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An Octopus Anatomy-inspired Robotic Arm

Emanuele Guglielmino, Nikos Tsagarakis, Darwin G. Caldwell

Abstract— **This paper focuses on the design of a robotic arm inspired to the anatomy and morphology of an octopus arm. The octopus is a boneless animal and its amazing dexterity is due to its muscular structure where longitudinal (axial), transverse (radial) and oblique muscles seamlessly interact while preserving hydrostaticity i.e. volume conservation ("muscular hydrostat" [19]). Mimicking some features of the octopus is instrumental to design a dexterous and compliant system. After analysing the relevant anatomical and morphological characteristics of the octopus arm, the key biomechanical features of interest to the design of a robotic arm have been identified. A design methodology has been developed based on the analysis of the muscular hydrostat properties. A prototype arm has been built using bespoke contracting pneumatic muscles and expanding elements. In the current stage of development the system has 15 actuated degrees of motion (DOM) and 8 degrees of freedom (DOF), all independently controllable through valves and a dedicated electronics and software interface. Pros and cons of the current design as well as practical prototyping trade-offs are thoroughly described.**

Keywords: muscular hydrostat, octopus, morphometric analysis, continuum robots, artificial muscles, pneumatics.

I. INTRODUCTION

Classical antropomorphic robotic arms are composed of rigid links and have a limited number of degrees of freedom (DOF). These robots can successfully perform a variety of tasks in industrial automation processes (e.g. metal cutting, welding etc).

In operative conditions where there is a need for highly dexterous and soft yet reliable devices, robots with a stiff structure are insufficient to satisfy these needs. This has lead to the development of continuum or hyper-redundant robots. As opposed to stiff robots, they typically have a large number of DOF, or an infinite number of DOF i.e. they can be considered as truly distributed parameter systems [1]. Potential applications of such robots span from people rescuing in narrow or hostile environments [2], to medical applications in minimally invasive surgery [3, 4]. Differently from robots having rigid links, in continuum robots the manipulation load is not necessarily placed at the end-effector, but due to their structure, whole-arm manipulation is possible.

A wide range of continuum robots have been built. Their design is often to some extent biologically-inspired [5]. In nature a very flexible behaviour is exhibited *inter alia* in elephant trunks [6], snakes [7] and human tongues [8]. Such bio-structures have no skeleton thus their muscles also act as supporting structures. Therefore there is considerable interest in developing robots that mimic their functionalities. An interesting example is the robot developed by Walker and co-workers inspired to an elephant trunk with a backbone without any rigid link [9-11]. It is lightweight, able to produce significant forces and its actuation is pneumatic.

As far as actuation technologies are concerned a wide range of technologies has been used to actuate continuum robots. Besides pneumatics several other technologies have been investigated, both traditional ones such as cable systems [12] and more innovative such as ionic polymer metal [13] and shape memory alloys: Ayers prototyped a myomorphic actuator for a robotic lobster using PWM-controlled shape memory alloy wires [14]. Some continuum robots also stepped up to patented solutions [15] and commercial products [16].

One of the most astonishing examples in nature of dexterous behaviour is the octopus. The octopus body has no rigid parts and hence can be viewed as a truly continuum structure. It can bend and twist in all directions, it can seamlessly vary the stiffness of its arms or part of them and it can apply relatively high forces with respect to its weight. One of its most appealing features is for instance its capability to squeeze and pass through very narrow gaps in the rocks.

Soft robots inspired by the octopus have to tackle the challenge to emulate its virtually continuum structure using engineering technologies. A second challenge (not addressed in this paper) is the control of such complex structures whose response is dictated by the geometry of the muscular systems, the number of muscles activated and their way of activation.

The aim of this work is to design and prototype a flexible robotic arm for engineering applications whose design captures and embeds some key features of the octopus. The octopus is a sea animal but in this first prototype the robotic arm has not been designed for underwater operations. Subsequent research will aim to develop another prototype for the underwater environment.

The actuation of the arm is pneumatic and uses a combination of contracting pneumatic McKibben muscles and expanding pneumatic elements. For ease in this work the term "muscle" will be also used to denote expanding elements, although muscles are typically considered contracting elements. An array of miniature valves controls each muscle independently. Such an arm can be used in

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exploration tasks in irregularly shaped and/or narrow environments as well as in object grasping tasks. It is also worth noting that a pneumatically-actuated device such as this one with electro-pneumatic valves that can be mounted remotely can be potentially employed in explosive atmosphere areas where the stringent requirements of the ATEX directive (or its American equivalent NEMA) must be met [17].

The paper is organised as follows: section II presents the octopus anatomical and morphological analysis; based on these results in section III the arm design is introduced. Section IV describes the actuation system and finally section V addresses the conclusions and comments on further developments.

II. OCTOPUS ARM BIOMECHANICAL ANALYSIS

The octopus is a good example in nature where the body shapes the way it acts, hence the analysis of some anatomical and morphological characteristics of the octopus arm and the extraction of relevant biomechanical information is key to the bio-inspired design of a robotic arm, besides being also beneficial for its control.

A. Muscular Structure

The octopus is a boneless animal and its extraordinary dexterity, motion and skeletal support rely on its anatomical muscular arrangement. An octopus arm has three main types of muscles [18]: longitudinal (axially placed along the arm) transverse (radial) plus a third family of muscles, known as oblique muscles. All muscles are attached to a central connective tissue. Fig. 1 shows an image of the octopus arm anatomy.

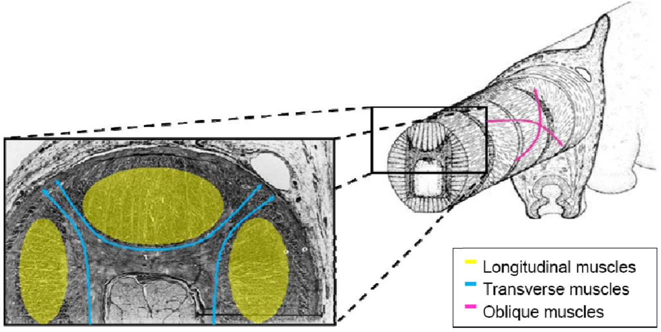

Fig. 1. Octopus arm anatomy.

The octopus has four longitudinal and four radial muscular structures. This system is kinematically redundant. Hence in the design presented a structure composed of a discrete number of three longitudinal and three radial muscular units has been considered.

B. Hydrostaticity

The octopus muscular system has the property of being constant in volume, i.e. a change in one dimension will cause an opposite change in another dimension (and vice-versa). In other words if muscles contraction causes a reduction of the cross-sectional area of the arm this results in an extension of it, while maintaining the volume constant. This property is known as hydrostaticity [19] and the organs exhibiting such a property are termed "muscular hydrostats". These natural structures have great flexibility and the application of this property to the design of the arm will be described in section III.

C. Morphometric Analysis

The octopus arm section decreases from the base (the point near the octopus head where each arm separates from the other) to the tip. To establish the appropriate dimensional ratio of the arm prototype, *in vivo* measurements (Fig. 2) were taken on several octopus arms on an anesthetised animal, with the support of a marine biologist. All experiments were conducted in accordance to EU regulations concerning welfare of animals used for experimental and other scientific purposes [20].

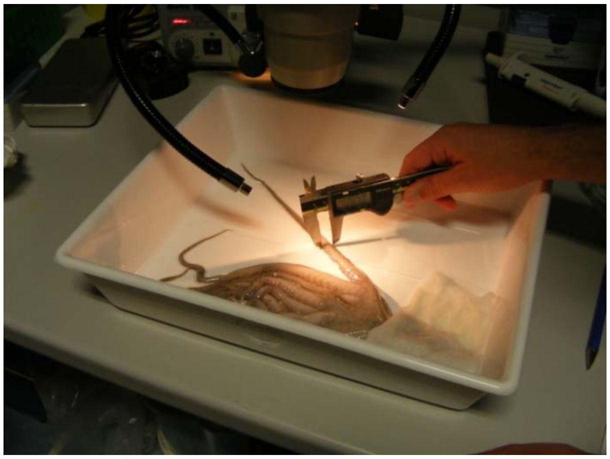

Fig. 2. Collecting morphometric measurements on an octopus arm.

Thickness/length ratio of different points along each arm and the rate of arm section reduction were measured. The entire arm length and the arm cross-section of several sections equally spaced along each arm were measured with a calliper gauge.

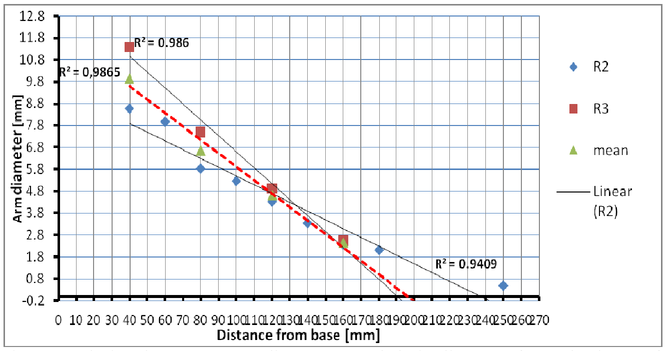

Fig. 3. Relation between arm diameters and their distance from the base of two sample arms (R2 and R3). The two grey lines represent the linear fitting of the experimental data and the red dotted line their average.

Morphometric data were then appropriately processed as customary in bio data analysis, in particular they were averaged twice to account for both measurement errors and the inherent variations in octopus arm lengths, and subsequently fitted. Fig. 3 shows measured data for an arm of 10-mm diameter base, having rate of reduction of 6%. A linear fit (correlation coefficient $R^2 = 0.9865$) captures well the trend of the experimental data. These figures are the starting point for the design of the arm.

D. Octopus Motion

The octopus performs a wide range of motions that have studied in other contexts by marine physiologists [21].

The octopus performs all its motions by appropriately activating its three types of muscles. Hence in the prototype all muscles should be independently controllable.

Arm bending, elongation (extension) and stiffening are basic motion motions whose combination can create more complex motion patterns. Local arm bending is produced by counter-activation of longitudinal and radial muscles at the two arm side. Arm elongation can be produced by counter-action of the longitudinal and radial muscles. Stiffening is performed by the co-action of longitudinal and radial muscles. Torsion is produced by activation of the oblique muscles and is not considered in this work.

In the prototype presented longitudinal muscles are approximated as elongating elements and radial muscles as contracting elements; hence elongation of a part of the arm can be obtained by activating longitudinal muscles. Stiffening can be produced by activating the longitudinal muscles. Bending in the prototype can be generated by shortening radial muscles while opposite longitudinal muscles extend.

From an engineering viewpoint one of the most interesting motions is the so-called "reaching" motion (Fig. 4) performed by the octopus arm to reach a target, e.g. a small fish. The reaching movement is performed by producing an initial bend of the arm followed by a stiffening wave that propagates along the arm.

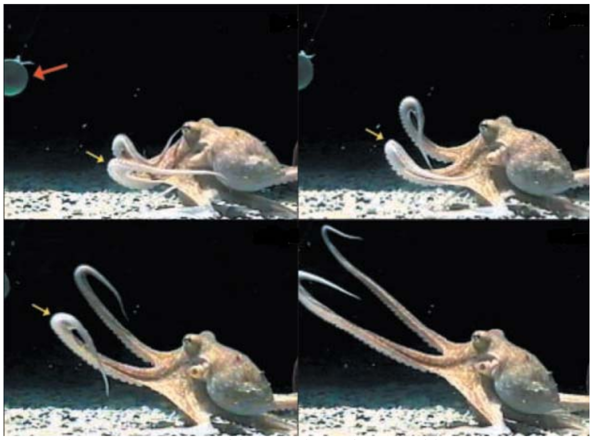

Fig. 4. Octopus reaching motion when catching a target.

III. ARM DESIGN

The arm is designed starting from the anatomical and morphological analysis presented in section II.

Our approach towards the replication of the octopus actuation anatomy and morphology is to approximate the properties of the octopus arm continuum structure with a finite number of pneumatically-activated extending and contracting artificial muscles.

The design concept is based on joining a sufficient number of flexible segments each one having three longitudinal muscles and three radial muscles, all equally spaced at 120° in the corresponding plane. Fig. 5 schematically shows the geometrical structure of two segments (only the longitudinal muscles are depicted). The geometry is hence axisymmetric.

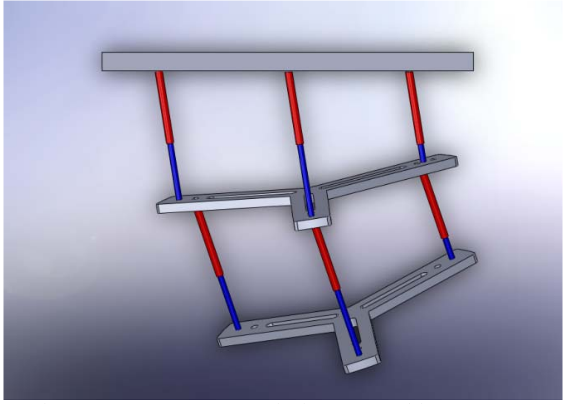

Fig. 5. Octopus arm geometrical structure with two segments.

All muscles should be independently controllable and the segments should have the capability to become stiffer in sequential manner. If M is the number of degrees of motion (DOM) per segment and N is the number of segments the arm will have M*N DOM. The number of DOF can be worked out based on the actual kinematic constraints in the muscle interconnections.

A. Kineto-static Analysis of the Muscular Hydrostat

The aim of this sub-section is to establish design relationships for sizing the arm by analysing the mathematical properties of the octopus muscular hydrostat. The analysis is carried out capitalising on the principles and methods of the structural engineering domain, widely used in very different engineering contexts. With reference to a muscle unit composed of a longitudinal and a radial muscle (Fig. 6), let consider a radial plane passing through the neutral axis (the axis where tensile and compression stresses are nil, that in this geometry coincides with the rotation axis). Exploiting the axisymmetry of the system, hydrostaticity means that the strain tensor is diagonal.

$$\boldsymbol{\varepsilon}_{ij} = \begin{pmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{pmatrix} = \begin{pmatrix} \varepsilon_0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\varepsilon_0 \end{pmatrix} \tag{1}$$

The diagonal entries ε_{ii} are the monoaxial strains in cylindrical coordinates [22]. The opposite sign of ε_{11} and ε_{33} is due to the hydrostaticity ($\varepsilon_{22} = 0$ because there is no circonferential strain). By integrating the strain tensor, the muscle displacements can be obtained:

$$u_{11} = \int \varepsilon_{11} dx_1 = \int \frac{\partial u_{11}}{\partial x_1} dx_1 \tag{2}$$

and analogously for u_{33} .

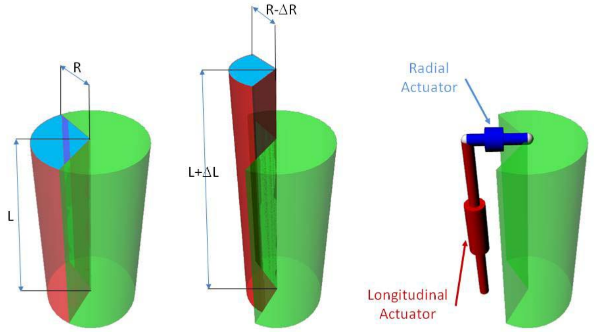

Fig. 6. Muscular hydrostat principle.

If L_0 and R_0 are the original lengths of a longitudinal and a radial muscle respectively, and the longitudinal muscle expands of the quantity *ΔL* while the radial one contracts of the quantity *ΔR*, the new lengths are (Fig. 6):

$$L = L_0 + u_{11} = L_0 + \Delta L \tag{3}$$

$$R = R_0 - u_{33} = R_0 - \Delta R \tag{4}$$

The increment and decrement in length of the longitudinal and radial muscle respectively are functions of the control pressure of each muscle. Hence $L = L(P_1)$ and $R = R(P_2)$, with P_1 and P_2 being respectively the control pressures of the longitudinal and radial muscles. $L(P_1)$ is assumed to be physically a monotonically increasing function representing an extending longitudinal muscle element, whereas $R(P_2)$ is a monotonically decreasing function describing a contractile radial muscle element. Hydrostaticity means that the volume *V* is constant, i.e.:

$$\pi R^2(r)L(z) = V \tag{5}$$

The volume conservation property yields:

$$\pi R^2(P_2)L(P_1) = \pi[R(P_2) - \Delta R(P_2)]^2[L(P_1) + \Delta L(P_1)] = V \tag{6}$$

hence

$$\Delta L(P_1) = \frac{L\Delta R(P_2)[2R(P_2) - \Delta R(P_2)]}{[R(P_2) - \Delta R(P_2)]^2} \tag{7}$$

The above expression relates the extension/contraction of a longitudinal muscle to the contraction/extension of a radial muscles for the purpose of volume conservation. In order to design a multi-segmented structure it is then necessary to find a design relationship that, based on the hydrostatic property, relates the maximum deflection achievable per segment as a function of the segment geometry and number of segments. With reference to Fig. 7, in steady-state if the longitudinal and radial muscles are both pressurised the max achievable rotation *Δα* of the *(n+1)th* segment can be calculated as:

$$\Delta\alpha_{n+1} = \tan^{-1}\frac{\Delta L_n}{R_n[1+\cos(\frac{2}{3}\pi)] + \Delta R_n} \tag{8}$$

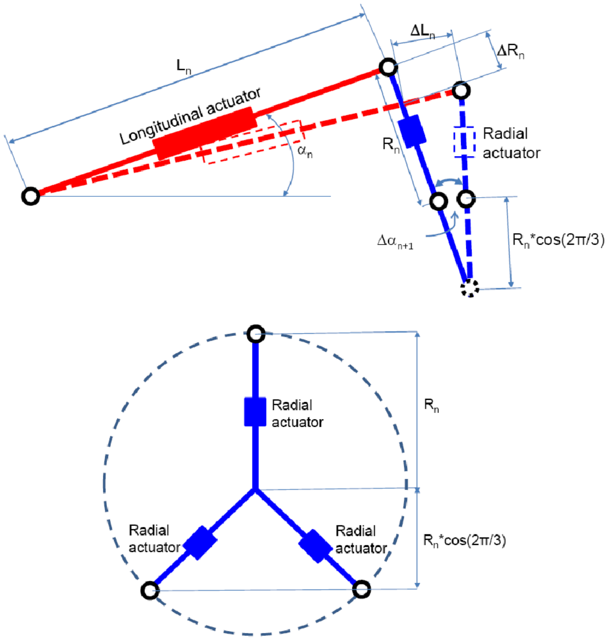

Fig. 7. Achievable rotation of a segment when the longitudinal muscle expands and the radial muscle contracts.

B. Arm Prototype

The design of the octopus arm, being part of a more complex system, requires a systems engineering approach that caters for all static and dynamic requirements and any technical and practical constraints. Based on the results of the morphometric analysis of sub-section II-C it was decided to make a prototype as proportional as feasible to an octopus arm but larger in size due to practical prototyping constraints (e.g. muscle size, fittings, sealing). In this first segment prototype (Fig. 8) only the longitudinal muscles were realised by means of three muscles, mounted in a triangular arrangement and fixed to plastic star-shaped rigid segments (made with a rapid prototyping machine). This simplified segment was initially built mainly to assess pneumatic dynamic system response and reliability of the design, in particular air leaks that can majorly affect the response. From a dynamic viewpoint it is critical to find an effective system to interconnect the muscles in the most compact way without penalising the air flow required.

Custom nylon bolts were manufactured with a hole through the bolt top where fittings were mounted to 1-mm flexible hoses used to supply air to each muscle. This single segment resembles a parallel machine.

Subsequently a second prototype having both longitudinal and radial muscles was built. Fig. 9 shows its structure. The structure has two segments and a part of a third (hence the number of DOM is M*N+3, where M=6 and N=2).

For each segment the longitudinal muscles were made with three silicon hoses whose working principle is similar to pneumatic bellows [24]. The radial flexibility was introduced via three McKibben muscles [25]. These actuators have high force-to-weight ratio (as in the octopus muscles).

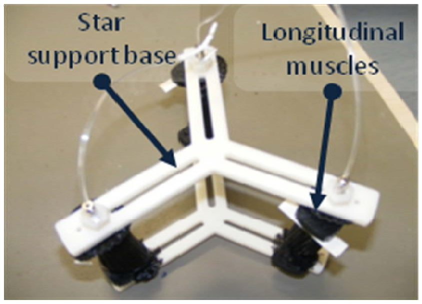

Fig. 8. Segment prototype.

The video shows the arm in operation when radial muscles are all contracting causing shrinking and when two longitudinal and two radial muscles are respectively expanding and contracting, thus producing bending. From the analysis of the structure the DOF per segment are 4: 3 kinematic DOF (two rotations, one longitudinal translation) and 1 structural DOF (radial contraction), thus totally 8 DOF.

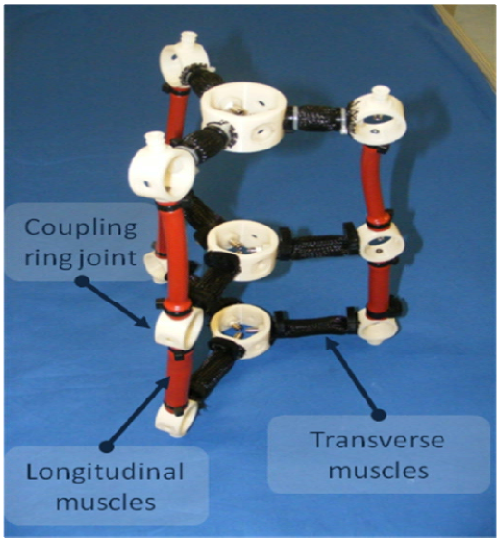

Fig. 9. Arm prototype structure.

The longitudinal and radial muscles were connected with cylindrical coupling ring joints. The central joint is the mechanical equivalent of the connective tissue where the muscles are attached. Enhanced sealing was obtained using labyrinth-like seals for connecting muscles.

It is worth noting that from a structural viewpoint this structure can be approximated to a reticular structure [22] i.e. the actuators can be viewed as elements experiencing mostly normal stress and negligible shear stress and bending moment, interconnected via ideal kinematic constraints. This would allow to use 3D reticular structure algorithms when the number of segments increases significantly.

Attempts were also made to make a fully flexible arm making compliant circular joints, made in the same braided material of the radial muscles. Albeit this solution is appealing as it is a fully compliant structure, it is in fact penalising the achievable bending as the energy transmitted from a segment to the subsequent is not entirely converted into kinetic energy, thus producing motion, but a significant part is converted into deformation of the joints.

IV. ACTUATION CONTROL

Muscles are all independently pressure-controlled by an array of miniature 3-way valves. Each valve controls in-flow and out-flow in each muscle.

The supply pressure is provided by a main compressor line where pressure levels for longitudinal and radial muscles can be adjusted independently by pressure regulators. Fig. 10 shows the pneumatic drive layout with all valves, the pressure regulators and the I/O boards. A software interface was developed to control them.

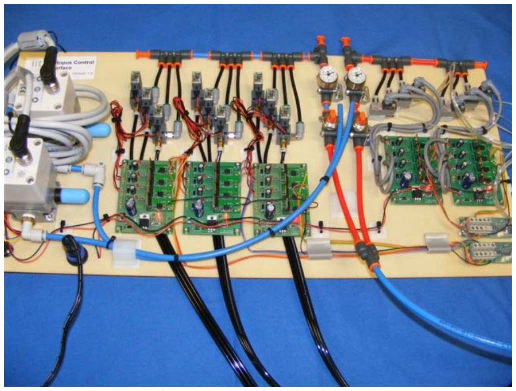

Fig. 10. Pneumatic drive.

The pneumatic response to a square wave voltage input was experimentally measured. The test revealed that the valve step response (without muscle) can be well approximated by a first order dynamics having a 60 ms rise time. Next the response with the muscle connected was measured. The additional volume of the muscle and the additional resistance of the hoses slows down the response to 500 ms.

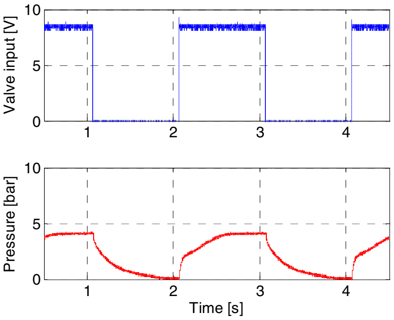

Fig. 11. Typical pneumatic muscle step response.

The dynamics is still first order but the non-linear effects are evident as the trend is not equiexponential, as it can be seen from Fig. 11. The performance of the arm are summarised in Fig. 12 and Fig. 13. They respectively plot the percentage longitudinal extension and the percentage radial contraction of the arm vs. control pressure. They are in the order of 20%-30% for the max operating pressures (rubber types were different). The characteristic of the silicon rubber should be noted: in order to activate the longitudinal muscles a threshold pressure (inherent to the rubber material) must be reached. The max average (secant) bending when two longitudinal muscles and the opposite radial muscle are activated for each segment is around 20°. Eventually Fig. 14 shows the activation of radial and longitudinal muscles.

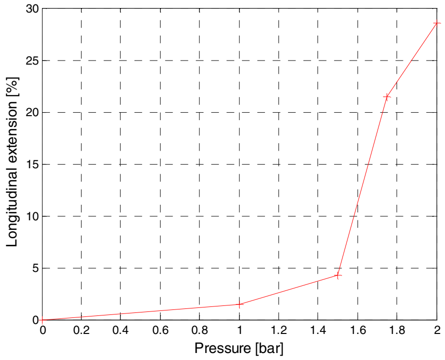

Fig. 12. Percentage arm extension vs. longitudinal muscle pressure.

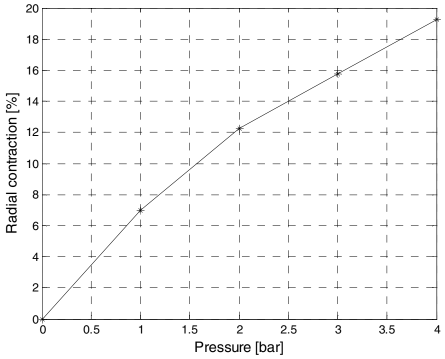

Fig. 13. Percentage arm contraction vs. radial muscle pressure.

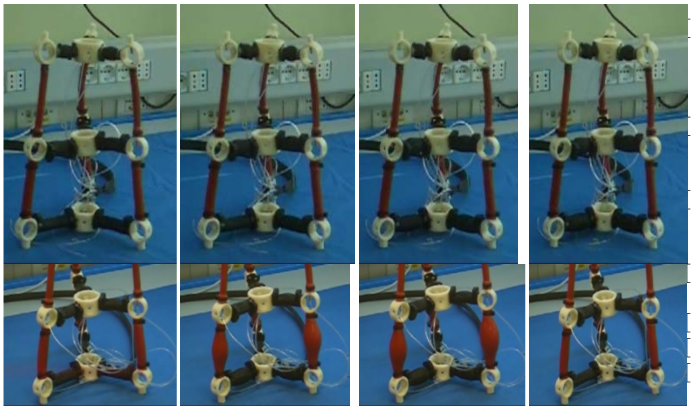

Fig. 14. Activation of radial (top) and longitudinal muscles (bottom).

V. CONCLUSIONS AND FUTURE WORK

A pneumatically-actuated arm inspired to an octopus arm and to the hydrostatic properties of its muscular system was designed and prototyped. The next step will be to increase the number of segments of the arm. A second prototype for underwater operations will be subsequently built. Control issues will be then investigated. Arm design and arm control are strictly coupled and they should be seen only in the context of the relationship to each other. Bio-inspired algorithms are the key to achieve good dynamic performance.

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