driven Underwater Soft Robots

Study	Core Actuation Material	Biomimetic Actuation Strategy	Actuation System Complexity	Cooling / Thermal Management	Power Supply / Driving Voltage	Output Force	Locomotion Mode Diversity	Autonomous Environmental Interaction	Biocompatibility
This work	SMA (large-strain SMA and SMA spring)	Coordinated BCF and MPF (pectoral fin and caudal fin)	Low (direct electrical actuation)	Integrated liquid cooling (vegetable oil, improving response and lifetime)	Low voltage (5–12 V)	Large	Multimodal (straight swimming, coordinated turning, autonomous obstacle avoidance)	Yes (ultrasonic obstacle avoidance)	High (no rejection from fish schools)
SoRoFAAM-1 (Tsimbo et al., 2023)	SMA	BCF (caudal fin only)	Low	Cyclic heating strategy (improved heat dissipation)	Low voltage	Medium	Single mode	No	Medium
Kim et al. (2017)	SMA	MPF (pectoral fin only)	Low	Not explicitly reported	Low voltage	Small (15 mN)	Single mode	No (lacks buoyancy control)	Medium
Marchese et al. (2014)/ Katzschmann et al. (2018)	Pneumatic / hydraulic	BCF (caudal fin only)	High (pumps, valves, gas cylinder)	Not applicable	Not applicable	Large	Mainly single mode	No	Low (high noise)
Berg (2019)	Motor and cable	BCF (caudal fin only)	High (motor, gears, cables)	Not applicable	Not applicable	Medium	Mainly single mode	No	Medium (some noise)
Wang et al. (2024)	DEAs	BCF (caudal fin only)	Low	Ambient cooling	High voltage (kilovolt level)	Medium	Single mode	No	High (silent)
Safari et al. (2022) / Sunkara et al. (2016)	IPMC	BCF or MPF (caudal fin or pectoral fin)	Low	Operates in wet environment	Low voltage (1–5 V)	Small	Multimodal possible, but with complex control	Yes in some studies; Sunkara et al. achieved obstacle avoidance	High (silent)