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A Pragmatic Bio-inspired Approach to the Design of Octopus-inspired Arms

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Abstract— **This paper presents the results of a multidisciplinary project where biologists, mechanical engineers and electronic engineers worked together to develop bio-inspired soft continuum arms, whose design captures and takes advantage of key features of the octopus anatomy and control. The cross-integration of such diverse expertise was channelled towards the design of soft continuum arms whose characteristics were inspired by nature, but with a focus on readily available engineering technologies and their effective integration from a system viewpoint.**

On one side the mechanical structure and the control was designed looking at the animal, in particular at the coupling between its anatomy and control system that allows the animal to survive in its ecosystem.

On the other side engineering issues and constraints were carefully accounted for, namely material softness, intrinsic safety, energy efficiency, cost effectiveness and manufacturing aspects.

The design evolution is presented through three different generations of prototypes where both bio-inspiration and engineering requirements are appropriately blended.

I. INTRODUCTION

Roboticists can find in nature a prime source of inspiration for designing new generations of robots [1], [2]. Distilling engineering principles and design concepts from the observation of nature is not trivial. In order to gain a competitive design edge from nature observation, a holistic approach is crucial: a team with complementary background needs to synergically co-operate towards finding the optimal trade-off between biological insights and engineering constraints, e.g. materials, manufacturability, energy efficiency, reliability and cost.

In an animal that lives in a particular ecosystem the brain and body evolve together from birth. This triangular interplay among brain, body and environment allows natural creatures to survive in a changing environment.

Analogously in a robot the control system and its mechatronic structure ought to be designed together. This approach to design is sometimes referred to as embodied, as opposed to a more classical engineering approach, where the integration between mechanical design and control is not always very tight [3].

Conventional robots are typically made of stiff links and are not easily adaptable to tasks different from those for which they have been designed.

Conversely in tasks requiring high dexterity and compliant interaction continuum robot arms are a good candidate choice with respect to jointed robotic arms. They allow whole-arm manipulation (differently from traditional robots where the load is handled only by the end-effector), hence providing more versatility when interacting with load. The inherent softness results in an intrinsically safe system when interacting with humans or fragile payloads, but at the same time the capability of tuning stiffness allows to apply high forces if required. Applications of such robots span from search operations in hostile environments [4], to medical [5], [6] and underwater applications [7].

Octopus and more generally boneless cephalopoda (e.g. squids) and other invertebrate animals are living examples of such a concept. The octopus is a boneless animal that uses its muscular system also for its structural support. The way an octopus moves and behaves is pivoted around a body that has infinite degrees of freedom (DOF). Octopus arms are natural continuum arms, are extremely flexible and can regulate continuously the amount of bending and stiffening [8], [9].

A significant amount of research has been carried out on continuum robots over the years, providing a wealth of results. Some works focused on the difficult task of modeling and controlling a continuum structure. Yekutieli et al proposed a dynamic model for an octopus-inspired continuum arm that includes the key anatomical features [10], [11]. Kuwabara et al used echo state networks for the timing-based control of a soft robotic manipulator [12].
A wide range of continuum robots has been built with classical technologies. A good example is the pneumatic continuum arm developed by Walker and co-workers inspired by the elephant trunk [13], or the snake robot [14] composed of serially connected electrically-driven links. Other approaches to actuation made use of less conventional technologies, such as electro-active polymer actuators [15] This technology however, although promising, at present requires significant actuating electric power, thus demanding large power supply units, and posing non-negligible issues on electrical safety, in case of robots meant to co-operate with humans. Several other technologies and manufacturing processes have been investigated over the years [16], [17], [18], [19].

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The aim of this work is to develop flexible continuum robotic arms whose design trade-offs between bio-inspiration and engineering needs.

The paper is organized as follows: section II presents the relevant octopus biological features. Section III illustrates the design requirements of the continuum arm. Section IV introduces actuation and control hardware. Section V presents and assesses three generations of prototypes. Finally, section VI draws conclusions and outlines future work.

II. BIOLOGICAL BACKGROUND

This section provides the relevant biological insights, purposeful to identify the features relevant to the design of soft continuum robotic arms.

The octopus is an invertebrate animal. Its arm muscular system is composed of three families of muscles: longitudinal (axial), transverse (radial) and oblique (helically wound). The longitudinal muscles are arranged in four trunks interlaced with the transverse muscles (Fig. 1).

The other key feature of the octopus muscular system is its hydrostaticity, the property of keeping the muscle volume constant: a change in one dimension (e.g. lengthening) will cause an opposite change in another dimension (radial contraction) and conversely.

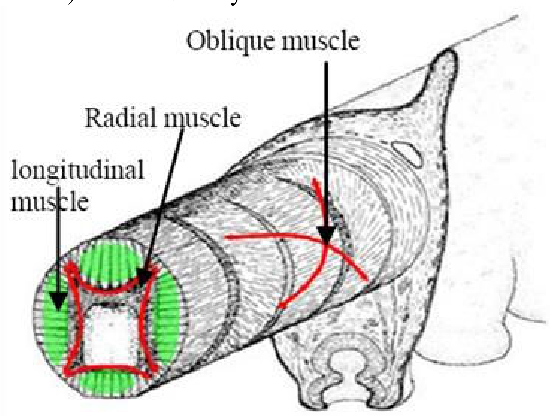


Fig. 1. Octopus arm muscular anatomy

The octopus neurophysiology is very peculiar compared to vertebrate one. It has a hierarchical and distributed brain architecture where the peripheral nervous system (PNS, located within the body and along each of the arms) has a higher number of neurons than the central nervous system (CNS, located between the animal's eyes, Fig. 2).

Neuroscientists found that octopus arms' complex movements result from the combinations of a number of motions that can singularly be obtained by activating the relevant muscles arranged as previously described. The CNS triggers motions and sets initial values for muscle contraction. Then the PNS applies commands to the appropriate muscular groups [20].

In this way nature has solved the problem of controlling the fully flexible and compliant octopus arm with a light computational load.

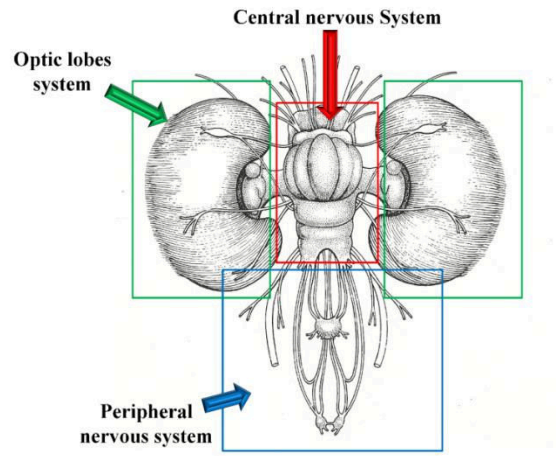


Fig. 2. Octopus CNS

III. DESIGN REQUIREMENTS

A. Introduction

The design of continuum arms inspired by the octopus has to tackle the challenge of mimicking a soft and virtually continuum structure using engineering technologies.

The high level requirements of a soft continuum robotic arm can be summarized as follows:

1) *Mechanical architecture:* the topology of actuators should be inspired by the muscular anatomy of the octopus, and their number chosen as a trade-off between dexterity (e.g. arm bendability) and engineering constraints.
2) *Soft mechanical hardware:* softness of the actuators and all other materials is a fundamental part of the design.
3) *Soft electronics:* also electronic hardware should be designed as soft as possible to match the mechanical design.
4) *Simple control algorithm.*
5) *Capability to operate underwater or outside water.*
6) *Energy efficient actuation.*
7) *Intrinsic safety.*
8) *Ease of assembly and reliability.*
9) *Low-cost.*

A number of prototypes was built in this project following an evolutionary-type approach to reach the solution that best fits all the requirements defined above.

After a preliminary assessment of the functionalities of the muscles with respect to the arm requirements it was established that:

a) Even if in the animal there are four longitudinal and for radial muscles from a kinematic viewpoint the fourth one is redundant, so it was decided to use three as muscles modularity.

b) out of the three families of muscles (longitudinal, radial and oblique) only the first and the second ones are considered. Oblique muscles are responsible for torsion which is not a requirement in a manipulator arm. Torsion is typically beneficial in engineering terms as a means to transmit torque through a shaft, but it is not generally useful in a robotic structure.
c) Radial muscles would be potentially useful if seemingly cooperating with longitudinal muscles to achieve a bending motion, but in a robot having a prevailing longitudinal dimension, radial muscles would have smaller dimensions and the required mechanical interfaces with longitudinal muscles as well as the additional wiring and power requirements would hamper the potential benefits of having them. This will be proven passing from the first to the second prototype.

IV. Actuation and Control Hardware

A. Actuation

In the light of the requirements of softness, intrinsic safety, low cost, energy efficiency and ease of assembly it was decided to realize the actuating muscles (both longitudinal and radial) by means of custom-made braided pneumatic Muscle Actuators (pMA) [21]. These actuators are composed of a braided yet flexible outer shell wrapped around an inner containment layer typically made from a rubber or elastomeric material. Contraction is the classical operating mode for the pMA with a theoretical maximum contraction at a braid angle 54.7˚. Besides this traditional contraction mode, pMAs can be potentially also used in the less common expansive mode. Operation in this mode occurs by starting from an initially compressed position rather than the traditional elongated state, and creating a small gap in-between the inner rubber layer of the muscle and the braid. When pressurized these actuators will now expand following the same model applied for contraction, reaching an equilibrium position at the 54.7˚ braid angle.
In the muscle system developed for the arms all muscles are independently pressure-controlled by either an array of miniature 3-way valves (SMC, model SY3120-5LOU-C4-Q) piloted via a RS232 link.

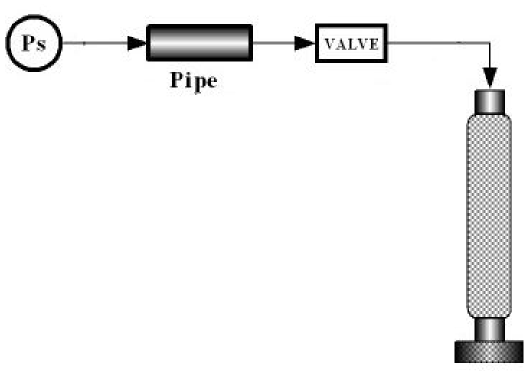


Fig. 3. Pressure control circuit of a pneumatic muscle

From a fluid power viewpoint a pMA works in pressure-control mode (Fig. 3), not in flow-control mode like a conventional linear pneumatic cylinder. With an electrical analogy this type of fluidic drive is somehow equivalent to a potential divider (the 3-way valve) and a capacitance (the pMA) and can be modelled similarly to an RC circuit. Pressure-control mode (that in classical engineering applications is used e.g. in ABS brake control) is generally more energy-efficient than flow-control, as the flow is only due to air compressibility dynamics in a compliant chamber, and there is no contribution of the flow occurring as a consequence of a moving part (i.e. the piston of a linear cylinder).

Reliability is another fundamental issue in the design. In particular, care has to be taken to minimize air leaks that can majorly affect the response and the energy consumption. Therefore it is critical to find an effective way to interconnect the muscles compactly, without increasing the air flow rate due to undesired leakage.

B. Control Hardware

The PNS is implemented in an embedded controller using custom-designed flexible boards (Fig. 4), with a circular form factor so as to better match the cylindrical geometry of the arm mechanics. Albeit some components mounted on the board are rigid (e.g. the DSP, a Texas Instruments, model TMS320F288), still with an appropriate layout of the components it is possible to obtain a fair amount of bending of the board, that is useful if the board is mounted on the arm itself.

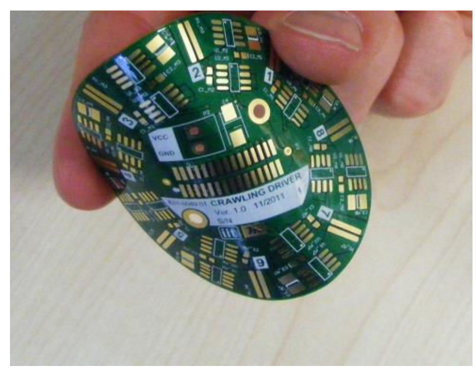


Fig. 4. Flexible circular shaped electronic board

The PNS algorithm runs on the DSP and sends time-based individual coordination commands to the valves controlling each actuator.
This control is in line with the neurophysiological findings whereby a single high level CNS controller communicates with local PNS controllers. Details can be found in [22].
Essentially the controller performs the following steps.

- CNS (an external PC) triggers movements and sets arm desired motions (e.g. elongation or bending).
- PNS converts CNS information to time-based individual muscle activation using stereotyped motion strategies.

Elongation is achieved by simultaneously contracting the radial muscles and relaxing longitudinal ones (or only actuating longitudinal muscles, if radial ones are not present). In the former case as the radial diameter is reduced the arm length will increase to maintain muscular hydrostatic (constant volume) properties.

Bending is achieved by selective muscle activation, i.e. contraction, of one or more of the longitudinal muscles and co-contraction of the radial muscles in segments above and below the required bend point. If radial muscles are not present only longitudinal muscles are selectively activated. This bio-inspired control is implemented without requiring mathematically involved or computationally heavy model-based algorithms that are difficult to treat and implement in real-time.

V. Arm Prototypes

Three generations of prototypes have been developed. We will refer to them as follows:

- *Longitudinal and Radial Muscle Prototype*
- *Longitudinal Muscle Prototype 1.0*
- *Longitudinal Muscle Prototype 2.0*

A. Longitudinal and Radial Muscle Prototype

A first prototype having both longitudinal and radial muscles was fabricated (Fig. 5). This model was designed to mimic the muscular hydrostat features of the octopus arm by combing longitudinal elongation with radial contraction. Each segment has four DOF and the whole structure has 16 DOF.

In order to effectively interconnect longitudinal and radial muscles, custom nylon bolts were made with a rapid prototyping machine. These have a hole through the bolt top where fittings were mounted to 1-mm hoses used to supply air or water to each muscle. Air or water supply was provided by either an external compressor or a very compact hydraulic pump.

The arm has a conical shape with arm radius ranging from 8.5cm to 11.5cm. With shorter longitudinal muscles the extension only resulted in very little bending (5 degrees).

In addition, because the radial muscles were used in contraction mode, the length change was limited to 25% of the original length which consequently had negligible effect on increasing the bending angle of a continuum section.

Because of these limitations, it was decided to drop radial muscles. Furthermore, the space utilized to mount radial muscles can now be removed to reduce the continuum arm radius and hence obtain greater elongation.

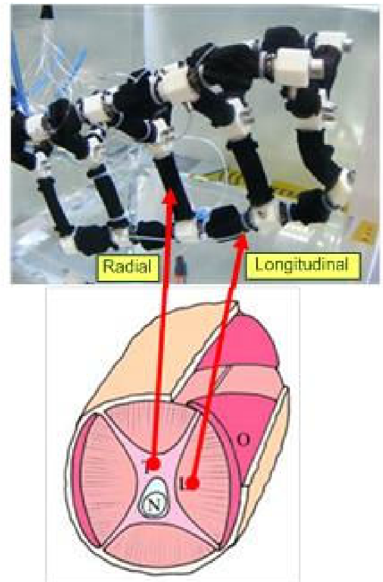


Fig. 5. First generation arm prototype with longitudinal and radial muscles in water, and correspondence with octopus anatomy

B. Longitudinal Muscle Prototype 1.0

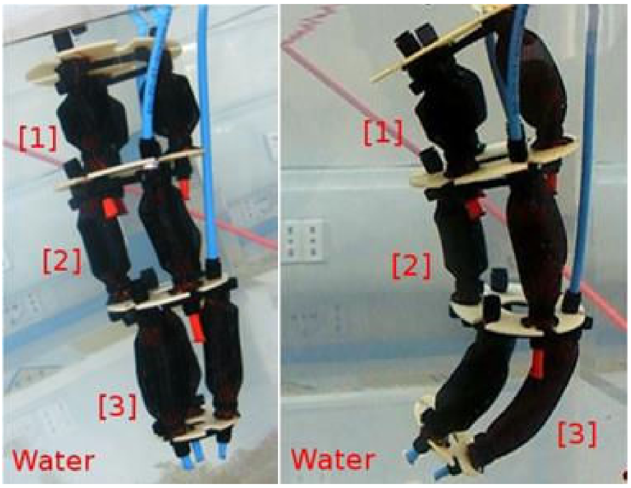
This second generation prototype (Fig. 6) was built without radial muscles. These muscles would be potentially useful if properly cooperating with longitudinal muscles, but as previously stated, in an arm having a prevailing longitudinal dimension the benefits of radial muscles would be negligible compared to the increasing design complexity.

Therefore the second prototype was built, made of three segments, each using three expanding pMA muscles fixed to a supporting structure of plastic.

This prototype was built more compactly with a conical shape that has a progressively smaller radius from the base (5cm) to top (2.5cm). The lower continuum sections have shorter pMAs which were lengthened towards to tip. This design decision was taken to reduce the sagging phenomena observed, when operated in air, in the lower continuum sections due to the weight of the continuum sections mounted on top.

This prototype was tested both in air and in water (de-ionized to prevent valve rusting), driving the muscles with water supplied by an external compact pump.

This prototype showed significant improvement with respect to the previous prototype.



(a) (b)

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

Tests to assess achievable extension were carried out and yielded results illustrated in Fig. 7 where an extension of 40% was achieved. Extension (normalized with respect to muscle length at rest) was plotted against muscle input pressure.

Subsequently bending tests were carried out. One muscle of the prototype was driven with increasing pressures up to 2 bars and lengths of all three muscles were recorded.

The results are shown in Fig. 8, where for each section the angle is calculated and plotted against time. In this test a max bending of 53˚ was observed.

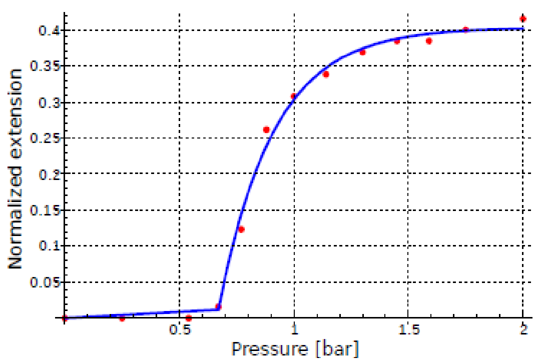
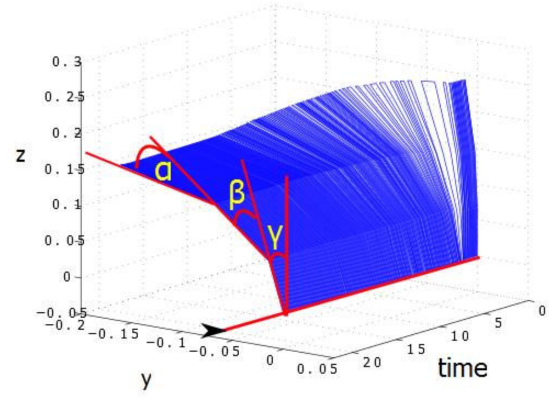
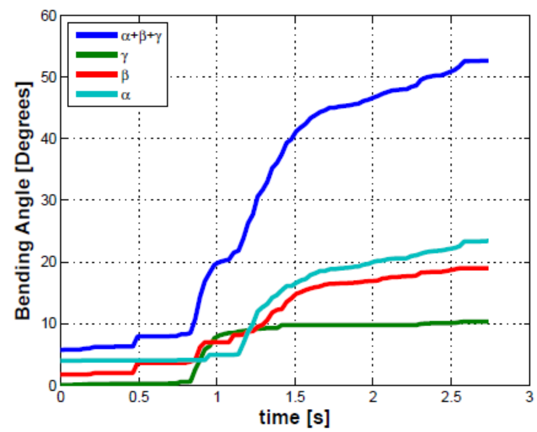


Fig.7. Longitudinal muscle extension vs. pressure (red dots are measured data)

However, it was understood that a further decrease of the radius could significantly increase the bending angle of each continuum section. Without rigid links and with constrained actuation space, the only beneficial factor in terms of the actuation space of continuum arms is its bending angle. Higher bending angle would mean greater workspace that allows to attain and demonstrate sophisticated application oriented tasks such as object inspection and whole-arm manipulation.



(a)



(b)

Fig. 8. Bending performance tests: (a) bending profile over time (b) bending angle vs. time for different segments where alpha, beta and gamma are the respective bending angles of continuum sections 3, 2 and 1

C. Longitudinal Muscle Prototype 2.0

From the experience gained from the first two prototypes a third generation prototype was built.

The prototype continuum arm is shown in Fig. 8. In this third generation arm, in addition to the fact that there are no radial muscles, the conical shape that has featured in previous prototypes was abandoned in favour of a more uniform construction.

It consists of three variable length pMAs designed to extend in operation, fixed to circular rigid end plates at 120˚ apart.

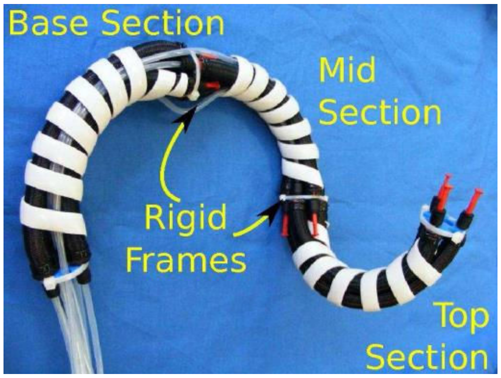


Fig. 9. Third generation arm prototype: bending in air

Actuators are constrained to extend parallel to the neutral axis by bundling them together with light nylon wire ties at regular intervals and polyethylene spiral binding. This allowed to utilize longer pMAs (15cm) and at the same time far shorter section radius (1.25cm) as seen in Fig. 9. Due to the increased length the pMAs exhibited 6cm length increase contributing to a maximum bending in excess of 180 degrees. All three continuum sections were fabricated identically and therefore this third generation of the prototype could achieve kinematic decoupling thanks to the large increase of the workspace with sufficient redundancy. Hence it is possible to generate potential application scenarios such as object inspection and whole arm manipulation.

VI. Conclusions and Future Work

The paper has presented three fluidically-actuated continuum arms whose design was inspired by the octopus anatomy and control. After providing the relevant biological background, the high level design requirements were defined, where bio-inspiration and engineering issues where appropriately blended.

Three arms with different features were prototyped and controlled, and elongation and bending assessed. The controller was based on a bio-inspired hierarchical and distributed architecture, where a host computer based CNS is used to send planning control commands to a PNS implemented on a on a flexible board hardware.

Future developments will include developing a multi-arm robot to investigate more complex motions and multi-arm coordination.

References

[1] Y. Bar-Cohen and C. Breazeal, "*Biologically inspired intelligent robots*," Bellingham Wash, SPIE Press, 2003.

[2] D. Trivedi, C. D. Rahn, W. M. Kier and I. D. Walker, "Soft robotics: Biological inspiration, state of the art, and future research," *Applied Bionics and Biomechanics*, Vol. 5, pp. 99–117, 2008.

[3] R. Pfeifer, M. Lungarella and F. Iida, "Self-Organization, Embodiment, and Biologically Inspired Robotics," *Science*, Vol. 318, No. 5853, pp. 1088-1093, 2007.

[4] A. Wolf, H. B. Brown, R. Casciola, A. Costa, M. Schwerin, E. Shamas and H. Choset, "A mobile hyper redundant mechanism for search and rescue tasks," *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 2889-2995, Las Vegas, 2003.

[5] N. Simaan, R. Taylor and P. Flint, "A dexterous system for laryngeal surgery", *IEEE Int. Conf. Robotics and Automation*, New Orleans, pp. 351–357, 2004.

[6] G. Chen, M. T. Pham, T. Redarce, C. Prelle and F. Lamarquem, "Design and modeling of a micro-robotic manipulator for colonoscopy," *5th Int. Workshop on Research and Education in Mechatronics*, Annecy, France, 2005.

[7] P. R. Bandyopadhyay, "Trends in biorobotic autonomous undersea vehicles," *IEEE Journal of Oceanic Engineering*, Vol. 30, No. 1, pp. 109–139, 2005.

[8] Y. Sumbre, Y. Gutfreund, G. Fiorito, T. Flash and B. Hochner, "Control of Octopus Arm Extension by a Peripheral Motor Program," *Science*, Vol. 293 (5536), pp. 1845-1848, 2001.

[9] D. Sumbre, G. Fiorito, T. Flash and B. Hochner. "Neurobiology: Motor control of flexible octopus arms," *Nature*, Vol. 433, pp. 595–596, 2005.

[10] Y. Yekutieli and R. Sagiv-Zohar, "Dynamic Model of the Octopus arm. I. Biomechanics of the Octopus Reaching Movement," *J. Neurophysiology*, Vol. 94, pp.1443-1458, 2005.

[11] Yekutieli Y, Sagiv-Zohar R, Hochner B and Flash T, "Dynamic Model of the Octopus Arm II. Control of Reaching Movement", *J. Neurophysiol.* 94 1459-68.

[12] J. Kuwabara, K. Nakajima, R. Kang, D. Branson, E. Guglielmino, D. Caldwell and R. Pfeifer, "Timing-based control via echo state network for soft robotic arm" *IEEE-INNS International Joint Conference on Neural Networks,* Brisbane Australia, 2012, pp 2943-50

[13] W. McMahan, V. Chitrakaran, M. A. Csencsits, D. M. Dawson, I. D. Walker, B. A. Jones, M. B. Pritts, D. Dienno, M. Grissom, and C. D. Rahn, "Field trials and testing of the OctArm continuum manipulator," *IEEE Int. Conf. on Robotics and Automation*, 2006, pp. 2336–2341.

[14] M. Tanaka and F. Matsuno, "Experimental study of redundant snake robot based on kinematic model" *IEEE Int. Conf. on Robotics and Automation,* Roma, Italy,2007, pp 2990-95

[15] Choi H, Jung K, Ryew S, Nam J, Jeon J, Koo J and Tanie K, 2005 "Biomimetic soft actuator: design, modeling, control and applications" *IEEE/ASME Trans. Mechatronics* 10 581-92

[16] J. Bishop-Moser, G. Krishnan, C. Kim, and S. Kota, "Design of Soft Robotic Actuators using Fluid-filler Fiber-reinforced Elastomeric Enclosures in Parallel Combinations", *IEEE/RSJ Int. Conf. on Intelligent Robot Systems*, Vilamoura, Portugal, pp. 4262-4269, 2012.

[17] A. Grzesiak, R. Becker, and A. Verl, "The Bionic Handling Assistant – A Success Story of Additive Manufacturing", *Assembly Automation,* Vol. 31, No. 4, 2011.

[18] W. McMahan, B. A. Jones, and I. D. Walker, "Design and Implementation of a Multi-section Continuum Robot: Air-Octor" *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Edmonton, Canada, pp. 3345-3352, 2005.

[18] A. Sadeghi, L. Beccai, and B. Mazzolai, "Innovative Soft Robots Based on Electro-Rheological Fluids", *IEEE/RSJ Int. Conf. on Intelligent Robot Systems*, Vilamoura, Portugal, pp. 4237-4242, 2012.

[19] K. Suzumori, S. Iikura, and H. Tanaka, "Development of Flexible Microactuator and its Applications to Robotic Mechanisms," *IEEE Int. Conf. on Robotics and Automation*, Sacramento, California, pp. 1622-1627, 1991.

[20] L. Zullo, G. Sumbre, C. Agnisola, T. Flash and B. Hochner, "Nonsomatotopic organization of the higher motor centers in octopus", *Curr Biol.*, Vol. 9, No. 19, pp. 1632-6, 2009.

[21] C.-P. Chou and B. Hannaford, "Measurement and modeling of McKibben Pneumatic Artificial Muscles", *IEEE Trans. on Robotics and Automation*, Vol. 12, No. 1, pp. 90–102, 1996.

[22] D. T. Branson, R. Kang, E. Guglielmino, and D, G. Caldwell, "Control Architecture for Robots with Continuum Arms Inspired by *Octopus vulgaris* Neurophysiology," *IEEE Int. Conf. On Robotics and Automation*, St. Paul, Minnesota, May 2012.