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A Bio-Inspired Flexible Arm for Subsea Inspection: A Water Hydraulically Actuated Continuum Manipulator.

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Abstract: This paper outlines the outcomes of a multidisciplinary initiative aimed at creating flexible arms that leverage key aspects of soft-bodied sea animal anatomy We designed and prototyped a flexible arm inspired by nature, while focusing on integrating practical engineering technologies from a system perspective. The mechanical structure was developed by studying soft-bodied marine animals from the cephalopod order. Simultaneously, we carefully addressed engineering challenges and limitations, including material flexibility, inherent safety, energy efficiency, cost-effectiveness, and manufacturing feasibility. The design process is demonstrated through two successive generations of prototypes utilizing fluidic actuators. The first one exhibited both radial and longitudinal actuators, the second one only longitudinal actuators, thus trading-off between bio-inspiration and engineering constraints.

Keywords: continuum arm; soft robotics; underwater; bio-inspired design; hydraulic actuation

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1. Introduction

Underwater manipulators are essential for tasks like sea floor exploration, marine sample collection, and debris retrieval, which are critical across disciplines such as biology, ecology, and the offshore industry [1], [2]. Traditional rigid-body manipulators, while effective for heavy mechanical tasks, are large and cumbersome, limiting their adaptability for delicate operations like biological sampling [3], [4]. Human divers often perform such tasks at depths of 0-30 meters, but prolonged underwater work poses significant physical and mental strain [5]. Soft robotic arms, inspired by natural soft-bodied animals, offer a solution by providing adaptable and safe interactions with the environment [6], [7], [8]. These robots are increasingly favored for their ability to operate in unstructured environments and handle fragile objects, making them ideal for delicate underwater tasks [9], [10], [11], [12], [13]. For example, this robotic arm can be deployed in pipeline inspections where flexible manipulators can better access narrow spaces that rigid robots cannot.

A new area of robotic research has focused on the development of soft robotic systems; among the different robotic technologies proposed, it is worth mentioning octopus-inspired arms by Laschi et al. [14] [15], soft grippers for coral reef sampling by Galloway et al. [16], origami-based soft grippers by Teoh et al. [17] and other bio-inspired robotic solutions [18], [19], [20]. Despite these advances, the control of soft robotic manipulators, particularly underwater, remains challenging due to a strongly nonlinear behaviour, environmental disturbances, and actuators constraints. Researchers have explored various control strategies [21], [22], [23]. Thuruthel et al. proposed a model-based reinforcement learning algorithm [24], Hyatt et al. proposed a neural network-based predictive control model for pneumatic soft manipulators [25]. Li et al. developed a reduced-order control model using the orthogonal decomposition algorithm [26]. Additionally, an automatic seafood collection system featuring a reinforcement learning-based controller was proposed in [27].

The integration of bio-inspired design and engineering in robotics requires a holistic approach, where control systems and mechanical structures are co-developed. This design philosophy, known as embodied design, contrasts with classical approaches that separate mechanical design and control. Such an approach is highlighted in [28]. While continuum robots offer significant advantages, challenges remain in balancing the desired flexibility targets with engineering constraints like power efficiency, manufacturability, and reliability [29].

Several studies have compared the performance of rigid and flexible robotic arms, highlighting their respective advantages and limitations.

Rigid robotic arms, while offering high precision and load-bearing capabilities, often face challenges in terms of flexibility and adaptability in dynamic environments [30]. On the other hand, flexible robotic arms, as explored by [31], provide greater adaptability and the ability to handle delicate tasks but suffer from increased complexity in control and reduced power efficiency. Recent advancements have sought to merge the benefits of both approaches, with several works focusing on optimizing the control strategies and power consumption of flexible systems [32]. Our design aims to build on these insights by offering a balance between flexibility and efficiency while reducing control complexity, which positions it as a competitive alternative to both traditional rigid arms and more complex flexible systems. This comparative analysis, as illustrated in the accompanying table, underscores the practical advantages of our design in terms of energy efficiency, control simplicity, and durability.

Soft robotics has drawn significant inspiration from octopus biomechanics due to the creature's unparalleled dexterity, adaptability, and fluid movements. Several studies have focused on developing bioinspired robotic arms with soft, flexible structures that mimic the octopus's ability to grasp, manipulate, and navigate confined spaces as describe above.

Building on these previous efforts, we propose here hydraulic actuation and structural optimization. Unlike traditional tendon-driven systems, our design employs a micro-hydraulic actuation mechanism that enhances force output while maintaining flexibility.

The aim of this work is to develop a concept for flexible robotic arms designed for soft underwater tasks, balancing bio-inspired principles with engineering requirements. The paper is organized as follows: Section II outlines the design requirements of the arm. Section III describes the arm design and prototypes. Section IV explores the actuation and dynamic performance. Finally, Section V presents the conclusions and discusses potential directions for future work.

2. Design Requirements

Designing continuum robotic arms presents the challenge of replicating a soft, nearly continuous structure using engineering techniques. The key requirements for devel-oping such a flexible robotic arm can be summarized as follows:

- Soft mechanical parts: ensuring the softness of actuators and other materials is crucial in the design.
- Actuators and their layout should be designed to replicate the muscular system of soft-bodied, dexterous creatures, with the number of actuators chosen to balance dexterity (such as the ability to bend) and practical engineering constraints.
- Straightforward control algorithms.
- Ability to function underwater.
- Energy-efficient actuation.
- Inherent safety features.
- Ease of assembly and reliability.

Two prototypes were developed during this project using an iterative approach to identify the design that best satisfies all the requirements. After an initial assessment of the underwater soft biological muscle functions in relation to the arm's needs, it was concluded that, although many underwater cephalopod species (e.g., octopuses, squids, cuttlefish) possess complex muscular structures (Figure 1) [32], including longitudinal, radial, and oblique muscles, and exhibit hydrostatic (i.e., iso-volume) properties, it was necessary to simplify these structures when using soft engineering materials. Consequently, only the longitudinal and radial muscle groups were considered, as the oblique muscles, responsible for twisting motions, were deemed unnecessary for a manipulator arm.

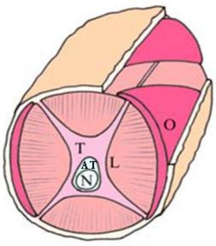

Figure 1. Schematic view of the octopus arm anatomy showing longitudinal muscles (L) and transverse muscles (T) and oblique muscles (O).

While radial muscles could theoretically assist longitudinal muscles in achieving bending motions, in a robot with a dominant longitudinal axis, radial muscles would need to be significantly smaller. The additional mechanical connections, wiring, and power requirements would outweigh the potential benefits of including them, as demonstrated experimentally by the prototypes.

3. Arm Design

The design of the robotic arm is informed by the anatomical and morphological analysis previously discussed. To replicate the actuation anatomy and morphology of the boneless animals, our approach involves approximating such continuum structure using a finite set of fluidically-activated artificial muscles capable of extension and contraction. The biological structures have hyper-redundant sets of muscles (e.g. 4 radial and 4 longitudinal muscles, as depicted in Figure 2). As the fourth muscle is kinematically redundant, the design concept has revolved around connecting a series of flexible segments, each equipped with 3 longitudinal and 3 radial muscles, all positioned at 120° intervals within the same plane [33].

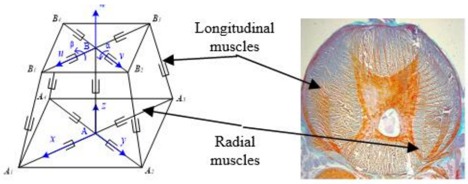

Figure 2. Kinematic equivalent of a cephalopod anatomical structure (shown with an ultrasound image).

Figure 3 illustrates the geometric layout of two such segments, with only the longitudinal muscles shown. This configuration results in an axisymmetric geometry.

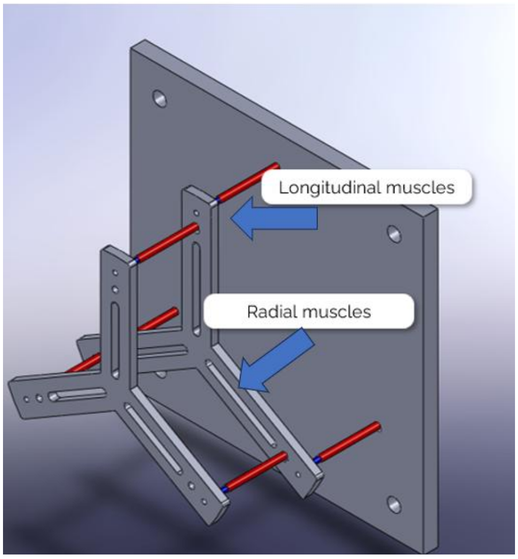

Figure 3. Arm geometrical structure using 3 muscles. In the example two segments are present. The red lines represent longitudinal muscles and the grey line at 120° the radial muscles.

Each muscle in the system is designed to be independently controllable, allowing for precise and flexible manipulation of the arm. The segments are capable of sequentially increasing their stiffness, which enhances the arm's adaptability to different tasks and environmental conditions. If *m* represents the number of degrees of motion (DOM) per segment and n represents the number of segments, the arm will have a total of *m*n DOM. This relationship defines the arm's movement capabilities at both the segment and system levels. The exact number of degrees of freedom (DOF) can be determined by considering the kinematic constraints imposed by the muscle interconnections, which dictate the possible configurations of the arm.

To optimize the arm's design, we aim to establish design relationships that help determine the appropriate dimensions of the arm. This involves analysing the mathematical properties of the muscular hydrostat (iso-volume) behaviour, a characteristic of biological muscles, with the goal of leveraging this property during the design phase. The ability of biological muscles to change their shape and stiffness while maintaining constant volume is key to achieving efficient force generation and precise movement control.

Focusing on a muscle unit composed of one longitudinal and one radial muscle (Figure 3), we consider a radial plane that intersects the rotation axis. This configuration allows us to understand the deformation behaviour of the muscles under different conditions.

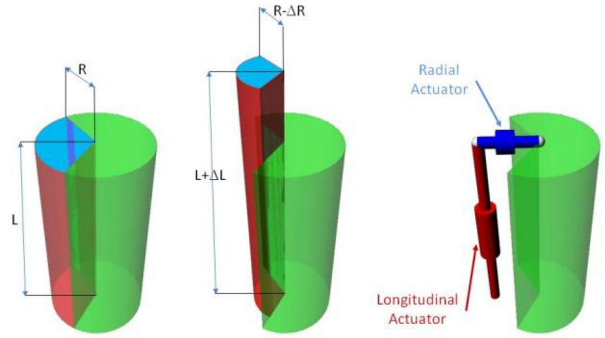

Figure 4. Muscular hydrostat principle concept (left) and equivalent actuators (right)

If L_0 and R_0 represent the initial lengths of the longitudinal and radial muscles, respectively, and the longitudinal muscle stretches by ΔL while the radial one contracts of the quantity ΔR, the new lengths are determined by (Figure 4):

$$R = R_0 - u_{33} = R_0 - \Delta R \tag{1}$$

$$L = L_0 + u_{11} = L_0 + \Delta L \tag{2}$$

The lengthening of the longitudinal muscle and the shortening of the radial muscle are both influenced by the control pressures applied to each muscle. Therefore $L = L(P_1)$ and $R=R(P_2)$, where P_1 and P_2 represent the control pressures for the longitudinal and radial muscles, respectively. $L(P_1)$ is considered a monotonically increasing function, reflecting the extension of the longitudinal muscle, while $R(P_2)$ is a monotonically decreasing function, representing the contraction of the radial muscle.

The condition of hydrostaticity implies that the volume V remains constant. This can be expressed mathematically as:

$$\pi R^2(r)L(z) = V \tag{3}$$

The property of volume conservation leads to the following expression:

$$\pi R^2(P_2)L(P_1) = \pi[R(P_2) - \Delta R(P_2)]^2[L(P_1) + \Delta L(P_1)] = V \tag{4}$$

hence

$$\Delta L(P_1) = \frac{L\Delta R(P_2)[2R(P_2) - \Delta R(P_2)]}{[R(P_2) - \Delta R(P_2)]^2} \tag{5}$$

The expression above links the extension or contraction of the longitudinal muscle to the corresponding contraction or extension of the radial muscle, ensuring volume conservation. This relationship reflects the fundamental principle of muscular hydrostatics, where the volume of the muscle system remains constant even as the individual muscles change in length.

This principle governs the behaviour of the muscular hydrostat, ensuring that the system behaves in a manner consistent with biological muscle properties, where volume is preserved despite changes in shape and stiffness.

4. Arm Prototype

Two distinct prototypes were developed to explore and validate the design concepts for the fluidically-actuated flexible arms for underwater applications. These prototypes were designed to test different configurations and assess their performance in various operational conditions.

The first prototype, was a Longitudinal and Radial Muscle Prototype, that incorporates both longitudinal and radial muscle elements, which allows for a more complex and biologically inspired structure. This design enables a range of movement and flexibility by utilizing both types of muscle actions to manipulate the arm's shape and stiffness.

The second prototype, the Longitudinal-only Muscle Prototype, simplifies the design by focusing solely on the longitudinal muscle element. This configuration was chosen to examine the performance of a less complex structure while maintaining the essential functionality of the system.

By comparing the two prototypes, we aim to evaluate the advantages and trade-offs of each design in terms of flexibility, control, energy efficiency, and overall effectiveness for soft manipulation tasks, particularly in underwater or other challenging environments.

4.1. Longitudinal and Radial Muscle Prototype

The first prototype, which integrates both longitudinal and radial muscles, was developed to replicate the muscular hydrostat properties found in cephalopod arms (Figure 5). This design effectively combines the elongation of longitudinal muscles with the contraction of radial muscles to achieve the desired motion and flexibility. Each segment of the prototype is equipped with four degrees of freedom (DOF), leading to a total of 16 DOF for the entire structure. This multi-degree-of-freedom configuration allows for complex and adaptive movements, enabling the arm to simulate the dexterity and versatility of biological systems.

To facilitate the integration of both muscle types, custom nylon bolts were fabricated using a rapid prototyping machine. These bolts were designed with precision to include a hole at the top, through which fittings were attached to 1-mm hoses that supplied air or water to each muscle. The use of air in preliminary tests provided a controlled environment to assess the basic functionality of the prototype, while water was employed in subsequent underwater tests, conducted in a water tank, to simulate real-world conditions. The fluid delivery was managed through either an external compressor for the air or a compact hydraulic pump for the water, ensuring that each muscle received the necessary actuation force to perform its intended function.

This design approach not only ensured the practical integration of the muscle systems but also provided a testing platform for evaluating the performance of fluidically-actuated continuum arms. The combination of longitudinal and radial muscle actions in a single prototype represents a first step toward mimicking the versatility of natural systems while addressing the engineering challenges posed by the complexity of fluid-actuated robotics.

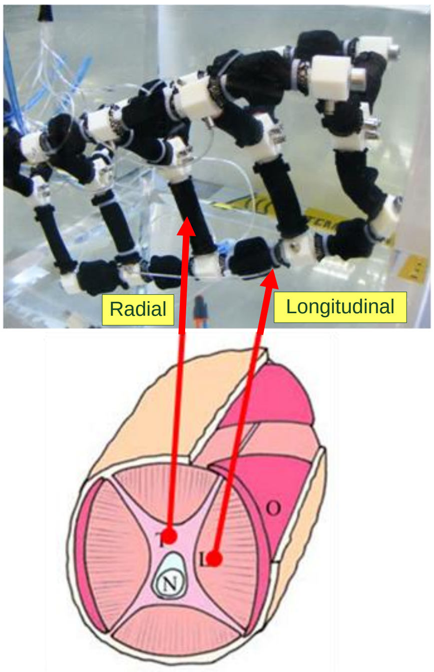

Figure 5. First generation arm prototype with longitudinal and radial muscles in water, and correspondence with cephalopod anatomy

In the first prototype, the use of shorter longitudinal muscles resulted in minimal bending, with the continuum section achieving only a 5° change in angle. Additionally, the radial muscles, which were set to operate in contraction mode, caused the change in length to be limited to 25% of their original length. This limitation led to a negligible effect on the bending of the arm, thereby reducing the overall contribution of the radial muscles to the desired movement. Given these observations, the decision was made to exclude the radial muscles from the subsequent prototype.

While radial muscles provide advantages in biological systems by working synergistically with longitudinal muscles to facilitate more complex movements, their contribution in this context was found to be minimal compared to the increased engineering complexity they introduced. By removing the radial muscles, the space previously occupied by them became available for other design improvements, allowing for enhanced flexibility and greater elongation of the structure. This change streamlined the design, leading to a simpler yet more effective system, better suited for the next iteration of the prototype.

4.2. Longitudinal Muscle Prototype

The second-generation prototype (Figure 6) was developed without radial muscles. Consequently, this prototype consists of three segments, each equipped with three expanding Pneumatic Muscle Actuators (PMA) mounted on a plastic supporting structure.

The design includes shorter PMAs in the lower continuum sections that gradually extend towards the tip. This approach was chosen to mitigate sagging observed in the lower sections when operating in air, caused by the weight of the segments above.

The prototype was tested in both air and water, with muscle actuation driven by water supplied from a compact external pump. The results indicated a significant improvement over the previous prototype.

This new prototype consists of three segments, each equipped with three expanding PMAs mounted on a plastic supporting structure. The design incorporates shorter PMAs in the lower continuum sections, gradually extending toward the tip of the arm. This configuration was specifically chosen to address issues observed in the previous prototype, such as sagging in the lower sections when operating in air. The sagging was caused by the weight of the segments above, and this new design aims to distribute the load more evenly, improving overall performance.

The prototype was tested in both air and water environments, with muscle actuation driven by water supplied from a compact external pump. The testing in both conditions allowed for an assessment of the arm's performance. The results of the tests indicated a significant improvement over the first-generation prototype, demonstrating enhanced elongation, and greater overall flexibility. This second prototypes marked an important step in refining the design, and the improvements achieved with the second-generation prototype laid the groundwork for further optimization in future iterations.

Figure 6. Second generation arm prototype: Underwater bending test (a) prototype at rest; (b) prototype bending

Tests were conducted to evaluate the achievable extension of the second-generation prototype. These tests demonstrated an extension of up to 40%, indicating a significant improvement in performance over the previous design. The extension was normalized relative to the muscle length at rest. The results were plotted against the muscle input pressure, as shown in Figure 7, illustrating the relationship between the applied pressure and the resulting extension.

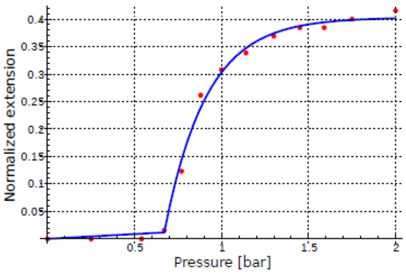

Figure 7. Longitudinal muscle extension vs. water pressure (red dots are measured data and blue line simulated ones)

Following the extension tests, bending tests were conducted to evaluate the flexural capabilities of the second-generation prototype. During these tests, one muscle of the prototype was subjected to increasing water pressures, with pressure increments up to 2 bar. The lengths of all three muscles were measured at each pressure level to assess their behaviour and the corresponding bending response of the continuum structure. These measurements allowed for a detailed analysis of how the muscles' elongation affected the overall curvature and flexibility of the arm. The results from these bending tests provided valuable data on the arm's ability to achieve controlled, precise bending, which is crucial for its performance in dynamic environments, such as underwater applications.

Although much is understood about the neurophysiological control strategy of the octopus, it remains essential to translate this knowledge into a practical controller for a man-made prototype. Drawing from biological insights, tasks that are typically computationally intensive in traditional control approaches are simplified and assigned to the distributed system within the arm's peripheral nervous system (PNS). The central nervous system (CNS) only needs to send basic movement commands and the target muscle position, while the PNS handles the conversion of this information into the actions of the individual actuating elements [34].

The incorporation of AI, particularly machine learning algorithms, into the control system enables real-time adaptive learning, allowing the system to optimize and fine-tune the behavior of the peripheral nervous system (PNS) by continuously refining the mapping between central nervous system (CNS) commands and actuator responses based on sensory feedback, thus improving the efficiency and flexibility of the robotic arm’s movements over time.

Closed-loop feedback with pressure sensors and vision tracking can refine control, but has limited impact due to our bioinspired design and reliance on passive dynamics. For instance, pressure sensors enhance force regulation. But since our soft materials naturally adapt to fluid redistribution, the need for precise control is reduced. Vision tracking aids motion correction, yet our octopus-inspired geometry and inertia-driven movements already ensure smooth, efficient actuation. While feedback improves precision, our system inherently achieves stability and adaptability through its soft structure and passive mechanics, reducing reliance on active corrections.

5. Actuator Design and Performance Assessment

5.1. Actuation Design

Considering the needs for flexibility, built-in safety, cost efficiency, energy effectiveness, and ease of assembly, the decision was made to design and develop the actuating muscles (both longitudinal and radial) using custom-engineered braided PMAs. [35]. Originally designed for pneumatic applications, these actuators can also be effectively utilized with water, taking advantage of water's higher compressibility to achieve a faster dynamic response. The PMAs feature a braided, flexible outer shell that encases an inner containment layer, typically made of rubber or an elastomeric material. While PMAs are primarily intended to operate in contraction mode, with the maximum theoretical contraction occurring at a braid angle of 54.7°, they can also function in an expansion mode. In this mode, starting from a compressed state, a small gap forms between the inner rubber layer and the braid. When pressurized, the actuators expand similarly to their contraction mode, stabilizing at the same 54.7° braid angle.

In terms of mechanical design, higher reliability can be achieved with stronger materials composing the actuator and also with redundancy inserting a fourth actuator that can be automatically connected in case of failure of the three actuators. Such redundancy is also present in nature, as octopus has actually 4 longitudinal muscles. Another point of failures are valves, that can get stuck. This can be monitored with limit switches on the valve themselves.

In the muscle system developed for the robotic arms, each muscle is individually regulated by pressure through a series of compact 3-way valves (Figure 8), which are controlled via an RS232 connection. This configuration allows for precise muscle actuation control and provides flexibility in dynamic environments. From a fluid dynamics standpoint, a PMA functions in pressure-control mode, unlike conventional linear cylinders, which typically operate in flow-control mode. Pressure-control mode, which is often utilized in systems such as ABS brakes and other force-controlled applications, is more energy-efficient because it relies on the compressibility of fluid within a flexible chamber, rather than the movement of a mechanical part like a piston. This contributes to a more energy-efficient system overall, aligning with the project's goals of optimizing energy usage and enhancing system performance.

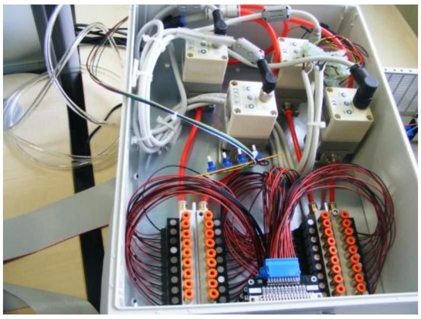

Figure 8. Pressure-regulator used in the experimentation, showing pressure regulators and switching valves connected to each actuator

In the prototype incorporating both radial and longitudinal muscles, elongation is achieved by simultaneously contracting the radial muscles and relaxing the longitudinal ones. This coordinated action allows the arm's length to increase while maintaining its structural integrity and hydrostatic properties (constant volume). Conversely, in the prototype with only longitudinal muscles, elongation is achieved solely by actuating the longitudinal muscles. In this case, as the radial diameter decreases due to the absence of radial muscle contraction, the arm compensates by increasing its length to uphold the principle of constant volume.

Control of the muscles is managed independently via a system of 3-way valves, with each valve regulating the inflow and outflow of its respective muscle. The supply pressure is delivered through a main line, with pressure levels for the longitudinal and radial muscles adjusted independently using dedicated pressure regulators. This modular control system ensures precise and efficient actuation tailored to the specific requirements of the task.

Bending is achieved through selective activation of one or more longitudinal muscles, which contract to induce curvature at the desired location. In the case of the prototype with radial muscles, bending is further refined by the co-contraction of radial muscles in the segments above and below the intended bend point, enhancing stability and control. For the longitudinal-only prototype, bending is accomplished solely through the selective contraction of longitudinal muscles.

This bio-inspired control strategy eliminates the need for complex, computationally intensive model-based algorithms, offering a simpler and more practical solution for real-time application. By focusing on independent muscle control this approach provides a robust and energy-efficient method for soft manipulation in underwater environments.

5.2. Dynamic Performance

We analyzed the dynamic performance of the muscle-actuated system, recognizing that inspection tasks do not require a rapid response time. We used first air than water. Although air is not representative of an underwater application, it was easier to use for preliminary testing at laboratory level.

The dynamic behaviour of the muscle system can be modelled as a first-order system, with the pneumatic muscle represented as a capacitance C which is directly influenced by the stiffness of the working fluid, and the pressure losses from valves, hoses, and fittings modelled as an equivalent resistance R (Figure 9). The system's dynamics can thus be expressed as:

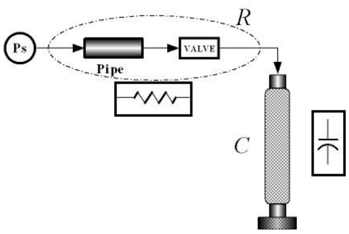

Figure 9. Muscle-actuation and its electric equivalent.

$$P_s - P = RC\frac{dP}{dt} \quad (6)$$

In order to find an analytical expression for the capacity we need first to introduce the bulk modulus that quantifies the resistance of a fluid to compression. In pneumatic and hydraulic systems, the compressibility of the fluid is key in determining the resonant frequency, particularly in high-pressure conditions or rapid pressure changes. This compressibility causes the fluid to act like a spring, restricting system response. Essentially, air or water in the system can be seen as a spring. The bulk modulus BB is defined as the inverse of the volumetric change rate ΔV/V resulting from a pressure variation ΔP.

To derive an analytical expression for C, we introduce the bulk modulus, B, which quantifies a fluid resistance to compression. This property is particularly critical in hydraulic systems, as fluid compressibility significantly impacts system resonance, especially under high-pressure conditions or during rapid pressure changes. In essence, water within the system acts as a spring, restricting the speed of response. The bulk modulus B is defined as:

$$B = \frac{Pressure \quad change}{Volumetric \quad strain} = -V\frac{\Delta P}{\Delta V} \tag{7}$$

by differentiating (7) with respect to time, with some simple calculations we can obtain the expression of the fluidic capacity:

$$C = \rho\frac{V}{B} \tag{8}$$

In theory water is much faster than air, however often times this is not the case, especially at lower pressure. In fact the theoretical bulk modulus assumes no air is present in the fluid, which is rarely achievable. Even minor air entrainment significantly lowers the effective bulk modulus, reducing the system bandwidth compared to its theoretical value. While water still offers a higher bandwidth than air, the actual performance is influenced by the nonlinear dynamics of system components. Consequently, the bandwidth cannot be fully characterized in an open-loop configuration by simply applying a chirp signal to the valve solenoids, as it varies with the input amplitude.

To assess the system dynamic behaviour, the pressure response to a square wave voltage input was experimentally measured. The tests revealed a response time of 500 ms for a single muscle. Although this response time is slower than the theoretical maximum, it remains adequate for inspection tasks, where speed is not a critical parameter. These findings underscore the role of fluidic properties, air entrainment, and nonlinear system dynamics in shaping the performance of hydraulic muscle-actuated systems.

Altough for lab testing we used pneumatics, for underwater applications hydraulics is mandatory. Hydraulic and pneumatic actuation each offer distinct advantages and trade-offs. Hydraulic system delivers significantly higher force output since liquids are incompressible, making it ideal for tasks requiring strong grasping and lifting.

Our micro-hydraulic approach optimizes energy use while maintaining compactness. Pneumatic systems, though simpler, operate with a compressible flow, leading to efficiency losses due to higher leakage and compression inefficiencies.

6. Conclusions and Future Work

This paper has introduced two fluidically-actuated continuum arm concepts specifically designed for soft manipulation tasks in underwater environments. After exploring the relevant biological background and examining nature's strategies for movement and adaptability, we established high-level design requirements that effectively integrate bio-inspiration with engineering considerations. The first concept features both radial and longitudinal actuators, closely mimicking the complex structure found in biological systems. The second concept, designed with only longitudinal actuators, simplifies the biological model to accommodate engineering constraints while still aiming to preserve essential functionality.

We successfully prototyped and controlled two distinct arm configurations, evaluating their elongation and bending capabilities under various conditions. These experiments demonstrated the potential of fluidic actuation for soft and adaptable robotic manipulation, showcasing their versatility for underwater tasks. The results indicate promising pathways for further enhancement, particularly in terms of efficiency and control.

Future work will focus on refining the design, emphasizing mechanical robustness and resilience to the harsh conditions of real marine environments. This includes testing prototypes in more complex underwater scenarios, enhancing their durability, and improving their performance. Moreover, we plan to explore additional capabilities such as autonomous navigation and multi-functional task execution, which will expand the range of applications for these soft robotic arms. Ultimately, the integration of advanced materials and further optimization of the control systems will bring us closer to achieving practical, deployable robotic solutions for underwater exploration, inspection, and manipulation tasks. Future research will highlight the use of simulations to accelerate testing, the exploration of cost-effective materials, and improved fluid supply mechanisms. Specifically, we will investigate using computational fluid dynamics (CFD) models to refine actuation efficiency.

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