

Design and Iterative Evaluation of a Sea Star-Inspired Robot with Autonomous Rays

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Abstract—Sea stars (*Asteroidea*) exhibit exceptional locomotive robustness, maintaining effective mobility even following severe peripheral injury or limb autotomy. However, the precise interplay between morphological parameters and the control system that produces this robust locomotion remains an open question. To investigate this relationship, we have built a robotic platform that embodies the modularity observed in sea stars. The platform consists of five compliant, cable-driven limbs that attach magnetically to the central body. This modularity permits easy limb reconfiguration to test different morphological arrangements. To increase propulsion, the limbs are covered with an artificial skin featuring molded silicone bristles. These bristles produce passive anisotropic friction, which is analogous to the adhesive and locomotive action of a sea star’s tube feet. Empirical testing of various bristle arrangements revealed that bristle distribution is a critical parameter influencing locomotive efficacy. This platform provides a physical model to systematically study the complex relationship between morphology and control in organisms with non-centralized nervous systems, while enabling the design and iterative evaluation of morphology-dependent locomotion in sea star-inspired robotic systems.

I. INTRODUCTION

Biological sea stars (*Asteroidea*) exhibit locomotor resilience and environmental adaptability, capable of navigating complex benthic terrains despite the absence of a centralized brain. This robust mobility is mediated by a highly decentralized nervous system that coordinates thousands of hydraulically actuated tube feet, coupled with a network of mutable collagenous tissue capable of dynamically modulating body stiffness [1]. Crucially, sea stars possess the ability to maintain effective, directed locomotion even after limb loss [2], [3]. This inherent fault tolerance arises from a profound interplay between their radially symmetric morphology, distributed actuation mechanisms, and localized environmental interactions, highlighting a masterpiece of decentralized control and mechanical adaptability.

The profound morphological plasticity observed within the class (*Asteroidea*) serves as a versatile biological template for multi-appendage robotic development [1], [2], [4]. These organisms exhibit significant inter-species variance in ray count, structural stiffness gradients, and gait strategies, suggesting that sea star-inspired robotics encompasses a vast design space rather than a singular architectural archetype. Central to navigating this space is the selection of an actuation modality, which serves as the primary determinant

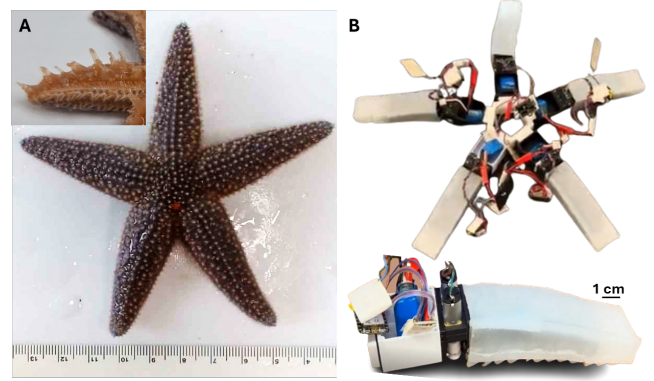


Fig. 1. **Bioinspired design of the modular robotic sea star.** (A) A biological sea star (*Asteroidea*). The inset highlights the ambulatory tube feet located on the oral surface of the ray, which drive biological locomotion. (B) Our bio-inspired, modular robotic sea star, featuring five actuated rays radially distributed around a central body. The bottom panel illustrates an isolated, fully autonomous single robotic ray module.

for the system’s mechanical impedance, control bandwidth, and environmental adaptability.

Extant literature demonstrates a broad spectrum of actuation strategies aimed at emulating *Asteroidean* mechanics [5]–[15]. Researchers have utilized fluidic and hydraulic systems to replicate the hydrostatic functionality of biological tube feet [6], [16], while pneumatic soft actuators have been widely adopted to facilitate high-compliance limb deformation and multi-modal gait transitions [7], [8]. Solid-state, thermally-activated designs leveraging Shape Memory Alloys (SMA) offer advantages in miniaturization and high energy density [9], [10], whereas electromechanical motor-driven mechanisms provide the high-bandwidth coordination required for complex limb kinematics [11]. Furthermore, magnetically-coupled platforms have recently emerged as a viable solution for specialized tasks involving reversible substrate attachment and precision steering [6], [13].

While these methodologies offer distinct functional advantages, cable-driven architectures represent a compelling middle ground. They facilitate efficient force transmission and high power-to-weight ratios while preserving the passive structural compliance necessary for traversing unstructured terrestrial environments. Building upon these precedents, the current work adopts a modular, cable-driven limb architecture. This platform enables a systematic investigation into the coupling between limb configuration and surface-interaction physics, specifically, the role of distributed passive anisotropic friction. By utilizing a modular framework, we provide a physical model to evaluate the inherent ro-

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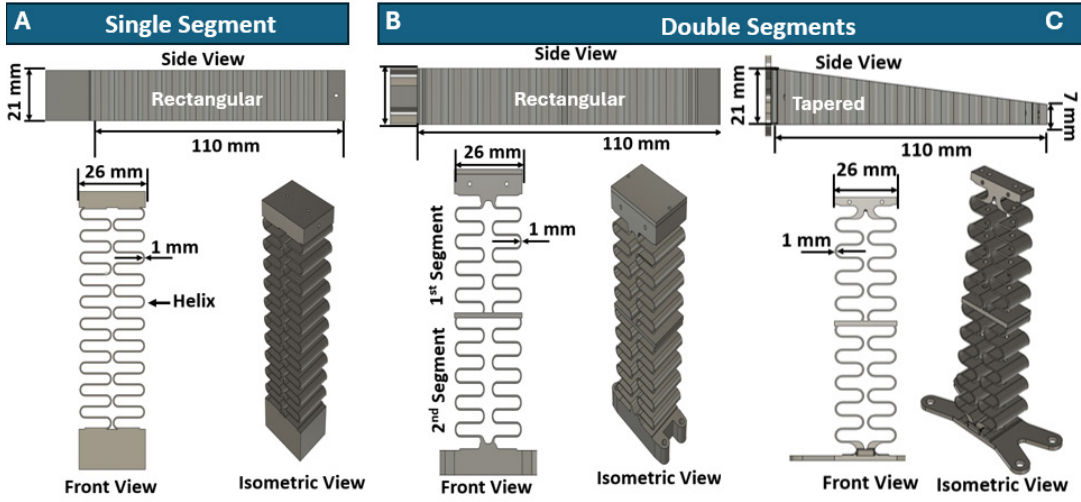


Fig. 2. **Structural design of robotic ray.** (A) Single Segment Double Helix. Mirror-image helices, 1 mm wall thickness, 1 mm hollow channel for cables. (B) Double Segment Double Helix. Two segments, 2.2 mm wall thickness, better load distribution, and controlled bending. (C) Tapered Double Segment design, withstands maximum load, no bulging, improved compression, and bending.

bustness and fault tolerance typical of decentralized, multi-appendage biological systems.

Recent studies have demonstrated that combining tendon-driven actuation with soft, compliant structures enhances kinematic flexibility and multi-modal performance [17], while the integration of bending, contraction, and expansion modalities significantly improves overall locomotion efficiency [18], [19]. However, the underlying mechanisms by which limb number, spatial arrangement, and surface friction collectively enable adaptive locomotion remain poorly understood. A significant gap persists in experimentally characterizing this morphology–control coupling, particularly in understanding how different limb configurations influence locomotion performance and morphology-dependent behavior in modular robotic systems.

To systematically investigate this morphology–control coupling, we developed a modular, bio-inspired robotic platform featuring cable-driven, compliant limbs (Fig.1). Unlike monolithic soft robots, our design incorporates magnetically detachable limb modules centered around a central hub, establishing a rapid-reconfiguration framework. This allows for the empirical study of how varying limb counts and spatial distributions affect locomotion performance and fault tolerance. Each 3D-printed, compliant limb is capable of multimodal deformation (compression and bending) and operates under a decentralized, limb-level control architecture, mirroring the distributed autonomy of biological Asteroidea. While this platform is ultimately designed to study deep morphology–control co-adaptation, the work presented here focuses primarily on physical reconfigurations, with control aspects limited to preliminary baseline evaluations.

To emulate the specialized substrate interactions of biological tube feet, we integrated an artificial passive skin embedded with directional bristles onto the ventral surface of the limbs. By systematically varying bristle orientation and distribution, we examine how passive frictional asymmetry generates directional friction-based locomotion. Together,

these elements provide a comprehensive physical testbed for dissecting the contributions of morphology, limb configuration, and substrate interaction to robust multi-appendage locomotion.

In summary, the primary contributions of this work are: (1) The design and development of a modular robotic sea star utilizing cable-driven, compliant limbs to physically study decentralized coordination. (2) An empirical investigation into the role of bristle-mediated passive anisotropic friction in optimizing propulsion efficiency and directional control. (3) The evaluation of a reconfigurable testbed to investigate how structural redundancy affects fault tolerance, supported by preliminary characterizations of its decentralized control architecture. Ultimately, this framework lays the groundwork for developing robust, adaptive morphology–control co-design strategies for soft, resilient robotic systems operating in unpredictable environments.

II. MATERIALS AND METHODS

The platform architecture prioritizes modularity to enable systematic investigations into topological variations. A hexagonal chassis serves as the central structural hub, featuring magnetic interface ports that facilitate the rapid coupling and de-coupling of individual rays. This configuration allows for the empirical evaluation of locomotion across a range of 1 to 5 appendages, providing a repeatable framework for studying the influence of different limb configurations on locomotion performance and coordination. By utilizing magnetic interconnects, we minimize the downtime between experimental trials, allowing for the consistent reconfiguration of the robot’s morphology to characterize performance across various limb arrangements.

A. Single Autonomous Robotic Ray Architecture

In this project, the sea star ray constitutes the fundamental locomotion module and, consequently, the most critical component of the robotic system. Each ray functions as an independent appendage capable of generating autonomous

motion; thus, its mechanical behavior directly determines the overall mobility, efficiency, and locomotion performance of the sea star platform.

The primary design objective was to engineer a ray capable of achieving uniform axial compression and controlled bending under external loading while maintaining reliable autonomous actuation. To meet these requirements, a cable-driven actuation strategy was selected for its mechanical reliability, rapid response, durability, and simplified control architecture. Compared to alternative actuation approaches, cable-driven systems minimize electromechanical complexity by reducing the number of required components, such as DC motors, onboard power sources, and control electronics, thereby enabling a lighter and more energy-efficient design.

A central design challenge was achieving an optimal balance between structural compliance and load-bearing capacity. The ray needed to be sufficiently lightweight to maximize actuation efficiency, yet mechanically robust enough to transmit cable-transmitted forces effectively, overcome ground friction, and produce consistent forward locomotion. This balance between compliance and structural integrity is essential for ensuring predictable deformation patterns and efficient terrestrial propulsion.

a) Inner flexible bone design: To achieve both compression and bending within this cable-driven configuration, we developed an initial ray composed of two mirrored helical structures. Each helix consists of stacked 1 mm thick flat plates separated by 4.5 mm gaps to facilitate axial compression, with adjacent plates connected by half-circular ring connectors to form a compliant helical architecture. The two helices are joined by solid top and bottom plates that provide structural support and cable attachment. Circular holes along the helices guide the actuation cables, which are anchored to the top plate of the ray (length = 110 mm, width = 26 mm) and driven by a DC motor to generate bending.

The initial design consisted of a single continuous helical segment with an overall height of 21 mm (Fig. 2A). Although capable of bending and compression under low loads, it exhibited non-uniform deformation and localized bulging under a 10 N load (Sec. II-C, Fig. 5A). The long unsupported helix reduced load distribution efficiency, resulting in structural instability unsuitable for reliable locomotion.

To improve structural robustness while preserving the same geometric parameters, the helix was divided into two shorter segments using an intermediate 2 mm thick plate (Fig. 2B). This reduced the unsupported length, improved load distribution, and eliminated bulging under the same 10 N load, providing stable compression and bending.

To further reduce weight while maintaining mechanical performance, the segmented design was modified into a tapered architecture (Fig. 2C). Since ground interaction primarily occurs along the bottom surface, while the upper region mainly provides structural support, the ray height was gradually reduced from 21 mm to 7 mm. This modification decreased the overall weight by approximately 33% while preserving uniform compression and bending. In addition, the cable routing was aligned parallel to the top surface to im-

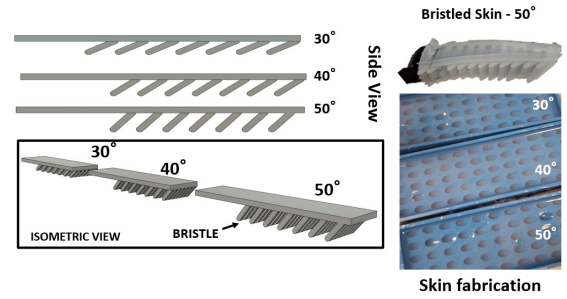


Fig. 3. **Artificial Skin Design and Fabrication.** (Left) Three bristle angles (30°, 40°, and 50°) are shown. (Right) Fabrication of the silicone-bristle skin using a custom-designed mold.

prove actuation efficiency and simplify integration. Through iterative design, experimental evaluation, and simulation-based analysis, the ray evolved from a single continuous helix to a segmented and lightweight tapered architecture, achieving improved structural stability, reduced mass, and reliable cable-driven locomotion.

b) Artificial Skin: Recent advancements in soft robotics demonstrate that tilted bristle arrays facilitate rectified locomotion by exploiting frictional anisotropy [20], [21]. This architecture establishes an asymmetric frictional bias, enabling low-impedance forward sliding while generating high-traction resistance in the opposite direction [20]. Inspired by these principles, we integrated a bristled artificial skin onto the ventral surface of a sea-star-inspired ray to provide directional traction without compromising its inherent bending kinematics (Fig. 3). While the segmented helical backbone enables controlled deformation, effective propulsion depends on generating sufficient ground reaction forces to mitigate backward slip, ensuring the efficient conversion of internal mechanical work into forward displacement.

The propulsion efficiency is governed by the interfacial frictional properties engaged during cable-driven compression and bending. Consequently, the geometric orientation, spatial distribution, and attachment configuration of the bristles are critical design parameters. The skin was fabricated as a 2 mm soft silicone layer to achieve an optimal balance between structural integrity and mechanical compliance. This slender profile ensures the skin can withstand repeated compressive loading without inducing buckling or parasitic constraints on the underlying helical structure. By minimizing interference with the ray's axial kinematics, the design preserves the mechanical fidelity of the actuator while enabling robust ground interaction.

To emulate the functional role of biological tube feet, molded silicone bristles (SI Movie 00:15-00:19) were integrated into the skin's ventral surface to induce passive anisotropic friction. These passive bristles facilitate net forward translation by maximizing traction during the power stroke (shortening and bending) and minimizing resistive drag during the recovery phase. Through a systematic assessment of different geometric orientations (see Sec. II-C.b), we characterized how the bristle alignment influences the magnitude of this frictional bias, providing complementary experimental and numerical insights to guide the design of

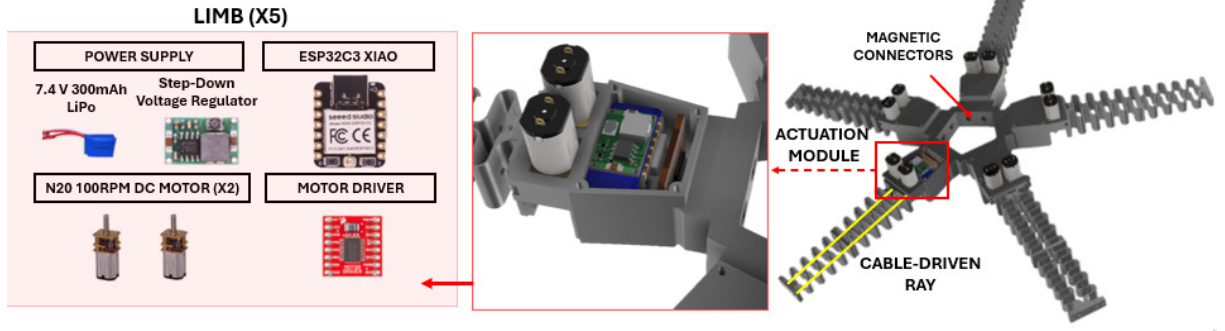


Fig. 4. **Robot Subsystems and Components.** The robotic sea star consists of five rays symmetrically distributed around the central body. The internal electronics package includes a LiPo battery, voltage regulator, motor driver, and two micro-g geared DC motors. The rays are operated via a cable-driven actuation system, mimicking the muscular-tendon dynamics of biological appendages.

the artificial skin.

B. Actuation and Control System

The complete robotic system is shown in Fig. 4, consisting of five detachable limbs mounted using magnetic joints for ease of reconfiguration and testing. The electronic system includes a distributed limb-level control architecture, with one onboard microcontroller per limb. Additionally, a graphical user interface (GUI) was developed to interact with each limb wirelessly via an ESP32 antenna. Communication between the GUI and each limb, as well as direct communication among limbs without the GUI, is managed using the ESP-NOW protocol.

Power consumption was estimated at 875 mA per limb under maximum load conditions; therefore, a 300 mAh battery was selected to support continuous operation for at least 20 minutes. In response to the measured load of 1.501 Kg f during cable pulling and given a drum radius of 2.25 mm, each limb is actuated by two N20 100 RPM 150:1 low-power 6V DC motors (SI Movie 00:10-00:15).

C. Modeling & Simulation

a) Finite element (FEA) simulation of Structural Integrity: FEA simulations were performed in Abaqus to evaluate the structural integrity and mechanical performance of the proposed sea star ray configurations. Since the lightweight ray consists of thin 3D-printed PLA plates, FEA was used to investigate load-induced deformation, stress distribution, and potential structural instabilities that could not be fully characterized experimentally. The initial configuration (Structure A) was analyzed first, and the simulation results guided subsequent design refinements.

For the structural assessment of Structures A and B, static analyses were performed in Abaqus (Fig. 5). The bottom surface of each ray was fixed to represent ground contact, while a gradually increasing compressive load was applied to the top surface. Both structures compressed uniformly up to approximately 7.5 N. Beyond this load, the single continuous helix (Structure A) exhibited lateral bending and localized bulging, indicating insufficient stiffness in the long unsupported helix. In contrast, the segmented design (Structure B) withstood a 10 N compressive load while maintaining uniform deformation and a more uniform stress distribution,

demonstrating improved load transfer and structural stability (SI Movie 00:20-00:24).

A second set of simulations evaluated the cable-driven bending performance of all three configurations (SI Movie 00:25-00:31). The bottom surface was fixed, six actuation cables were routed through the ray and tied to the top plate, and identical tensile loads were applied to each configuration. Compared with Structures A and B, the tapered design (Structure C) exhibited more uniform compression, greater bending displacement, and smoother curvature under the same cable tension while reducing structural mass. These results indicate that the tapered architecture improves actuation efficiency without compromising structural stability.

Overall, the FEA validated the evolution from a single continuous helix to a segmented and lightweight tapered design. The simulation framework also provides a basis for future optimization of geometric parameters, material selection, and strength-to-weight ratio to further improve locomotion performance.

TABLE I

FEA-CALCULATED REACTION FORCES (N) DURING ACTUATION AND RECOVERY PHASES ACROSS DIFFERENT BRISTLE ANGLES. F_C DENOTES THE CABLE FORCE APPLIED BY THE MOTOR-DRIVEN CABLE ACTUATOR.

Bristle Angle	ACTUATION		RECOVERY	
	Actuation Force (N)	Recovery Resistance (N)	Net Force Difference (N)	
30°	4.7	3.7	1.0	
40°	4.4	1.9	2.5	
50°	4.1	1.7	2.4	

b) Modeling Passive Anisotropic Friction: FEA simulations were performed in Abaqus to investigate the influence of bristle orientation on contact behavior and anisotropic friction (Fig. 6). A flat rigid plate represented the ground surface, while the bristled underside of the skin was placed in contact with the plate. Bristle inclination angles of 30°, 40°, and 50° were evaluated. A uniformly distributed load representing the PLA ray weight was first applied to compress the bristled skin against the rigid plate. The plate was then translated in the forward and backward directions using a two-step dynamic implicit analysis to quantify directional

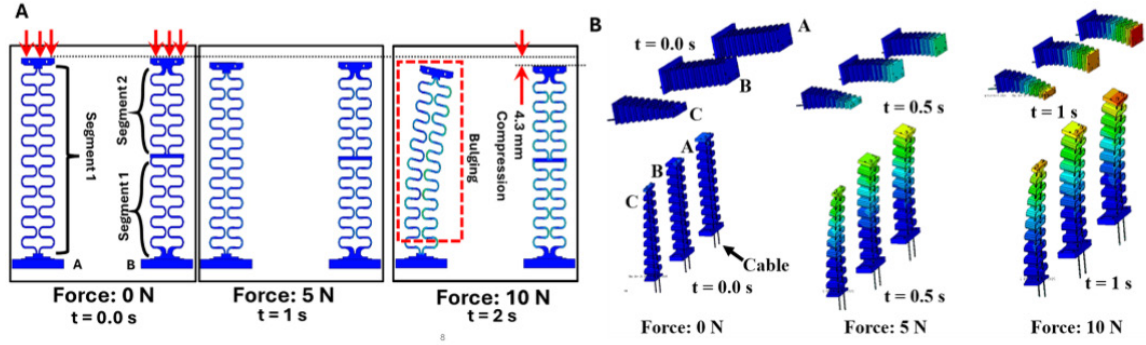


Fig. 5. **Finite Element Analysis (FEA) of the structural response across ray morphologies.** (A) Displacement profiles under a uniformly distributed load (0–10 N over a 2 s ramp) comparing single-segment and double-segment ray designs. (B) Tendon-driven actuation response for three ray variants under symmetric tensile loads of 5 N and 10 N. The contours represent the magnitude of total deformation, highlighting the axial compression and distal tip displacement inherent to each structural configuration (SI Movie 00:20:00:31).

friction. Node sets on the rigid plate were used to measure the reaction forces generated during contact (SI Movie 00:15-00:19).

To evaluate the influence of bristle geometry on directional friction, the reaction forces generated during the actuation and recovery loading directions were quantified for three bristle-angle configurations (Table I). During the actuation stroke, equal tensile loads ($F_C > 0$) were applied through the two actuation cables, compressing the ray and generating forward traction. During the recovery stroke, the cable tensions were released ($F_C = 0$), allowing the compressed ray to elastically return toward its initial configuration while the bristles slid against the ground. The reported recovery reaction force therefore represents the friction generated during this elastic recovery and does not include the internal restoring force of the compressed ray. The results reveal a clear trade-off: smaller bristle angles generate greater traction during actuation but also increase recovery resistance, demonstrating that bristle geometry plays a critical role in balancing directional friction and net propulsion.

While FEA identified the 40° configuration as providing the greatest theoretical frictional anisotropy, physical prototyping introduced real-world loading effects. The fully assembled robotic module weighs approximately 95 g, incorporating the artificial skin, structural frame, motors, battery, and onboard electronics. Under this operational load, the 50°

configuration minimized recovery drag while maintaining sufficient forward traction, ultimately yielding the greatest net forward displacement per cycle. Consequently, the 50° design was selected for the final physical prototype.

III. RESULTS

1) Mechanical Characterization of the Ray Module:

Following the optimization of the ray geometry and bristled integument via FEA, the combined assembly was modeled using tie constraints to ensure displacement continuity at the interface. A static general step was utilized to simulate the response of the two-stage tapered ray when placed in contact with a frictionless rigid plane. To characterize the deformation envelope, dual antagonistic cables anchored at the distal tip with a 3 mm transverse offset were subjected to a constant velocity boundary condition, replicating the compressive and flexural loads encountered during terrestrial gait cycles.

The mechanical integrity and actuation fidelity of the physical prototype were subsequently evaluated under controlled laboratory conditions (Fig. 7). The sea star ray, with an unactuated length of 109.5 mm, successfully sustained external loads of up to 15 N without evidence of structural failure or hysteretic deformation, confirming its suitability for load-bearing locomotion (SI Movie 00:32:00:36).

Under symmetric dual-cable actuation (5 N per cable),

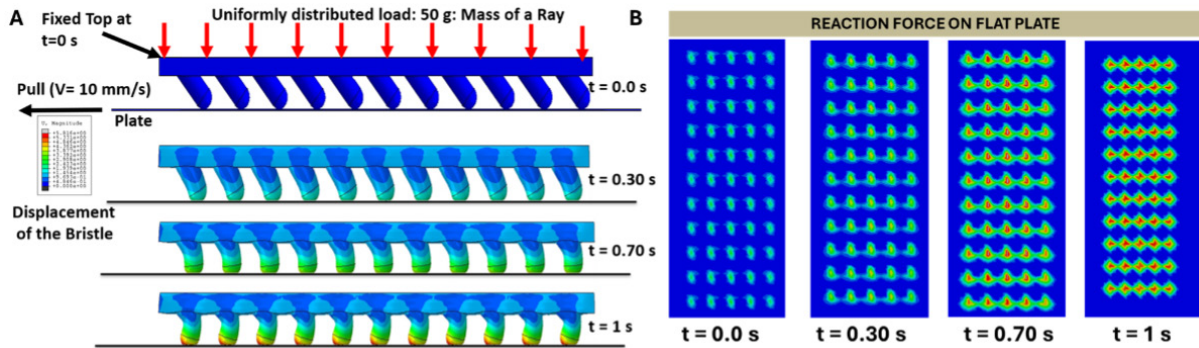


Fig. 6. **Friction analysis of a 50° bristle configuration.** (A) Simulated sliding test where the bristle skin is fixed and the substrate moves at a constant velocity (10 mm/s). Contours represent bristle displacement magnitude. (B) Resultant reaction force on the moving plate, demonstrating the directional friction generated by the bristled skin (SI Movie 00:15:00:19).

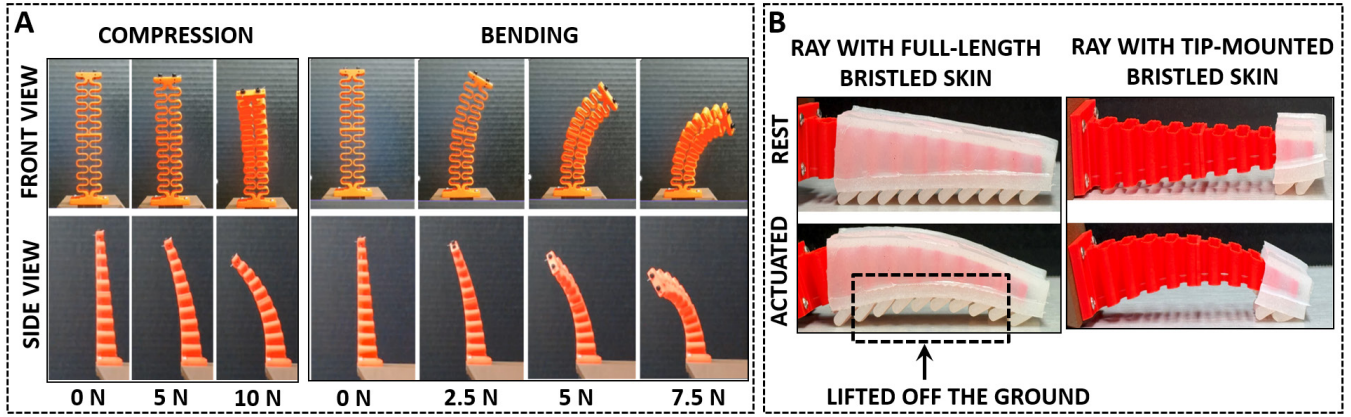


Fig. 7. **Mechanical validation of the bio-inspired ray and experimental comparison of bristle-ground interaction.** (A) Mechanical characterization of the tapered ray under axial compression (0, 5, and 10 N) and unilateral bending (0, 2.5, 5, and 7.5 N), demonstrating the compliant deformation required for cable-driven locomotion (SI Movie 00:15-00:19). (B) Comparison of full-length and tip-mounted bristled skins during the resting and actuated states. The tip-mounted skin maintains effective ground contact while reducing module weight, improving locomotion performance.

the ray demonstrated a distinct axial compression regime, resulting in an axial shortening of 15 ± 0.15 mm (13.7% longitudinal strain) and an inward tip displacement of 35 ± 1 mm ($\approx 32\%$ of the total length, averaged over three trials). Safety factor testing at 15 N further verified the structural robustness of the elastomeric matrix and internal routing channels under peak actuation forces.

To evaluate steering and lateral maneuverability, asymmetric single-cable actuation was employed to induce bending-dominated kinematics. A 5 N tensile load generated a localized bending angle of $23^\circ \pm 1^\circ$, coupled with 7 ± 0.09 mm of incidental axial compression (6.4% strain) and a 20 mm inward tip displacement (18.3% of the total length). These results demonstrate that the ray reliably transitions between high-force compression and compliant bending modes, establishing the fundamental kinematic primitives required for effective terrestrial propulsion.

An additional design refinement is illustrated in Fig. 7B, which compares the ground-contact behavior of the full-length and tip-mounted bristled skins during the resting and actuated states. The full-length skin weighs approximately 35 g, whereas the tip-mounted skin weighs only 10 g, reducing the total ray-module weight from approximately 95 g to 70

g. During compression, the full-length skin deforms with the ray, causing the bristles beneath the curved central region to lift off the ground and contribute minimally to traction generation. In contrast, the tip-mounted skin maintains effective ground contact throughout the actuation cycle while substantially reducing the module weight. This reduction in skin mass and improved ground contact decreased recovery resistance, resulting in improved forward locomotion.

2) *Locomotion Experiments:* The robot's locomotion was evaluated on a low-friction planar surface across a modular range of gait parameters. We recorded experiments from a top view via a Logitech webcam (30 fps).

The motion was defined by the actuation period (T), representing the duration of a single cycle, and the PWM duty cycle (S), which modulates the peak power delivered to the actuators (where 100% denotes full power).

Across all trials (18 in total), including single, three, and four-ray configurations with varying gait periods and duty cycles, the sea-star-inspired robot achieved a mean forward displacement of 1.27 ± 1.18 mm/s, with values ranging from 0.03 mm/s to 4.36 mm/s. These results indicate a substantial sensitivity to both morphological and actuation parameters.

One of the observations of this study is that skin morphology dictates both the magnitude and the vector of translational displacement. Under identical actuation parameters ($T = 0.5$ Hz, $S = 25\%$), decreasing the skin size resulted in a 60% improvement in forward velocity, rising from 3.72 mm/s to 6 mm/s (Fig. 8). However, the placement and scale of the compliant surface appear to govern the primary thrust direction; while larger skins facilitated forward motion, configurations with reduced skin localized strictly at the ray tips resulted in a reversal of the propulsion vector, causing the robot to move backward. Mechanically, this suggests that longer compliant surfaces with anisotropic friction increase the effective ray-ground interaction area, thereby improving transmission efficiency. Conversely, skin length does not significantly correlate with turning rate ($r \approx 0.02$), indicating that morphology primarily affects translational performance rather than directional stability in the current configurations.

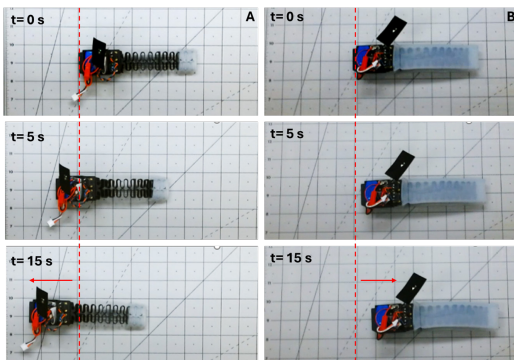


Fig. 8. **Experimental configurations for single-ray locomotion.** (A) Distal-only bristle distribution where the silicone skin is localized at the ray tip. (B) Full-length bristle distribution covering the entire longitudinal surface of the limb (SI Movie 00:37-00:41).

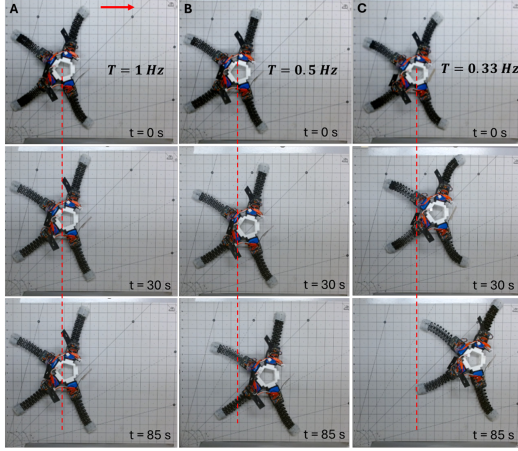


Fig. 9. **Influence of actuation period (T) on the forward displacement of a four-ray configuration.** (A) $T = 1\text{ Hz}$, (B) $T = 0.5\text{ Hz}$, (C) $T = 0.33\text{ Hz}$. Snapshots at $t = 0, 30$, and 85 s illustrate progression from the initial reference (red dashed line) along the locomotive vector (red arrow) (SI Movie 00:42-00:46).

Forward displacement exhibits a moderate positive correlation with the actuation period (T) in the four-ray configuration (Fig.9). Notably, at $T=1\text{ Hz}$, no displacement was observed. However, as the frequency was reduced to 0.5 Hz and 0.33 Hz , the forward displacement increased to 0.92 mm/s and 1.87 mm/s , respectively. This relationship suggests that slower actuation cycles (i.e., longer stroke durations) enhance propulsion speed. From a dynamics perspective, these extended periods likely facilitate more complete interaction cycles between the robotic rays and the environment, minimizing slip and reducing the occurrence of ineffective partial strokes.

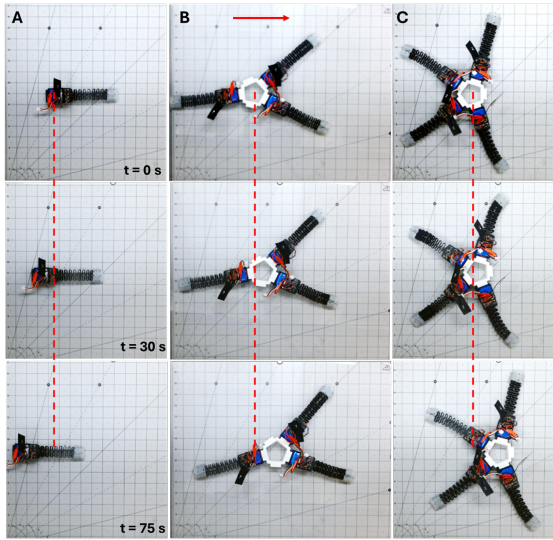


Fig. 10. **Locomotion performance of the robot with different ray configurations.** (A) Single arm, (B) Three-ray y-shape, (C) Four-ray. Snapshots at $t = 0, 30$, and 75 s illustrate progression from the initial reference (red dashed line) along the locomotive vector (red arrow) (SI Movie 00:51-00:56).

In contrast, the duty cycle demonstrates only a weak correlation with both displacement ($r \sim 0.24$) and turning ($r \sim 0.11$). These findings indicate that within the tested range (20%–100%), the system’s locomotion performance remains relatively insensitive to duty cycle variations, especially when compared to the dominant influence of skin length and actuation period.

The configuration of the rays plays a critical role in mechanical efficiency (Fig.10). While single-ray configurations produced the highest average speed when using a full-ray sleeve ($2.43 \pm 1.13\text{ mm/s}$, averaged through three runs), multi-ray configurations encountered significant torque problems due to high friction. To mitigate this, experiments with multiple rays were restricted to silicone skin covering only the ray tips. Surprisingly, increasing the number of rays did not increase forward displacement; under identical skin configurations (skin on the tip), the single-ray speed was $0.98 \pm 0.73\text{ mm/s}$ (backward, averaged through two runs) while the three-arm is $0.80 \pm 0.46\text{ mm/s}$ (averaged through four runs), and the four-ray is $0.92 \pm 0.01\text{ mm/s}$. This suggests that in the current mechanical implementation, additional rays introduce increased internal resistance, gait interference, and reduced stroke coordination efficiency. While natural sea stars rely on highly distributed coordination, this synergy has not yet been replicated in the robotic platform.

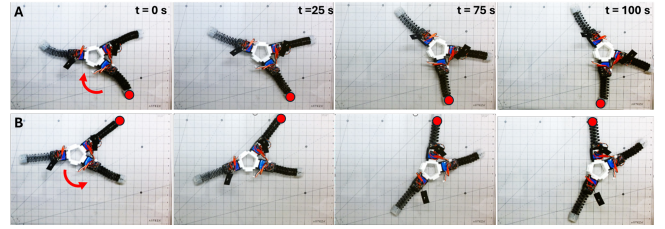


Fig. 11. **Directional steering characterization in a three-ray configuration.** (A) Clockwise (CW) and (B) counter-clockwise (CCW) turning sequences. Red dots show the pivoting ray, while red arrows indicate the direction of angular displacement. Time-lapse snapshots were captured at $t = 0, 25, 75$, and 100 s to illustrate the turning radius and gait efficacy (SI Movie 00:47-00:51).

Finally, turning behavior appears largely decoupled from the primary morphological and temporal parameters. When rays were activated with the same period and duty cycle, no turning was observed, indicating that the current actuation strategy produces approximately symmetric propulsion. Turning is not an emergent property of the passive morphology; rather, it requires deliberate asymmetry. This was demonstrated using a three-ray Y-shape configuration, where modulating the duty cycles of specific rays produced significant left ($0.44^\circ/\text{s}$) and right ($0.55^\circ/\text{s}$) turning rates (Fig.11). Ultimately, the data shows that while skin length and actuation period govern speed, directional control must be intentionally programmed through phase offsets or amplitude modulation.

IV. CONCLUSIONS

This work presents the development of a modular, bio-inspired robotic platform designed to investigate the complex

interplay between morphology, decentralized control, and morphology-dependent locomotion. By utilizing a rapidly reconfigurable framework with magnetic interfaces, we established a system capable of empirical testing across various limb counts and spatial arrangements. Our structural analysis and experimental results demonstrate that the tapered, segmented helical architecture provides an optimal balance between mechanical compliance and load-bearing capacity necessary for effective cable-driven actuation, effectively preventing the structural instabilities observed in simpler helical designs.

The integration of an artificial skin featuring molded silicone bristles successfully emulates the functional role of biological tube feet. Our findings indicate that passive anisotropic friction, governed by bristle inclination and distribution, is a critical parameter for generating efficient forward propulsion while minimizing resistive drag. By combining this specialized morphology with a decentralized control architecture, where each ray operates as an autonomous module, the platform provides a versatile experimental framework for systematically evaluating the effects of morphology and ray configuration on locomotion performance.

Ultimately, this research provides a biologically grounded methodology for designing soft, resilient robotic systems. Although the present study focused on evaluating fixed morphological configurations, the proposed modular platform establishes a foundation for future investigations of morphology-dependent locomotion. Future work will focus on integrating Central Pattern Generator (CPG) networks and Reinforcement Learning (RL) frameworks to enable adaptive inter-ray coordination, higher-level decentralized control, and robust closed-loop locomotion and turning. Specifically, we plan to leverage these CPG-RL architectures to maintain locomotion stability and adapt control policies in real time during controlled limb-loss (fault-injection) experiments. We also plan to investigate additional ray configurations, optimize the artificial skin and actuation strategy, and develop analytical and computational models to better understand the relationship between morphology, passive anisotropic friction, and locomotion performance, further advancing modular bio-inspired robotic systems for complex environments.

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A. Siddiquee conceptualized and designed the robotic rays and artificial skin and conducted the simulations. M. Castillo Gonzalez led the control development and experimental evaluation. Y. Zhu contributed to the control implementation and locomotion experiments. V. Utama conducted the structural integrity experiments on the robotic rays. Y. Ozkan-Aydin supervised the research and provided project administration. A. Siddiquee and Y. Ozkan-Aydin contributed to the writing and revision of the manuscript. All authors reviewed and approved the final manuscript. The authors would like to thank Dr. Olaf Ellers, Dr. Amy Johnson, and Dr. Matt McHenry for their invaluable insights and technical discussions regarding sea star biology and mechanics, and

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