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Study and fabrication of bioinspired octopus arm mockups tested on a multipurpose platform

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***Abstract*— This paper illustrates a robotic approach to the study of the *Octopus vulgaris* arm. On the base of the embodied intelligence theory, a study on the interaction among materials, mechanisms and actuation systems has been conducted. Starting from the observation of the performances of the octopus and drawing inspiration by its functional anatomy, several mock-ups, made by different materials and actuated by different cable arrangements have been tested. For this purpose a versatile platform has been designed and built, where the various solutions have been mounted and compared. The final aim of the work is to replicate the main complex movements of the octopus in a robotic platform. In particular the reaching movement, which best represents the stereotyped motion pattern of the octopus arm, has been reproduced.**

I. INTRODUCTION

The octopus is a marine invertebrate with amazing motor capabilities and intelligent behaviours. Its body has no rigid structures and has interesting characteristics of dexterity. The lack of rigid structure, the potentially infinite degrees of freedom (DOF) and the distributed control are some of the most peculiar features of the octopus. The lack of rigid structure allows the octopus to adapt his own body to the environment and squeeze through very small apertures, limited only by the size of its rigid brain capsule. As consequence of the infinite DOF the arms of the octopus are capable of twisting, changing their length and bend in all directions at any point along the arm. The eight arms are effectively used to locomote on the diverse substrates of the sea bottom and to reach, grasp and even manipulate objects with unexpected dexterity. Distributed control simplifies the management of this large number of degrees of freedom by means of simple stereotyped movements [1]-[3] which participate in generating more complex behaviours when the eight arms act in coordination [4].

Octopus arms, like mammal tongue, elephant trunk and others, belong to a class of structures called muscular hydrostat. These manifest two main characteristics: lack of rigid structures and conservation of volume [5]. Despite the absence of rigid structures, muscular hydrostats have the capability to vary their stiffness and to apply relatively high forces. Furthermore, as a consequence of the isovolumetric nature of the muscular hydrostat, passive elongation is possible as a result of the application of a radial force, i.e. by the contraction of transverse muscles in the octopus arms. The muscles in the octopus arm are arranged in longitudinal, transverse and oblique. Longitudinal muscles extend along the whole length of the arm. Transverse muscles connect the external connective tissues and, when contracted, they reduce the diameter of the arm thus increasing the arm length. Oblique muscles extend all over the arm and allow for torsion around the arm axis [6], Fig.1.

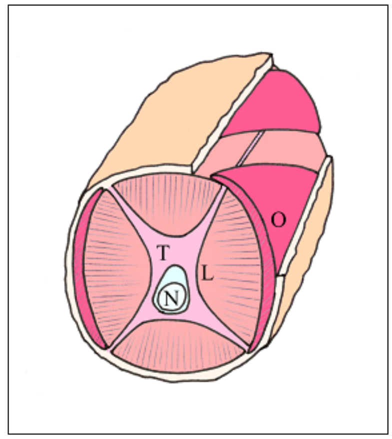

Fig. 1. Octopus arm section. (O) Oblique (T) transverse and (L) longitudinal muscles. (N) Nerve cord.

Starting from the observation in nature that adaptive behaviour emerges from the complex and dynamic interaction between the morphology, sensory-motor control and environment, the principle of "embodiment" is leading the research in the field of robotics [7]-[9]. Biological inspiration in soft robotics were followed in the last years with exciting results [10]. Here biological inspiration has been adopted for the design of an artefact that replicates the characteristics of an *Octopus vulgaris*. The octopus represents a biological demonstration of how the morphology of the body could be exploited to develop a robotic artefact whose motion capabilities are strictly connected to the shape of its body and its interaction with the aquatic environment. This approach differs from the traditional view according to which adaptive

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behaviour is merely based on control and computation. In contrast, the investigation is based here on the intimate relation which occurs between the body and the brain of the organism [11],[12]. The anatomical and behavioral elements previously mentioned have to be integrated into the robotic artefact from the beginning of the design process [13] and they have to provide the principle for the choice of the materials and the distribution of the actuators. A useful method for verifying specific hypothesis is to build mock-ups. A mock-up is a simplified device conceptually and phisically far from the final prototype which allows to verify several more specific capabilities. The final goal for the mock-up is to identify specifications for the design of the octopus-like artefact. For this purpose different mock-ups replicating one octopus arm have been developed. Three different types of mock-ups have been manifactured to investigate both passive and dynamic properties. The first one, which we refer to as passive mock-ups, were made up of silicone alone and lacked of any kind of actuation, while the others were actuated by cables. These two latter type of mock-ups are actuated, in the first case, with cables that approximate the function of 4 longitudinal muscles attached to the tip of the arm and, in the second case, with 9 transverse cables connected with the longitudinal ones distributed along the arm and 4 longitudinal attached to the tip. Silicone was found to provide the best solution for a soft isovolumetric structure. Furthermore, an experimental platform that has the capability to test the mock-ups underwater has been built in order to achieve quantitative data. For the dynamic tests on passive mock-ups the platform provides an oscillating motion to the base of the mock-ups. The platform has 15 motors that can actuate the cables to provide the motion to the arms. The objectives of these tests are to:

- identify the suitable material to build up the final arm prototype
- explore the morphology of mock-ups to do some complex actions with simple actuation
- reproduce some stereotyped movements of a single arm of an octopus

In particular the stereotyped movement that we tried to reproduce is one of the most important movements of the octopus, the reaching movement. One of the theories on the movement activation pattern suggests that the reaching movement is obtained by mean of a stiffening wave [14]. A stiffening front straightens the bend and propels it toward the tip of the arm.

The paper is structured as follows. Section II describes the platform built to test the mock-ups, section III describes the materials used to built passive mock-ups, section IV describes the mock-up used to test simple actuation and section V describes the complex mock-up used to reproduce the stereotyped movement of reaching. Then section VI shows the results obtained and section VII the conclusions and future works.

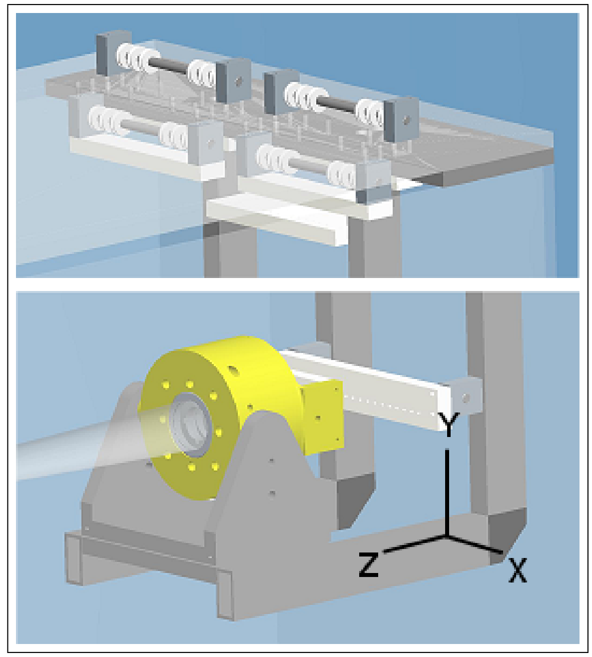

Fig. 2. CAD of the experimental setup. Top: detail of the pulley system. Bottom: detail of the adjustable base. It has a rotational degree of freedom around x-axis. Since the mock-ups are fixed to this base their position is changed as well.

II. MATERIALS AND METHODS

A. *Tank and Supporting Structure*

The apparatus built for testing purposes is made up of a tank, a supporting structure on which servomotors are lodged, pulleys and an adjustable base with two degrees of freedom onto which silicone mock-ups can be attached. The whole setup is shown in Fig.3. This is a multifunctional platform that can be utilized both for dynamic tests with passive mock-ups and for the actuation of cable-driven mock-ups. The device can be employed both in freshwater or salt water.

The supporting structure is composed by two parts. The first is a Perspex™plate with 15 servomotors (HS-785HB HITEC) fixed on it. Each servomotor has a pulley with a Dyneema™fiber cable wound around it that is pulled in response to the motion of the motor. Each cable is then partly wound around one pulley of a series of 15. The second part of the supporting structure is an L shaped aluminum component that holds the adjustable base on which the mock-ups can be attached. This part of the supporting structure is inside the glass tank and immersed in salt water. The materials used, therefore, are stainless and suitable for enduring the contact with salt water. The servomotors cables are connected to the cables inside the mock-up and are used to move both the adjustable base and the mock-up itself. In order to decrease the friction, pulleys and polytetrafluoroethylene (PTFE) small plates system were employed Fig.2.

B. *Electronic system*

The cables are activated by the system in Fig.4, composed of 15 servomotors, a controller (TI TechSH2 Tiny Controller)

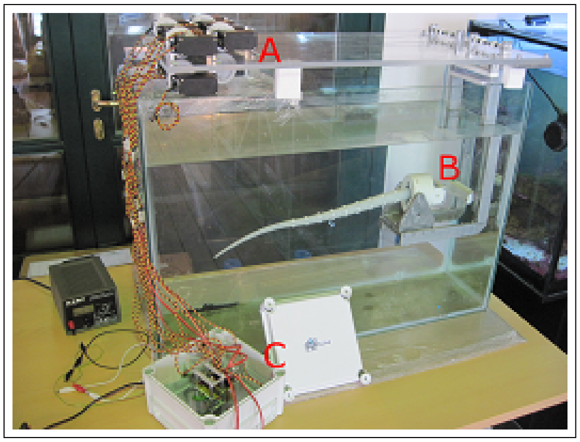

Fig. 3. Experimental setup: (A) Servomotors. 2 servomotors are devoted to move the base, that control the orientation of the longitudinal axis of the arm, to the top or to the bottom of the tank. The others are devoted to actuate the mock-ups. (B) L-structure, arm and the adjustable base (C) Control Board.

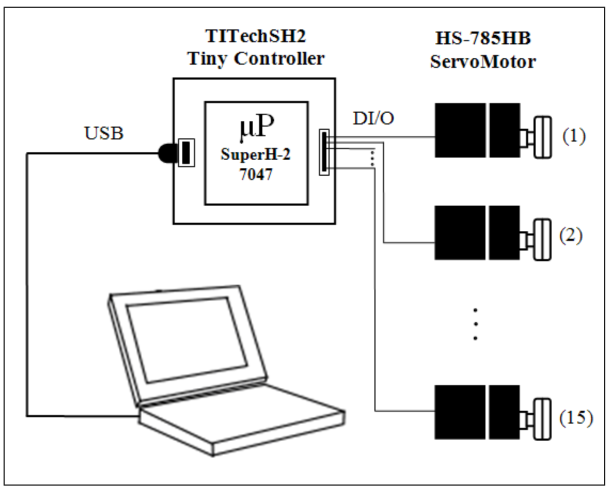

Fig. 4. Control architecture of the experimental setup.

and a Personal Computer (PC). Briefly, the servomotors are supplied by a power voltage of 6V, where the pulse width modulation controls the rotor position. The servomotor is able to rotate from 0 to 1260 degrees (3.5 turns), with a no-load speed of 42.8 rpm, genereting a stall torque of 1,29N·m. The core of TI TechSH2 Tiny Controller is the SuperH-2 7047 which is a 32-Bit RISC microprocessor with an oscillatory frequency of 11MHz. The micro-controller peripheral system is composed of several parts: Digital Input Output port, which is programmed in order to control the servomotors, USB port, that is connected to PC, allowing both on-chip programming and communication, etc. A software was purposely created so that the servomotors could be controlled via PC. The software was developed in C++.

III. Passive mock-ups

In order to compare the passive physical properties of the real octopus arm with the physical properties of several materials, a series of mock-ups were manifactured. These mock-ups have the same conic geometry and proportions

TABLE I
VARIOUS SILICONE RUBBER FILLED WITH DIFFERENT MATERIALS

External shell	Filled with
00-30	Air
00-30	Water
00-30	Gel
00-30	00-10
00-10	00-30

of a real octopus arm (length: 300mm; base diameter: 20mm). The chosen materials are commercial silicones ECOFLEX™silicone (00-30, 00-10 and Dragon Skin type, Smooth-On, Inc.) which were moulded into a series of mock-ups geometrically identical, in order to compare each other both in static and dynamic tests. The chosen silicones have a density of $1070Kg/m^3$, which matches resonably well the $1042Kg/m^3$ of the octopus arm [15]. With an heuristic methodology guided by qualitative observation, a first set of mock-ups was tested. Several combinations of an external shell of silicone and an internal core of other materials were tested, see TableI. Finally the best filling material was chosen and a combination of this material with an external skin of ECOFLEX™was tested again.

IV. Four longitudinal cables mock-ups

The mock-ups devoted to investigate how a simple actuation could produce complex action, have the same geometry of the previous one, plus 4 cables lodged inside. These cables run along the whole mock-up length and are fixed to the tip of the mock-up. The cables mimic the functionality of the longitudinal muscles. The mock-up was manually actuated to show the advantage of the morphological approach to the design of the arm and then it was attached to the platform and the feasibility of the four cables actuation was tested. The manual actuation was performed in air, while the platform solution allows an underwater series of reproducible tests.

V. Longi-transverse cables mock-up

A very complex cable-driven mock-up was designed and created by casting silicone in a purposely created mould. Inside this mock-up there are 40 cables. Of these, 4 cables are purely longitudinal while the remaining 36 are hybrid longi-transverse cables with a radial directionality which are capable of mimicking both the longitudinal and transverse action of the octopus muscles. It is important to notice that the longitudinal and transverse muscle are antagonistic muscles, and their joint contraction produce a local stiffening of the arm. A series of small rigid elements were embedded in the silicone matrix. These elements break down the axial tractive force exerted by the base cables in two components: axial and radial. These two force components mimic the joint-contraction of the two muscle groups in the octopus. There are 9 rigid elements along the mock-up that form 9 contraction units made up by a set of 4 cables each. The rigid elements are made so that the longi-transverse cables of the contracting units closer to the tip of the mock-up can

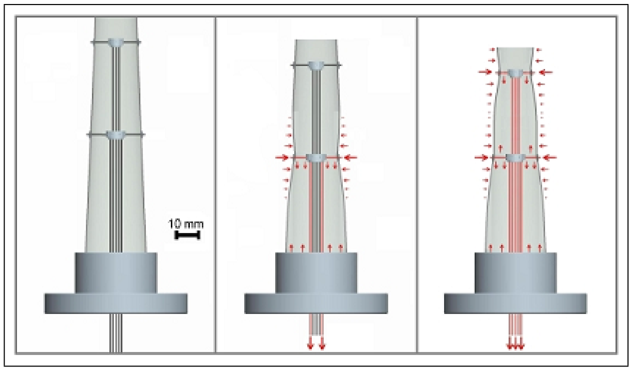

Fig. 5. Contraction example of the cables in the longi-transverse mock-up. The biggest arrows point to the contraction units where part of the cables go through the rigid elements and 4 cables are attached to the external part of the mock-up. When the cables of the contraction unit are pulled, a local stiffening is obtained.

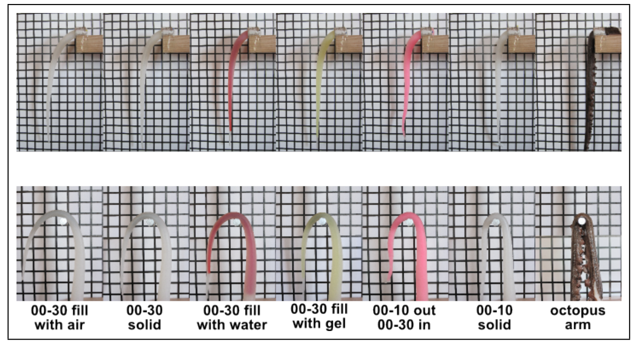

Fig. 6. Static material evaluation test.

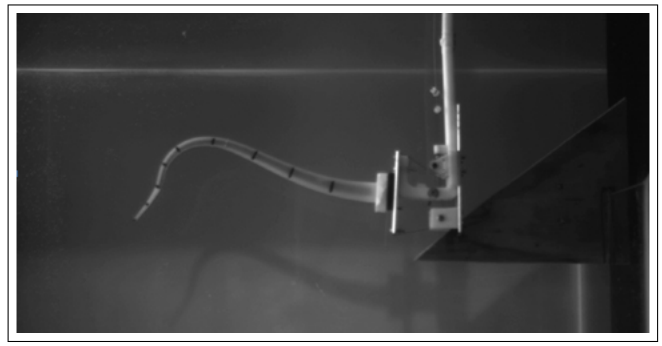

Fig. 7. Example frame of the passive material test, recorded with DALSA Falcon 1.4M. The markers and one mock-up are visible during the wave like movement induced by the rotation of the base in the L-structure.

move undisturbed in the rigid elements closer to the base. The cables of the contracting unit itself, on the contrary, can be directed in the radial direction with the least possible friction thanks to the morphology of the rigid elements. The four longi-transverse cables of the contracting unit are fixed on the silicone surface itself. The purely longitudinal cables extend up to two-thirds of the mock-up length where they are fixed to a rigid element that keeps them in place. These 4 purely longitudinal cable are arranged in the mock-up in this way: one the left side, one on the right side, one on the ventral part and the last one on the dorsal part. A silicone sheath has been placed around all of the cables. The mock-up length is 450 mm and the base diameter is 30 mm. The mock-up is attached to a rigid base that allows it to be connected to the supporting structure. The cables from the mock-up are attached to the servomotor cables by hooks.

VI. RESULTS AND DISCUSSION

The results illustrate several test performed, with and without the platform. More in details, in subsection A are reported the tests on passive mock-ups, aiming to elect the suitable materials to build the final prototype; in subsection B we explore some actions, pulling only one cable, of the four cable longitudinal mock-up and finally in subsection C we try to reproduce the stiffening wave with the longi-transverse cable mock-up.

A. Static Testing and Dynamic Results

This study was developed in two steps: a static comparison followed by a dynamic evaluation. The passive mock-ups were tested with the simple static test shown in Fig.6. By effect of the gravity in air we observe the curvature of the various arms. The grid in the background enables a qualitative evaluation of the material compliance.

In the static test, the 00-10 solid mock-up is the one that more closely mimics the geometry of the octopus bent arm . In the dynamic test, the mock-ups were mounted and tested on the platform one by one and the various parts of the arms were tracked during a wave-like planar movement. Each silicone arms were secured to the aluminium plate of the apparatus and were given the same input from the motor. The platform allowed one degree of freedom movement of the base of the mock-up. Nine visual markers (Fig.7) were applied to the arms and the wave-like movements were recorded with a commercial camera. The position of the markers during the movements was extracted by a manual procedure from the recorded frames. From the dynamic test it is possible to make a visual comparison between the x-y position of the various markers for each tested materials. An example of the markers tracks are plotted in Fig.8. We reconstructed the midline of the various mock-up extracting the mid points of the markers, positioned in center of the mock-up side and interpolating these mid points. In this way the central longitudinal axis of the mock-up is approximated. During the dynamic test, the mock-up composed of a core of water and a shell of 00-30 shows the most symmetric behavior along the x-axis and was elected as the most suitable material for the final artefact.

The results of the static and dynamic tests demonstrate that the 00-30 silicone arm, filled with water, shows the best behavior. Such an evaluation was made according to qualitative considerations as the compliance shown during the static test and the symmetry of movement during the dynamic test. Also the 00-30 silicone arm filled with 00-10 shows a good behavior according to the same criteria. The position of the midline during the wave-like movements for the 00-30 silicone arm filled with water is shown in Fig.9.

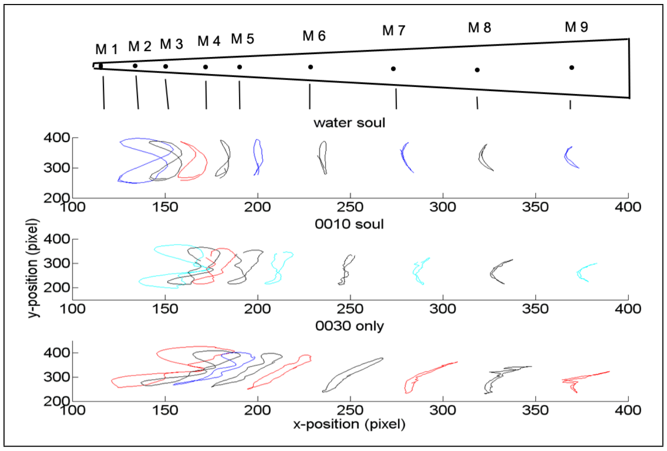

Fig. 8. Comparison between marker position during a dynamic test on 3 arms of different combination of materials. In the upper plot the schematic representation of markers location along the arm. From the top to the bottom: water, 0010, 0030. External shell is 0030 for all tests.

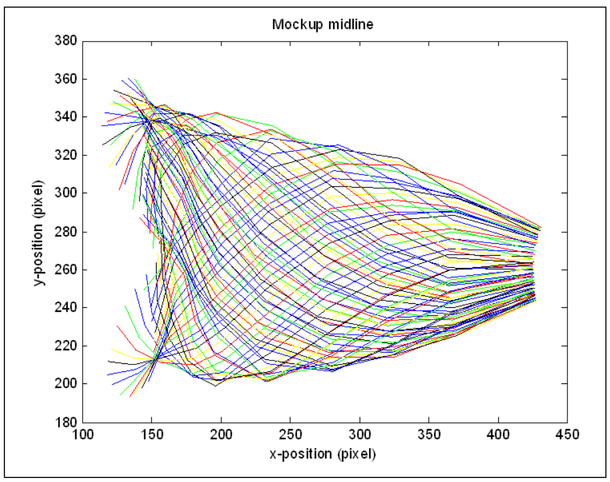

Fig. 9. Arm midline measured from the recording of a wave-like movement on a 00-30 silicone arm filled with water. Each line represents the profile of the midline at consecutive intervals of time.

B. Exploiting morphologies

Simple concepts had to be investigated to evaluate the capability of the 4 cables arm artefact to perform two tasks: grasping and pulling. The main idea is to use the same actuator for the two different activities. It is observed that, because of the continuous and soft nature of the arm, a smooth curl of the whole structure is achieved simply by pulling a single longitudinal cable. The capability to conform to obstacles or objects is peculiar for soft robots, and here we investigate some application of this property. In the first example a pen is positioned close to the surface in the distal part of the arm. The arm can wrap around the object and take it close to the base with only one longitudinal muscle, as shown in Fig. 10. In the second case the same actuation could produce a movement of the entire body, if the arm's tip is attached to the ground, Fig. 11. These observations could be useful for the control of the arm, because the activation of one actuator produces a complex interaction with the objects or with the environment, but only under predetermined and

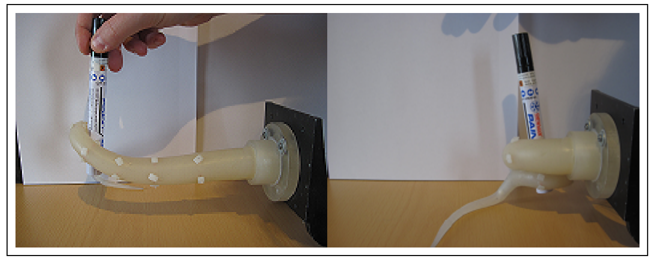

Fig. 10. A grasping example, obtained just with one longitudinal cable. The soft arm wraps around the pen without specific actuation, but just conforming to the object.

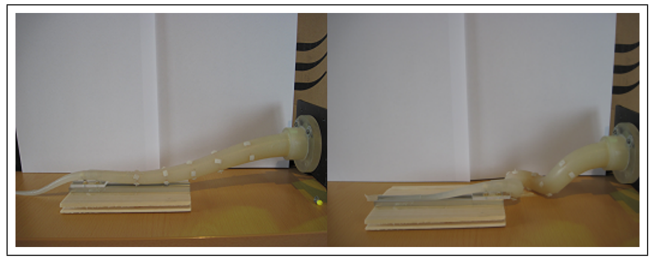

Fig. 11. If the tip of the arm is attached to a linear slider, pulling the longitudinal cable a curl occurs and the arm induce a 12 cm translation on the linear slider.

well defined initial conditions. These experiments confirm, as postulated by the embodied intelligence theory, that it is possible to simplify the control by exploiting the morphology of the body to achieve complex tasks.

C. Longi-Transverse Actuated Mock-up

The activation pattern for this mock-up was inspired by the reaching movement of the octopus. It was pointed out how the longitudinal and transverse muscle groups can function as antagonistic muscles. Stiffening would then occur when both muscle groups are simultaneously activated; an example is provide in Fig.5. The cable that was moved first is the purely longitudinal one on dorsal part, in order to start from the retroflex position. Afterwards, the longi-transverse cables were activated. The contracting units were sequentially activated in nine equal time intervals. The contracting units were actuated from the base to the tip, so that the stiffening bend created by the co-contraction of the longi-transverse cables straightens the mock-up. The midline during a reaching-like movement is plotted in Fig 12.

A full extension of the arm is not achievable by letting the arm under the sole effect of gravity . On the contrary, creating a local stiffening from the proximal to the distal part of the arm, we obtain a proper straightening of the arm, similar to the one observed during a reaching movement of the octopus. More investigations are required to enhance the performance.

VII. CONCLUSIONS AND FUTURE WORKS

A versatile platform for testing various kind of mock-ups has been designed and realized. The purpose of this platform is to actuate one octopus-like arm with different cables that mimic the function of the longitudinal or a combination of

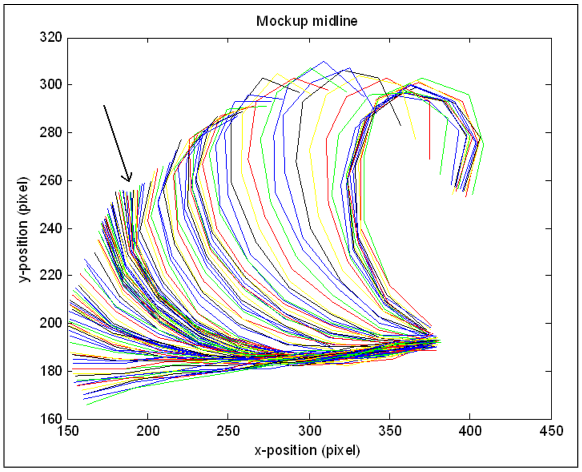

Fig. 12. Arm midline measured from the recording of a stiffening wave generated on the longi-transvere mockup. We can distinguish a part where the passive properties of the system are faster than contraction, than a second part where the stiffening of the arm provide to the right posture. The end posture is a straight line, as desired in a reaching movement. The arrow indicate the separation point of the two region.

longitudinal and transverse muscles. Specifications for an arm for an octopus-like robot were investigated based on the requirement dictated by materials and control theory. Materials investigated in the static and dynamic tests lead to the conclusion that the 00-30 silicone arm, filled with water, shows the most satisfying behavior. This observation will be taken into account in the development of future artefacts. We demonstrated that with the four cables arm some simple actions performed by just one actuator, could generate complex interaction with objects or the environment. Concerning the longi-transverse actuated mock-up, it was demonstrated that a reaching-like movement could be achieved by performing stiffening waves from the proximal to the distal part of the arm. In addition we will concentrate on the realization of other arms, investigating also the possibility to integrate other kind of actuation to mimic the transverse muscle. Thanks to designed platform and mock-ups, future work will be focused on validating octopus activation patterns provided by biological studies.

VIII. ACKNOWLEDGMENTS

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