POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Executive Summary of the Thesis

The Octopus Robot: From Biological Principles to a Soft Robotic System for Coordinated Multi-Arm Underwater Grasping

Laurea Magistrale in Mechanical Engineering - Ingegneria Meccanica

Author: Andrea Mirabelli

Advisor: Prof. Giovanni Bianchi

Co-advisors: Barbara Mazzolai, Emanuele Solfiti

Academic year: 2025-2026

1. Introduction

Underwater manipulation in unstructured and dynamic environments remains a major challenge in marine robotics. Tasks such as biological sampling, environmental monitoring, and delicate object retrieval require safe interaction with complex and fragile targets. Traditional rigid grippers, although precise and capable of high payloads, lack intrinsic compliance and are therefore increasingly being replaced by soft robotic solutions, which exploit compliant materials to passively adapt to unknown shapes. Among biological models, the octopus represents a paradigmatic system for advanced underwater manipulation, thanks to its flexible muscular hydrostat architecture and the cooperative use of multiple arms. Current research on octopus-inspired soft robotics has predominantly focused on single-arm systems, an approach that inherently limits grasp stability, payload capacity, and effective manipulation of free-floating objects in open water. This work addresses this gap by introducing and experimentally validating a novel multi-arm octopus-inspired soft robotic system. Starting from a tendon-driven single-arm architecture, a three-arm configuration with an additional translational degree of freedom is developed, to enable cooperative manipulation strategies. The design is guided by a dedicated biological investigation conducted in *Acquario di Genova*, from which key grasping principles were extracted and translated into engineering solutions. The development process included the design and experimental characterization of a single soft arm, with two distinct tendon-routing configurations, followed by the mechanical and structural design of the multi-arm platform, its fabrication, the implementation of the electronic architecture, and the development of dedicated control strategies.
The final experimental validation demonstrates that the cooperative multi-arm architecture significantly enhances grasping performance, confirming the effectiveness of bio-inspired coordinated manipulation for advanced underwater applications.

2. State of the Art

Underwater manipulation has traditionally relied on rigid robotic manipulators. Several studies have highlighted the challenges associated with these types of grippers, particularly in biological sampling tasks where excessive contact forces can compromise specimen integrity [6].

Soft Robotics has progressively gained relevance in this field, as deformable continuum structures enable adaptive contact with complex geometries, while reducing the need for accurate modeling and force control [8]. In marine environments, soft grippers based on bellows-type actuators have been successfully employed for delicate biological sampling tasks. These devices rely on thin, deformable chambers that expand under fluid pressure [3], generating large bending deformations while maintaining low contact forces. Other implementations have further optimized these architectures for ultragentle manipulation, enabling the grasping of extremely fragile organisms, while minimizing mechanical stress [9]. An alternative approach relies on tendon-driven continuum structures, in which embedded cables generate controlled bending through differential tension. This strategy allows the actuation components to remain isolated from the wet environment, offering improved structural simplicity while preserving a fully soft external structure.
Among tendon-driven solutions, octopus-inspired robotic arms represent one of the most extensively investigated bio-inspired implementations. Early octopus-inspired robotic arms successfully replicated the concept of "muscular hydrostat" (Figure 1), using silicone structures with embedded tendons and shape memory alloys [5].

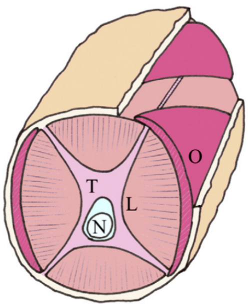


Figure 1: Schematic drawing of octopus arm section: (O) oblique, (T) transverse and (L) longitudinal muscles, (N) nerve cord. Reprinted from [2].

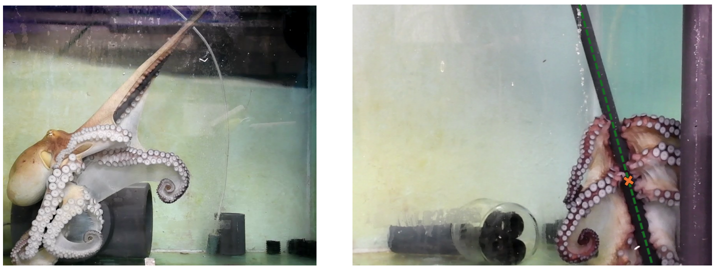
More recent developments introduced soft arms with integrated suction cups for enhanced grasping in confined environments, demonstrating improved adhesion and operational robustness (Mazzolai et al. [7]). Despite these advances, most existing implementations remain confined to single-arm architectures; although demonstrating effective bending and wrapping capabilities, they inherently lack the cooperative interaction observed in biological octopuses. This gap motivates the transition toward multi-arm octopus-inspired robotic systems capable of cooperative underwater manipulation.

3. Biological Investigation

To support the transition from single-arm to multi-arm robotic architectures, a dedicated biological investigation was conducted in *Acquario di Genova* to analyze natural octopus grasping behaviors in controlled conditions.
Several octopus arm actions have been extensively characterized in the literature, including fetching, reaching, and twisting motions, which describe the fundamental kinematic strategies adopted during interaction with the environment [1]. In parallel, decision-making processes underlying arm recruitment and target selection have also been investigated [4], systematically employing objects hidden behind obstacles. Consequently, these previous studies primarily address behavioral and cognitive aspects rather than unconstrained object manipulation.
For this reason, the experiments consisted in observing three species of octopus (*Enteroctopus dofleini*, *Octopus vulgaris* and *Octopus maya*), interacting with objects of different sizes and geometries (such as spheres, jars and sticks), in the open but controlled aquarium environments. The analysis revealed that octopus grasping rarely relies on the use of a single arm (with the exception of feeding behaviors).
A total of 128 grasping actions were extracted and analyzed from 10 hours of recordings, leading to:

- quantitative statistics on the number of arm used (Figure 3).
- discovery and characterization of two previously unreported grasping strategies (Figure 2).

The quantitative analysis revealed a clear and consistent pattern: grasping predominantly involved two or three arms, while attempts engaging more than three arms were never observed.
About the new grasping strategies, the first, here referred to as *Pinching*, was observed during the manipulation of elongated objects. This configuration involves the use of two arms positioned along the object's longitudinal axis, with the



(a)

(b)

Figure 2: Pinching (a) and Basal Grasping (b).

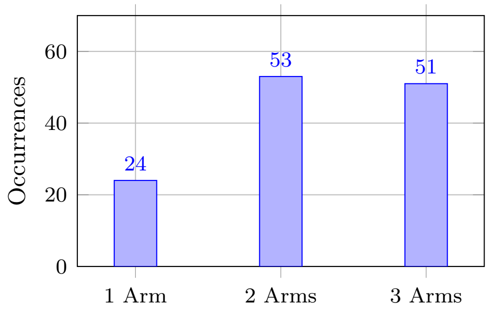


Figure 3: Number of engaged arms.

arms maintained in a straight posture and the suckers oriented inward to maximize surface contact. Such an arrangement enables strong compression of the object, ensuring high grip stability regardless of its spatial orientation. The second strategy, referred to as *Basal grasping*, was typically adopted for objects whose longitudinal axis was oriented perpendicular to the octopus body axis. In this case, three arms were recruited, with active suckers facing inward and contacting the object near the proximal (basal) region of the arms, close to the body.
These observations have been translated into design choices, as will be explained is Section 5.

4. Soft Arms Design, Fabrication and Characterization

Each robotic arm is based on a tendon-driven architecture, with electric servo-motors that pull high-strength synthetic cables routed inside a soft Ecoflex™ 00-30 silicone body. The internal routing of the tendons replicates the functional arrangement of the octopus muscular hydrostat, with longitudinal cables that enable ventral and dorsal bending, and a spiral-shaped tendon that generates twisting motion.
The soft bodies of the arms were realized using a pre-existing mold, ensuring geometric consistency with previously validated octopus-inspired designs. The fabrication process involved multi-stage silicone casting, integration of internal supports and tendons within the mold, controlled curing, and final assembly with the remote actuation unit. The design variables were:

- Cable arrangement
- Internal supports

Two distinct tendon-routing configurations were implemented and experimentally compared to evaluate their influence on curvature distribution, achievable workspace, and twisting capability: *Tendon configuration A* (Figure 4) features the ventral tendon anchored at the distal internal support, resulting in a larger radius of curvature during intermediate pulling (Figure 5b), making it particularly suitable for the arms dedicated to the *Pinching* strategy, where a "flatter" profile enhances longitudinal compression of elongated objects. *Tendon configuration B* inverts the ventral and dorsal anchoring positions, generating a more pronounced bending profile. A maximum lateral displacement of $120mm$ was observed within the two configurations (Figure 5a), defining the inter-arm distance required to ensure full coverage of the internal grasping workspace.
Two types of custom 3D-printed PLA supports were implemented and alternated along the arm to balance routing precision, manufacturing simplicity, and minimal stiffening.
On the ventral side, each arm features 10 passive suckers. These elements do not actively generate negative pressure, but achieve adhesion through physical compression on the object, expelling the internal fluid and so creating a pressure drop. Adhesion occurs only in water, and this will influence the grasping performance (Section 6). Active suction mechanisms were intentionally avoided to simplify the design and to focus the investigation on shape-based grasping strategies.

5. Multi-Arm Octopus Robot

Building upon the biological investigation and the experimental characterization of the single soft arm, a multi-arm robotic platform was developed. The proposed system represents a first functional prototype intended to validate the

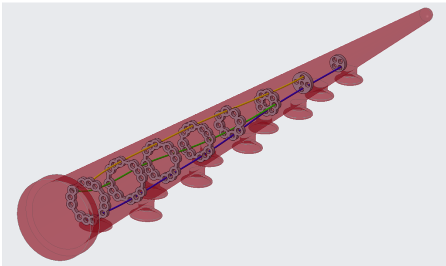


Figure 4: *Tendon configuration A*: ventral (blue), dorsal (yellow), and twisting (green) cables.

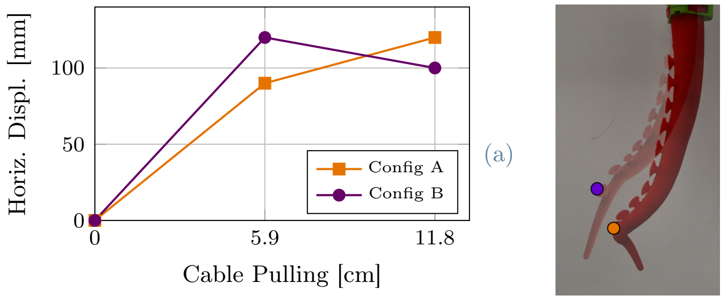


Figure 5: Tendon config. A and B comparison: lateral displacement (a) and bending profiles with 5.9cm of cable pulling (b).

feasibility of coordinated grasping strategies inspired by octopus behavior.

The design variables considered in the multi-arm architecture included: (i) the number of arms, (ii) their spatial arrangement and mutual orientation, (iii) the selection of tendon-routing configurations for each arm, and (iv) the integration of actuation and control components within the structural layout.

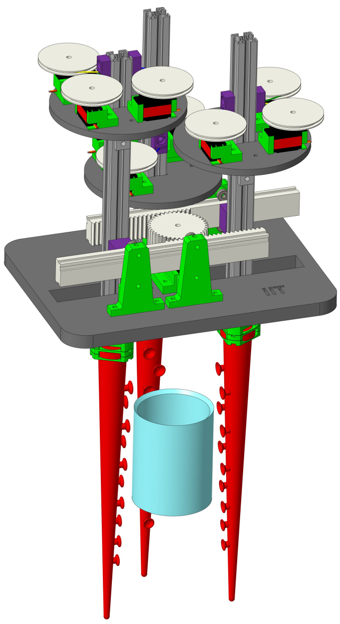


Figure 6: CAD model of the Multi-Arm Octopus Robot mounted in *Pinching* configuration.

Three arms were adopted as the minimum configuration capable of reproducing both strategies, while the experimentally measured maximum lateral displacement of 120mm defined the minimum inter-arm spacing. Two operative configurations were implemented: in the *Pinching* configuration (Figure 6), the robot features two arms (equipped with *Tendon Configuration A*) facing each other in the frontal part, while a third arm (equipped with *Tendon Configuration B*) is located in the rear part. An additional translational degree of freedom was introduced for the frontal arms, to generate longitudinal compression of internally positioned objects and to dynamically adjust the inter-arm distance during grasping. In the *Basal Grasping configuration*, the two frontal arms are rotated of 90°, with the suckers facing the rear arm.

The mechanical design is composed of three main subsystems: a rigid Support Base, three independent Tendon Actuation Units (TAUs), and an integrated Electronic Architecture.

The Support Base, laser-cut from a POM (Polyoxymethylene) sheet, serves as the primary mounting interface, allowing the robot to be fixed either to a ground support or, in future developments, to a remotely operated vehicle (ROV). It sustains the three arms and houses the rack-and-pinion mechanism, responsible for the translational degree of freedom, including also bearing elements and a centrally positioned servo-motor. The chosen pitch diameter of the pinion ($D_p = 80mm$) allows for a stroke of $S = 125mm$ (using Equation 1) for each arm, resulting in a considerable maximum inter-arm distance of 370mm despite the rotational limitation of the servo-motor ($\Delta\theta_{\max} = \pi$ rad).

$$S = \Delta\theta_{\max} \cdot \frac{D_p}{2} = \pi \cdot \frac{D_p}{2} \tag{1}$$

The TAUs consist in three circular bases, each mounted at the top of an arm. Each unit houses three Amewi 6221MG servo-motors for tendon actuation, and appropriately sized pulleys to achieve a tendon displacement of 118mm, matching the actuation range determined during the single-arm characterization phase.

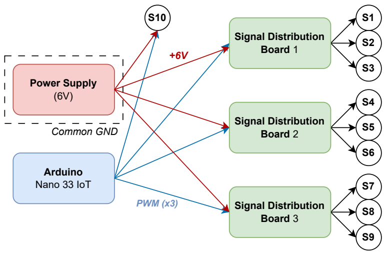


Figure 7: Electronic Architecture.

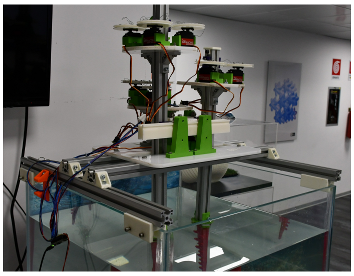


Figure 8: Mounting setup.

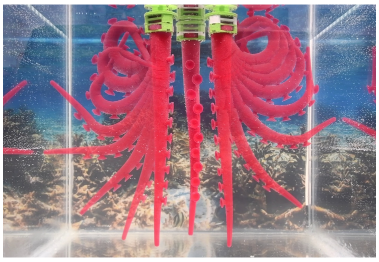


Figure 9: *Approach* phase.

The control architecture (Figure 7) is based on an Arduino Nano 33 IoT microcontroller, responsible for coordinated management of the 10 servo-motors. The custom control strategy was structured around three key principles: (i) non-blocking parallel control, enabling simultaneous actuation of the 10 independent motors; (ii) position control with velocity profiling, introduced to prevent oscillations and excessive tendon stress by avoiding abrupt step-response motions; and (iii) a simplified command interface, allowing the user to specify only:

```
[Motor IDs]  [Target Angle]
```

while the controller autonomously manages timing and speed profiles.
The control algorithm is organized into three sequential phases: an *Initialization Phase* sets all motors to their calibrated home position and initializes the internal state variables used for time tracking and velocity regulation; within the main control loop, operations are divided into two blocks: during the *Command Parsing Phase*, incoming serial commands are processed and the target position array is updated; during the *Actuation Phase*, the algorithm iteratively evaluates and updates each motor position.
The entire system was manufactured and functionally verified before moving on to experimental validation, described in the next section.

6. Experimental Validation

The robotic system was mounted on top of a 60x60x60cm tank, with the arms submerged in water (Figure 8).
To implement the biologically inspired strategies, a structured control sequence was defined, consisting of three main phases: (i) *Approach*, where the translational degree of freedom and dorsal tendons were actuated to maximize clearance for object approach (Figure 9); (ii) *Pre-Grasp Shaping*, in which the inter-arm distance was calibrated according to object size, using the translational DOF; and (iii) *Grasping Execution*, involving ventral tendon actuation to generate bending and object compression (Figure 10).
Two tendon actuation levels (50% and 80%) were tested to evaluate their influence on grasping volume, revealing distinct interaction regions within the arm workspace. For each actuation level, three translational configurations were investigated, corresponding to $0.75L_c$, $1.0L_c$, and $1.25L_c$, where L_c represents the characteristic length of the object tested.
The selected limits were defined during preliminary testing: tendon actuation below 50% resulted in insufficient arm stiffness to secure stable grasps, while actuation beyond 80% frequently induced "out-of-plane buckling" of the arms, causing loss of contact with the target.
Similarly, increasing the inter-arm distance beyond $1.25L_c$ led to unsuccessful grasping attempts due to excessive separation, whereas reducing it below $0.75L_c$ was constrained by mechanical limitations.
Grasping performance was evaluated through a series of dynamic tests aimed at quantifying the maximum payload capacity of the multi-arm system under the different operative configurations. To mimic the interaction with delicate organisms, the selected objects (becher, barrel, large sphere ($\varnothing 16cm$), small sphere, and a box) were made of lightweight plastic and featured complex geometries, which are typically challenging for traditional rigid grippers.
Payload performance was expressed as a mass interval $m_1 < m < m_2$, obtained by progressively increasing the object mass through the insertion of weights. Below m_1, the grasp remained consistently stable; at m_1, initial sliding phenomena were observed during at least one

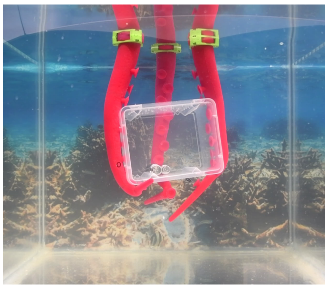


Figure 10: *Grasping execution* phase during the pinching of the plastic box.

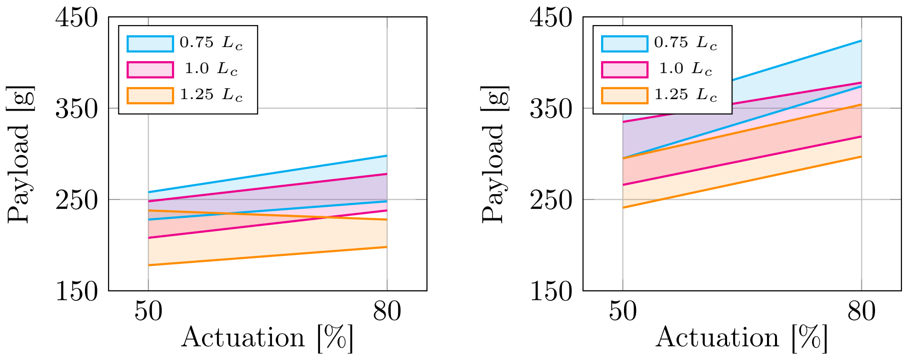


Figure 11: Large sphere grasping payload in air (left) and water (right).

trial, although the intrinsic compliance of the silicone often allowed the object to re-settle and stabilize within the arms. At m_2, grasping failed immediately and the object was released.
The comparison between single and three-arm configurations highlighted the improved payload capacity (from 200% to over 400% across the evaluated object set), achieved through cooperative manipulation. In air, the single arm was able to successfully grasp only the box, adopting a specific shape-based configuration, while no stable grasping strategy was identified for the remaining objects. This limitation is expected, as the single-arm setup primarily relies on sucker adhesion and is not designed for dry conditions. In water, passive suction enabled the single arm to secure additional objects; however, its payload capacity remained limited, particularly for larger geometries.
Moreover, in an open underwater environment, a single arm may simply push the object away instead of firmly grasping it when suction adhesion is not immediately established.
About the performance of the Multi-Arm Octopus Robot, a first comparative analysis can be carried out to explain its distinct behaviors in dry and wet conditions. The data shows a clear trend: thanks to the engagement of the passive suckers, in water an average performance increase of 34.3% was observed.
As a significant example, the results obtained for the large sphere are reported in Figure 11. While the influence of the surrounding medium is clearly confirmed by the upward shift of the colored regions, the plotted trends reveal two additional factors that systematically enhance payload capacity: reducing the inter-arm distance (from $1.25L_c$ to $0.75L_c$) and increasing the tendon actuation level (from 50% to 80%). This improvement results from higher normal compression forces, improved arms conformation around the target geometry, and a more favorable orientation of the ventral surfaces for effective sucker adhesion.
A strong dependency on object size was observed, with the small sphere (⌀10 cm) being particularly challenging to grasp, and showing the lowest recorded payload values (up to 78g in air and 98g in water).
Although effective, the *Basal Grasping* configuration generally showed lower performance than *Pinching*, except for horizontally placed elongated objects, such as the box.
In addition to these grasping configurations, a complementary strategy combining twisting and bending was qualitatively tested, enabling out-of-plane arm motion and grasping of objects, demonstrating the system's versatility in unstructured environments.

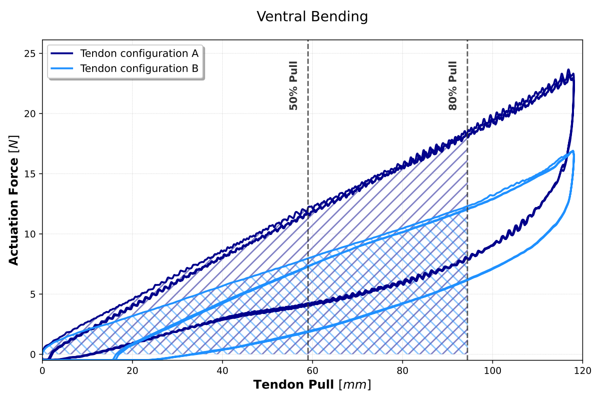


Figure 12: Force-Displacement curves.

Finally, to assess the mechanical effort required for actuation and derive preliminary considerations on energy efficiency, tensile tests were conducted on both tendon configurations, using a universal testing machine.

Force–Displacement curves (Figure 12) exhibited the expected viscoelastic hysteresis behavior of the silicone material, and the peak forces ($\sim 24N$) confirmed the adequacy of the selected motors for reliable arm actuation.

A comparative analysis highlights that configurations with anchoring points located further from the base (as the showed ventral bending for *Tendon configuration A*) require higher pulling forces, because of the larger volume of silicone material that must be compressed.

From an energetic perspective, the area under the loading curves indicates that higher tendon actuation levels (80%) significantly increase the required mechanical work, highlighting the functional and energetic relevance of the translational DOF: by reducing the inter-arm distance, the system achieves equivalent payload capacities with lower tendon actuation, thereby minimizing the mechanical work. Improved future iterations of the translational mechanism will allow a dedicated quantitative evaluation of its efficiency, ensuring operation within the identified energetic margin and maximizing the resulting actuation benefits.

7. Conclusions

The presented robotic system demonstrated the potential of multi-arm octopus-inspired architectures for underwater manipulation, while confirming the effectiveness of a design approach based on the observation and analysis of biological systems.

The experimental campaign confirmed the robustness and versatility of the system across different target geometries, showing performance improvements over the single-arm configuration, while also highlighting current limitations in the interaction with small objects.

Future developments will focus on optimizing the mechanical components, reducing the bulky nature of the current prototype to facilitate integration with external platforms, and implementing sensory feedback for closed-loop force regulation. The transition toward a fully deployable underwater platform will also require complete waterproofing of the mechatronic architecture and extensive in-field validation.

References

[1] Chelsea O. Bennice, Kendra C. Buresch, Jennifer H. Grossman, Tylar D. Morano, and Roger T. Hanlon. Octopus arm flexibility facilitates complex behaviors in diverse natural environments. *Scientific Reports*, 15(1):31875, September 2025.

[2] M. Cianchetti, A. Arienti, M. Follador, B. Mazzolai, P. Dario, and C. Laschi. Design concept and validation of a robotic arm inspired by the octopus. *Materials Science and Engineering: C*, 31(6):1230–1239, August 2011.

[3] Kevin C Galloway, Kaitlyn P Becker, Brennan Phillips, Jordan Kirby, Stephen Licht, Dan Tchernov, Robert J Wood, and David F Gruber. Soft Robotic Grippers for Biological Sampling on Deep Reefs.

[4] Ashley J. Gendreau, Camille Boucaud, Kendra C. Buresch, Allison S. Rooney, Halia Morris, and Roger T. Hanlon. How octopuses use and recruit additional arms to find and manipulate visually hidden items. *Biology Open*, 14(7):bio062011, July 2025.

[5] C Laschi, B Mazzolai, V Mattoli, M Cianchetti, and P Dario. Design of a biomimetic robotic octopus arm. *Bioinspiration & Biomimetics*, 4(1):015006, March 2009.

[6] Angela Mazzeo, Jacopo Aguzzi, Marcello Calisti, Simonepietro Canese, Fabrizio Vecchi, Sergio Stefanni, and Marco Controzzi. Marine Robotics for Deep-Sea Specimen Collection: A Systematic Review of Underwater Grippers. *Sensors*, 22(2):648, January 2022.

[7] Barbara Mazzolai, Alessio Mondini, Francesca Tramacere, Gianluca Riccomi, Ali Sadeghi, Goffredo Giordano, Emanuela Del Dottore, Massimiliano Scaccia, Massimo Zampato, and Stefano Carminati. Octopus-Inspired Soft Arm with Suction Cups for Enhanced Grasping Tasks in Confined Environments. *Advanced Intelligent Systems*, 1(6):1900041, October 2019.

[8] Daniela Rus and Michael T. Tolley. Design, fabrication and control of soft robots. *Nature*, 521(7553):467–475, May 2015.

[9] Nina R. Sinatra, Clark B. Teeple, Daniel M. Vogt, Kevin Kit Parker, David F. Gruber, and Robert J. Wood. Ultragentle manipulation of delicate structures using a soft robotic gripper. *Science Robotics*, 4(33):eaax5425, August 2019.