An octopus-bioinspired solution to movement and manipulation for soft robots

2011 Bioinspir. Biomim. 6 036002

(http://iopscience.iop.org/1748-3190/6/3/036002)

Bioinsp. Biomim. **6** (2011) 036002 (10pp) doi:10.1088/1748-3182/6/3/036002

An octopus-bioinspired solution to movement and manipulation for soft robots

M Calisti[1], M Giorelli[1], G Levy[2], B Mazzolai[3], B Hochner[2], C Laschi[1] and P Dario[1,3]

[1] BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy
[2] Hebrew University of Jerusalem, Jerusalem, Israel
[3] Centre for Micro-BioRobotics@SSSA, Istituto Italiano di Tecnologia, Pontedera, Italy

E-mail: marcello.calisti@sssup.it, michele.giorelli@sssup.it, guy.levy@mail.huji.ac.il, barbara.mazzolai@iit.it, Binyamin.Hochner@huji.ac.il, cecilia.laschi@sssup.it and paolo.dario@sssup.it

Received 11 January 2011
Accepted for publication 23 May 2011
Published 13 June 2011
Online at stacks.iop.org/BB/6/036002

Abstract

Soft robotics is a challenging and promising branch of robotics. It can drive significant improvements across various fields of traditional robotics, and contribute solutions to basic problems such as locomotion and manipulation in unstructured environments. A challenging task for soft robotics is to build and control soft robots able to exert effective forces. In recent years, biology has inspired several solutions to such complex problems. This study aims at investigating the smart solution that the *Octopus vulgaris* adopts to perform a crawling movement, with the same limbs used for grasping and manipulation. An ad hoc robot was designed and built taking as a reference a biological hypothesis on crawling. A silicone arm with cables embedded to replicate the functionality of the arm muscles of the octopus was built. This novel arm is capable of pushing-based locomotion and object grasping, mimicking the movements that octopuses adopt when crawling. The results support the biological observations and clearly show a suitable way to build a more complex soft robot that, with minimum control, can perform diverse tasks.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Traditional articulated robots, or hard robots, generate motion via numerous rigid links connected by joints. Their motion is kinematically constrained by the degrees of freedom at the joints, with minimum deformation in the linkages during normal operations. Either or both the number of joints and the degrees of freedom at certain joints can be increased in order to achieve high degree of dexterity. The resulting robots are classified as hyper-redundant robots and can potentially work in unstructured environments, that is where environmental constraints, such as position and size of the obstacles, are not known *a priori*. Continuously bending elements, used as different links, can as well be adopted to improve high degree of dexterity. The following generation of robots is classified as continuum robots, able to bend constantly along their length and to produce smooth curves [1]; they show no rigid links or evident rotational joints. A further step is an innovative generation of robots widening and completing the skills of continuum robots: the soft robots.

A soft robot is a continuum robot, with intrinsic compliant characteristics, capable of exploiting its soft structure. The soft structure of these robots is composed of soft materials (e.g. rubbers, silicones) and/or actuators. The actuators can either form part of the structure, such as EAP, pneumatic actuators and SMA, or be located externally to the structure, like in cable-driven robots, where the motion is transferred to the soft structure via cables. Apart from their building procedure, the main characteristic of soft robots is their low resistance to stress forces. Able to conform to obstacles, to different grounds and to variable size objects, they can therefore carry soft and fragile objects. The soft robots have infinite degrees of freedom and a limited number of actuators, so they are underactuated robots. Because of underactuation and compliant characteristics, the distributed loadings (e.g. gravity) and the local deformations can have a relevant effect on the robot structure. The structure deformation, which characterizes soft robots, leads to a loss of accuracy in locomotion and manipulation. A concise but clear review on hard- and soft-robot characteristics is reported in [2].

At present, much effort has been made to produce soft robots, which are broadly classified into robots with locomotory capabilities or robots with manipulation capabilities. Some examples of robots with locomotory capabilities have been presented in [3–10]. In [3, 4] a robot, made of a shape memory alloy, able to crawl and jump is presented. In [7, 8] a biomimetic robotic earthworm has been realized. This robot is able to locomote on various surfaces and to climb different slopes. An example of a soft robot able to change its shape and, consequently to crawl, is presented in [11]. All the robots presented are able to locomote, but no one, however, can interact with objects or manage any grasping activity.

Recently, several soft manipulators or hard manipulators with soft capabilities have been developed. Relevant results were obtained especially by [12–14] with Active Hose and OctArm. The Active Hose is a manipulator inspired by elephant's trunk. This robot is able to bend and was used for rescuing purposes. Currently, OctArm is being considered the most effective soft manipulator. It is continuous and lightweight but powerful and able to lift and manipulate several heavy objects, potentially with different sizes. It is controlled by an ad hoc software interface and moves thanks to pneumatic actuators. Its design allows encircling and lifting objects and force sensors along the structure ensure feedback. At the end of the robotic arm, a camera makes the control for the operator easier. Inspired by the octopus muscle arrangement, an arm made of silicone and cables was presented in [15]. The arm in [15] is continuous, can bend, shorten and wrap around objects by just pulling one cable.

The octopus could be a remarkable source of inspiration to create soft robots [16]. Its manipulation capability, together with its ability to move on almost every kind of surface, is of great interest to robotics. The body of the octopus has no rigid structures and it can easily adapt to the environment. It can squeeze into very small and narrow holes or it can splay over prey. The octopus has eight arms which can twist, change their length, bend at any point along the arm and, despite the lack of rigid skeletal support, can vary their stiffness and apply relatively high forces [17]. The control of such a wide freedom of movement is highly distributed and it is simplified by the use of stereotyped movements [18], such as, for example, a temporarily reconfiguration of the arm into a stiff, articulated, quasi-jointed structure. 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, as well.

In [19] a classification of the different behaviours an octopus can adopt was presented. This study aims at a qualitative observation of the various behaviours for each part of the body of the octopus, in order to identify their roles during these behaviours. However, the difficulty of recording and analysing octopus multiple arm movements leads to a lack in quantification and analytic data. Though the octopus can perform really complex movements, most of the neural commands are distributed along the arm, with limited central control [20]. This suggests that the central nervous system does not exert a fine control on each single part of the arm, but rather we may suppose that the interaction between body and environment provides the feedback to produce a proper movement autonomously.

The principle of embodied intelligence illustrates how intelligence is not only related to the nervous system, but also to other parts of the body. Consequently, several natural complex behaviours can be seen as the result of the interaction between the creature's body and the environment [21]. Pfeifer *et al* [22] defined some criteria to design robots able to interact with the environment to improve their general performance. The exceptional movement skills of octopuses could actually have their origin and explanation in the embodied intelligence principle. Some of the main concepts illustrated by Pfeifer *et al* [22] were developed in this study.

A proper exploitation of robot materials and environment makes us believe it possible to build a soft robot able to locomote and manipulate objects using really simple control strategies. We will illustrate how studying octopus crawling behaviour, we noticed some simplifications that we applied to the construction of a new robot able to locomote and manipulate objects. In particular, in this paper we present a soft arm, linked to a rigid base, which provides pushing-based locomotion and object grasping. Other actuation strategies that do not need a rigid base could be as well employed, using the same principles we will illustrate hereafter.

The paper is structured as follows. Section 2 illustrates the preliminary biological studies on the octopus and the results obtained and applied to design the robot. Section 3 illustrates the design of the robot, the implemented features, the mechanical structure and materials used together with the simple implemented control algorithm. Section 4 describes the methods used to evaluate locomotion and grasping performances. In section 5, we present robotic results in comparison with the biological counterpart. Section 6 states our conclusions conveying the obtained results.

2. Biological analysis

Octopuses move in a way difficult to classify and these movements are often difficult to specify and consequently difficult to investigate [23]. Crawling is the most varied mode of locomotion, involving so many postures and patterns that just a few have been defined. Various authors, in the past, used terms such as walking and swimming to mean crawling and jetting. The kinematic parameters of octopus crawling are being studied in one of the ongoing works at Hebrew University. Preliminary results of this work [24] showed that, while crawling, the octopus uses only the arms opposite to the crawling direction for pushing its body. The

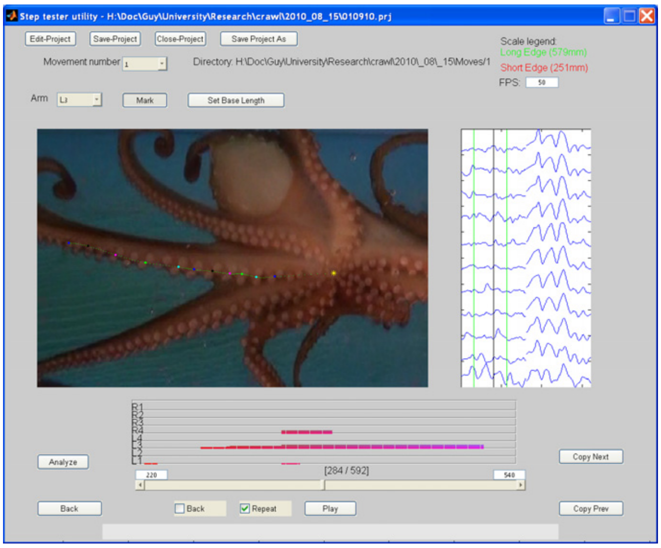

Figure 1. The Matlab® software used for analysis. The animal is video-recorded from underneath while crawling in shallow waters. Then the video clip is cut into single frames and the set of frames is inserted into this Matlab® tool. The relevant suckers are marked in each frame. Also other parameters are accepted by the tool (e.g. the number of FPS, etc). After feeding all the parameters and marking all the suckers, the data are sent for analysis.

analysis was performed by video-recording the animal from underneath while crawling and then comparing the elongation of the pushing arms with the displacement of the body. One screenshot of the videos analysis is shown in figure 1.

The movement of the octopus is not based on pulling or paddle-like pushing. One to four arms can join the task simultaneously and the direction and speed of the move is the simple combined vector of those arms. While crawling, the orientation of the octopus does not change even when turning to a new direction (i.e. there is no body rotation). The octopus simply changes the set of arms it uses into the ones that are opposite to the new direction. The single-arm pushing is performed by a rhythmical stepping-like motion composed of five stages: (1) shortening the proximal arm segment (sometimes with and sometimes without shortening the rest of the arm), (2) sticking some proximal suckers to the surface, (3) elongating the proximal segment between the attached part and the base of the arm, (4) releasing the attached suckers, and (5) shortening again to its basic length.

The arm of the octopus is almost completely composed of muscles [25]. Without activation this arm is really compliant, similar to a rope. The octopus can activate certain muscles to produce local stiffening, which allows exerting force to the environment. During the pushing action it is reasonable to consider the proximal part of the arm stiffened, as shown in figure 2.

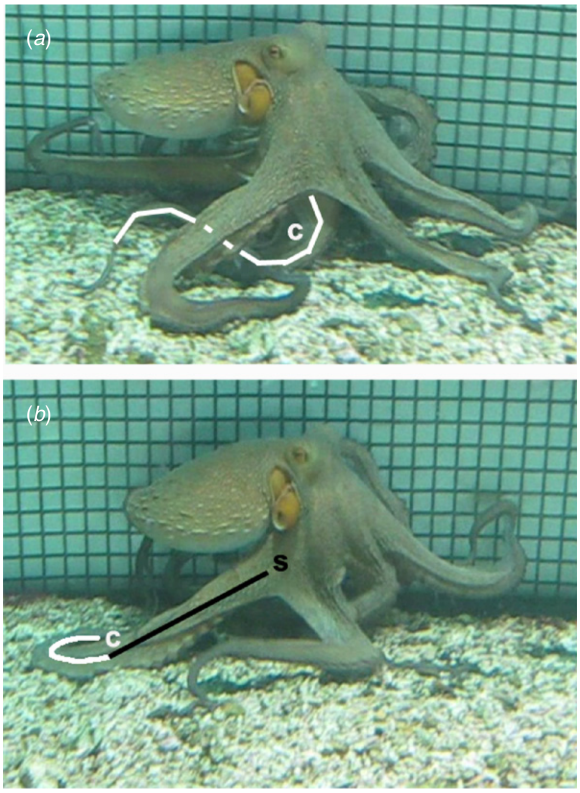

Figure 2. In picture (*a*) the octopus shortens the arm; stage (1). In picture (*b*) the suckers stick to the ground and the octopus elongates the arm, with the proximal part stiffened to exert force to the ground; stages (2–3). The curve (C) identifies the compliant part of the arm, as the curve (S) identifies the stiffened part.

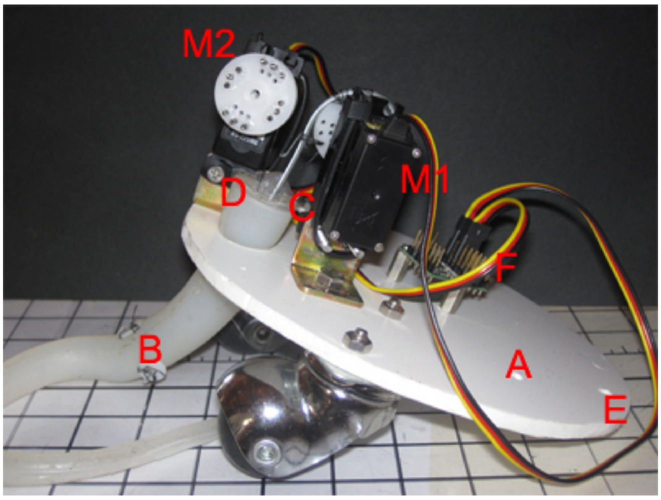

Figure 3. Various components of the robot are shown. A: platform, B: silicone arm, C: steel cable, D: Dyneema® cable, E: contact point, F: hardware module, M1: servomotor that actuates the steel cable, M2: servomotor that actuates the nylon cable.

3. Robot design

Considering the biological observation in section 2 we have built a bioinspired limb, which can elongate and shorten its proximal part to replicate the single-arm pushing movement of octopus crawling. We also require that limb can bend to mimic octopus manipulation capability. Taking into account previous work [15] we designed a soft conical arm (B, in figure 3), which can adapt its shape around varying size and differently shaped objects. It also allows shortening and elongating movements for the proximal part, and bending movement to the whole arm. In detail, the actuation system is made of a steel cable

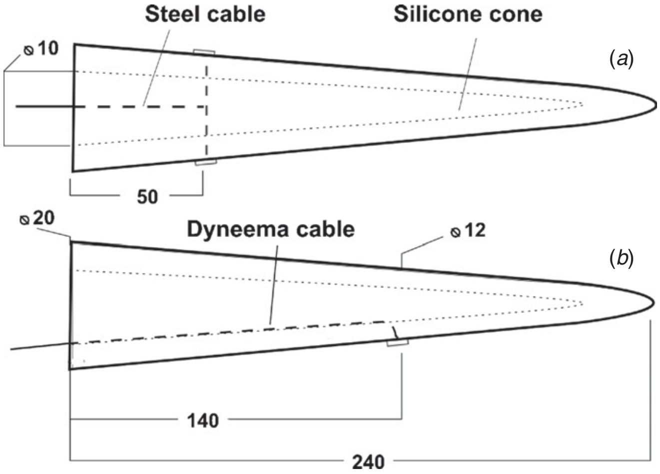

Figure 4. Dimensions (in mm) and internal structure of the soft limb. To better illustrate the structure the components are separated in (*a*), where the steel cable is shown, and in (*b*), where the Dyneema® cable is shown.

(C) that elongates and shortens the arm and one Dyneema® fibre cable (D) that bends the arm. The latter mimics the function of the longitudinal muscles of *Octopus vulgaris* [25], and we anticipate now that only one cable, attached on the tip, can bend the arm to grasp an object. We did not build sucker-like components, as the material used to build the arm provides the friction to stick to the ground and to grasp objects. We may reasonably suppose that components devoted to attach and detach the arm to a target will improve the performance, actually the study investigated an arm structure as simple as possible.

In order to test our arm, a specific platform (A), which mounts actuation devices, has been built. First of all we need a stable platform; thus, we mounted two wheels and we rested the front part of the platform on the floor. Thanks to the two wheels and the third contact point (E), the robot reaches a balance condition. Moreover, the wheels reduce the friction on the floor, facilitating arm movement transmission. The platform also lodges two servomotors (M1 and M2), that actuate the two cables, and a hardware module (F), that drives the servomotors. We will afterwards explain the morphological design in detail, in particular the arm and the actuation systems (motors and cables), the electronic module and the software system, which implements the control function.

3.1. Morphological design

In order to allow the crawling movement and the object grasping capability with the same arm, we built an arm, made of soft material, which could shorten, elongate and bend. In this work, an hollow silicone arm is presented (figure 4), but also a solid silicone arm was tested with similar results. ECOFLEX™silicone 00-30 was used as it has approximately the same density of the octopus arm, i.e. octopus arm's density is 1042 kg m^{-3}, whereas the silicone density is about 1070 kg m^{-3} [26] and, for our deformation range, Young's modulus is about 22 kPa. More details and tests are described in [15].

As pointed out in section 2, the arm elongation, with the proximal part stiffened, pushes the robot forward. In order to provide elongation and stiffening capability, a flexible steel cable is mounted at about one third of the arm length away from the platform and fixed at the other end to a Hitech HS-225MG servomotor. Thanks to the steel cable, the proximal part of the arm has the right stiffness to allow the crawling movement. We did not build an arm that can change in stiffness as the octopus does. We built an arm with a compliant part, one without the steel cable, and a stiffer part, the other with the steel cable. Coiling and uncoiling the steel cable produces the progressive stiffening of the arm. This sequence is illustrated in figure 5.

The steel cable is anchored to the silicone arm through three nylon cables fixed at its end. The three nylon cables are arranged with an angle of $\frac{2\pi}{3}$ rad. Moreover, each cable is fixed to the steel one between a plastic sheath and a heat-shrinking sheath, as shown in figure 6. Also the plastic sheath is secured to the steel cable with another heat-shrinking sheath. The nylon cables are protected by a plastic sheath to avoid cutting the silicone arm. This way the steel cable is placed, in static condition, on the axis of the arm (figure 6).

The other part of the cable is coiled on the pulley of the first servomotor (M1). When it is activated, the servo uncoils the steel cable. The angular displacement is transformed in a linear displacement of the steel cable, which stretches the nylon cables, generating the arm elongation. To bend the arm, a Dyneema® fibre cable is fixed at about two-third of the arm length and the other end is attached to the second servomotor (M2). This longitudinal cable is attached to the surface of the upper side of the arm. This assures that the pulling provided by the second servo is always oriented in the same direction. As we will explain in the next section, the bending is important not only for manipulation, but also to help crawling movement.

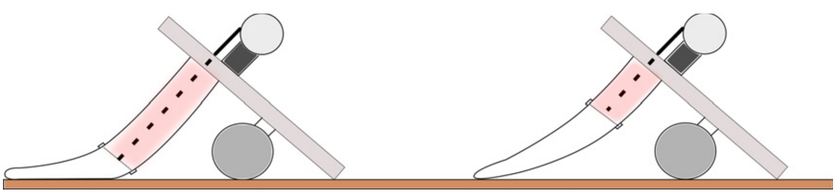

Figure 5. The dashed line represents the steel cable anchored inside the silicone arm. In the left part the cable is uncoiled and the arm is stiffened; in the right part the cable is coiled and the stiffened part is reduced. Propulsion is possible thanks to the elongation–shortening movements of the silicone arm, with a stiff part that exerts the force on the ground.

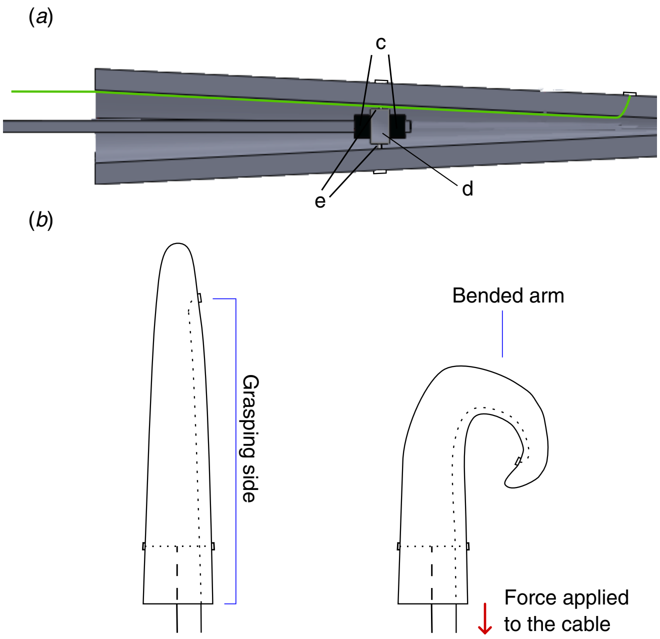

Figure 6. In (*a*) a longitudinal section of the silicone arm is shown. The steel cable is approximately on the axis of the silicone arm, while the longitudinal Dyneema® cable is attached to the internal surface of the arm. The three nylon cables 'e' that fix the steel cable to the arm are mounted between the heat-shrinking sheath 'c' and the plastic sheath 'd'. (*b*) Shows the simple actuation applied to perform a grasping. Coiling the Dyneema® cable the arm bends with an increasing curvature from the base to the tip; this spiral-like configuration allows wrapping around a target.

3.2. Electronic system

The electronic system consists of a servo controller (Pololu Micro Serial Servo Controller) and two servomotors (HS-225MG). The servo controller uses a microprocessor PIC 16F628A. It has an interface to communicate via serial protocol RS-232 and an interface to control servomotors. The microprocessor is provided with its own communication protocol between servo controller and personal computer. Through this protocol we can send data to set direction (clockwise and anti-clockwise rotation), range, speed, position and neutral of servomotors. The servomotors, supplied with 6 V, have an angular speed at no load of 9.5 rad s^{-1} and a stall torque of 0.47 Nm. They can rotate from 0 to π rad.

3.3. Control function

We performed locomotion experiments with the arm as illustrated in subsection 3.1, using different control sequences.

(i) *Double servo*: actuating alternately the two servomotors. The arm carries out this sequence of actions:
- releasing (coil Dyneema® cable)
- shortening (coil steel cable)
- attaching (uncoil Dyneema® cable)
- elongating (uncoil steel cable).

(ii) *Single servo*: actuating only the servomotor that moves the steel cable. In sequence these actions are carried out:
- shortening (coil steel cable)
- elongating (uncoil steel cable).

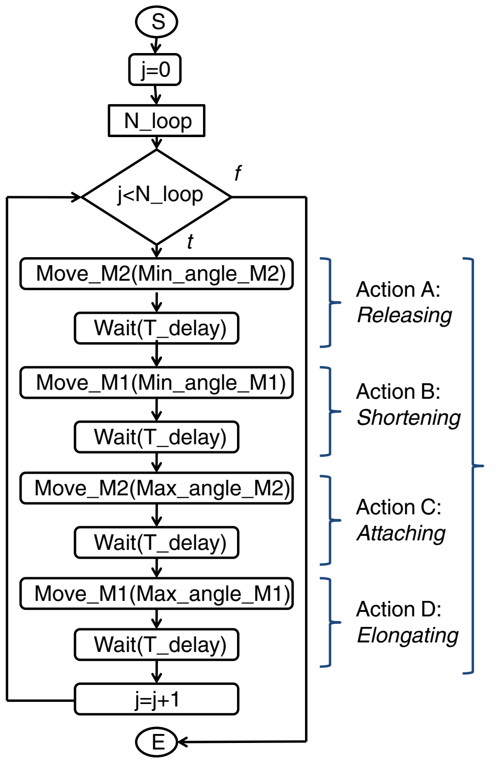

Figure 7. Flow chart of the controlling algorithm. N_loop is the number of pushing actions the robot will perform; Min_angle is the minimum angle the servos will be driven, i.e. Min_angle = 0 rad for both servos. Max_angle is the maximum angle the servos will be driven, i.e. will be $\frac{2\pi}{3}$ rad for M1 and π rad for M2. The function Move( ) sends the command to the servos and the function Wait( ) introduces a delay of time T_delay between two commands. The total time of the various actions from A to D is defined as the pushing period. Varying the delays we will change the period time. For the sequences *single servo* and *reduced friction* we use only the first servomotor (M1), so the code relative to actions A and C was deleted.

(iii) *Reduced friction*: actuating only the servomotor that moves the steel cable, with arm wrapped by slipping adhesive tape, to reduce the friction force. In sequence these actions are carried out:
- shortening (coil steel cable)
- elongating (uncoil steel cable).

Figure 7 provides a resuming flow chart showing the different actuations. Specific activation sequences are not needed for grasping. The arm could wrap around an object pulling the Dyneema® cable alone.

4. Methods

As far as we know a quantitative description of the octopus arm movements during crawling does not exist. Usually, crawling robots are evaluated by their locomotion capability. Our study makes it possible to evaluate the distance that the robot covers during each push; thus, the speed of the robot can be evaluated. Taking into account some previous works on octopus movement characterization [19, 27] and section 2, this section highlights the movement direction, effectiveness of the pushing, crawling speed and grasping capability.

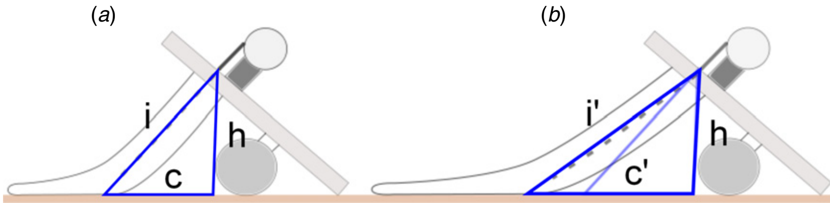

Figure 8. The maximum distance achievable is estimated with simple geometrical considerations. (*a*) Shows the arm before the push. (*b*) Shows the arm after the push.

4.1. Movement direction

As reported in section 2, the direction of movement of the whole octopus is opposite to the pushing arm direction. We replicated the same characteristic on our robot and verified the direction by video-recording the movement: the robot crawled on a transparent surface to allow a visual evaluation through the bottom, as shown in figure 9.

4.2. Effectiveness of the pushing action

Knowing the robot's geometry and the maximum achievable elongation of our arm, it is possible to state the maximum distance achievable during each push, which we refer to as $D_{\max}$. In figure 8 we draw a scheme of the $D_{\max}$ theoretically achievable. This is a maximum value we cannot exceed. A rough estimate is possible with simple geometrical considerations. Assuming that the uncoiled steel cable increases the i, we will have that $i' = i + \frac{2\pi}{3} \cdot r$, where r is the pulley radius. Knowing i and h it is possible to obtain c'. The maximum distance $D_{\max}$ is then obtained as $D_{\max} = c' - c = 49.9$ mm.

We consider that a certain activation sequence has high effectiveness if the distance covered by the robot with one pushing action is close to this maximal theoretical value. To evaluate the performance of our robot, we recorded the crawling and took ten shots before the push and ten after the push. Evaluating visually the distance covered by the robot on a calibrated grid, we estimate the effectiveness E as the ratio between the distance covered d, and the maximum distance $D_{\max}$.

$$E = d/D_{\max}. \tag{1}$$

4.3. Crawling speed

Finally we evaluated the crawling speed of the robot measuring the time the robot needs to cover a 100 mm track. We timed 9–12 runs with the same activation sequence and pushing period, to settle an average speed. Then we varied the pushing period while keeping the activation sequence unchanged. In this way we obtained a speed function which depends on the pushing period alone. With these tests we evaluate the crawling capability of our robot for the three activation sequences illustrated in section 3.3.

4.4. Grasping capability

In the presented robot, the whole arm is involved in the grasping activity. It is common in soft robots to use the whole body to perform the task desired. Shape and materials play a crucial role in this capability: our arm, a silicone cone with longitudinal cables embedded, bends with an incremental curvature from proximal to distal part when the Dyneema® cable is coiled. This curvature resembles a spiral making wrapping around an object possible. To evaluate the grasping capability we performed a test similar to the ones presented in [15]. In this test, a pencil and six screws with incremental diameter and weight were positioned close to the surface in the distal part of the arm. We pull the longitudinal nylon cable alone and verify if the arm wraps around objects.

5. Results and discussion

This section focuses on the results of the tests introduced in section 4. First the plot of the recorded movement of the robot will be presented, then the crawling speeds achieved with different activation sequences, and finally some examples of grasping will follow.

5.1. Movement direction

The robot moves following the expected direction, on a straight line. Figure 9 clearly shows the robot moving in the opposite direction to the elongation of the arm. The grid over which the robot moves allows a visual evaluation of the displacement showing that the path is almost parallel with the lines on the grid. Straight line crawling is partly due to the guidance of the base wheels and this has been verified with all the activation sequences tested.

5.2. Effectiveness of the pushing action

The analysis of the effectiveness of the various activation sequences leads to three different data. As reported in table 1, average values of effectiveness, obtained from ten consecutive pushing actions at the longest pushing period, were recorded. The activation sequences were listed as *double servo*, *reduced friction* and *single servo*.

The *single servo* activation has a low effectiveness because of a backward movement at the beginning of the pushing period, corresponding to the shortening action of the arm. When shortening, the distal part of the arm has a certain friction with the ground and pulls the robot backwards. On the other

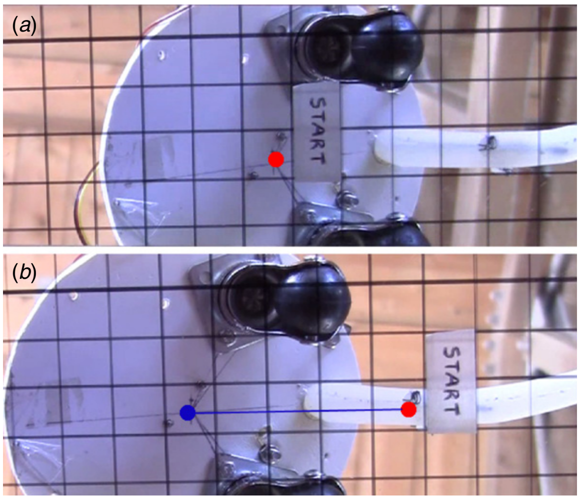

Figure 9. This figure shows two instants of the robot locomotion, video-recorded from underneath. (*a*) Shows a starting frame and (*b*) the frame after about three pushes. The central point of the platform is marked and the track is plotted. The track is parallel with the grid on the ground, visually showing the direction of the movement.

hand, a slipping arm cannot exert a force to the ground. The octopus adopts a simple solution: when the arm is brought

Table 1. Various effectiveness of the activation sequences.

Activation sequence	Effectiveness value (average and standard deviation)	
Double servo	0.60	0.03
Reduced friction	0.35	0.07
Single servo	0.34	0.03

to the body, the suckers are not attached to the ground. That means the arm has no friction. When the octopus stretches the arm, several suckers are attached to the ground, providing a remarkable friction.

To mimic this strategy in our robot, we developed the two activation sequences illustrated in section 3 called *double servo* and *reduced friction*. Although the *reduced friction* activation sequence avoids the backward movement, also during elongation the friction is partly reduced. The highest value of effectiveness was obtained with the *double servo* activation sequence, illustrated in figure 10. The arm moves in the four positions corresponding to releasing, shortening, attaching and elongating. Thanks to this strategy, when the arm shortens, the distal part is not in contact with the ground. Pulling the longitudinal nylon cable indeed, the arm curls and

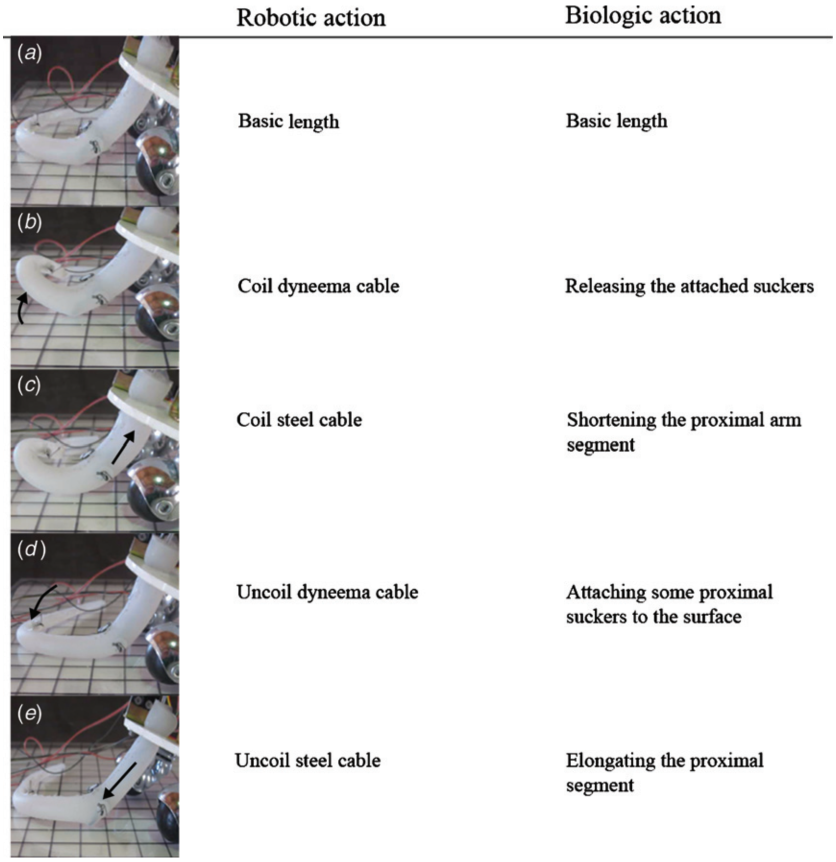

Figure 10. In this figure a parallelism between robotic actions and octopus action is shown. In (*a*) the robot is standing. In (*b*) it coils the Dyneema® cable, mimicking the release of the attached suckers. In (*c*) the steel cable has been coiled and the robotic arm shortens, mimicking the shortening of the octopus' arm. In (*d*) the Dyneema® cable is uncoiled letting the arm attach to the ground, mimicking the attaching of some suckers to the ground. Finally in (*e*) the robotic arm elongates, mimicking the elongation of the proximal part of the octopus' arm.

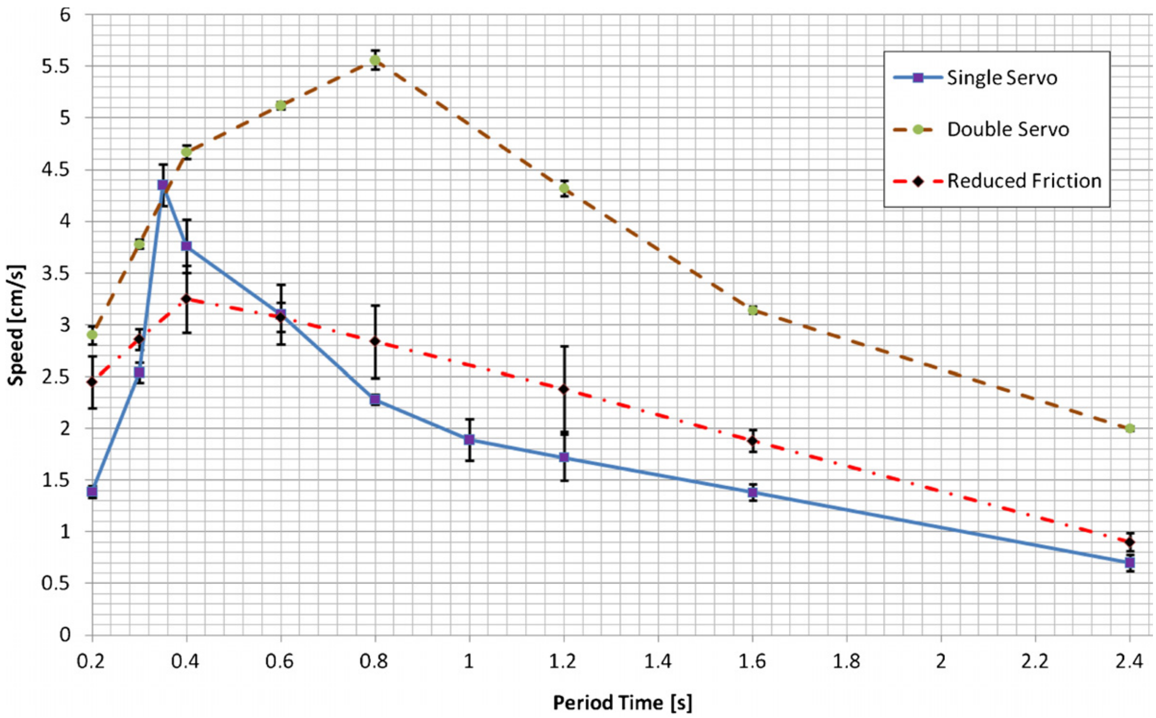

Figure 11. Speed plots of the different activation sequences.

detaches from the ground. Then with the next phases the arm attains its full elongation.

Using these three configurations, we investigated the influence of the pushing period on the speed. Varying the delays reported in figure 7 we analyzed the influence of the pushing period on the speed: if the period between two pushing actions is long enough, the arm will extend completely, thus achieving the maximum effectiveness it can obtain. In this case, the length of the proximal part of the arm varies from 48 to 72 mm. If the period between two pushing actions is not long enough, the effectiveness will be lower than the maximum possible. An optimal value for the period that could optimize the crawling speed was stated. If the period is lower than this optimal value, the effectiveness of the action decreases and we obtain a slower robot. If the period is higher than the optimal value, we waste time from cycle to cycle and the robot crawls more slowly than in the optimal condition. In figure 11 we report the speed as a function of the pushing period. The *double servo* configuration was the best performing one, at every period. While the *reduced friction* has higher speed for high periods, the *single servo* configuration has higher speed for low periods.

These plots are valid just for our servos, for which the no load maximum speed at 6 V is 9.5 rad s^{-1}. A faster servo should improve the speed, also shifting the speed peaks to the left of the plot. The speed peaks achieved by the various configurations are reported in table 2. The highest value is still low compared with the octopus crawling speed considered by [27] of about 200 mm s^{-1}; anyhow it is comparable with other soft crawling robots. In particular, our robot reaches an average speed comparing bioinspired robots that locomote really slowly (3.99 mm s^{-1}) [5] to a better performing robot that achieves 260 mm s^{-1} [3]. Our study is however more interested in comparing the diverse activation sequences than in the absolute speed value. The robot structure could be optimized to achieve a higher speed; anyway we expect that also in a faster robot the *double servo*'s activation should be better than the others.

Table 2. Maximum speed of the activation sequences.

Activation sequence	Maximum speed (cm s^{-1}) (average and standard deviation)	
Double servo	5.55	0.09
Reduced friction	3.29	0.35
Single servo	4.35	0.22

5.3. Grasping capability

The living octopus arm wraps around objects sticking several suckers to the target. In our solution without suckers, the grasping is not equally strong. However, the silicone arm is able to wrap around the object providing a functional grasp for light objects. Grasping examples are presented in figure 12. We tested if the arm could wrap around the target and if the robot could hold the target: manually moving the robot after the coiling, we evaluate if the grasp was effective enough to maintain the object in contact with the robot. We coiled about 40 mm of Dyneema® cable to shape the arm in the spiral-like configuration adopted to make it wrap around objects. This grasp does not have high accuracy, but it is really flexible: even if not completely wrapped around, the object could still be held. The arm will conform to the object and will squeeze it to the body, actually without grasping it but still providing a

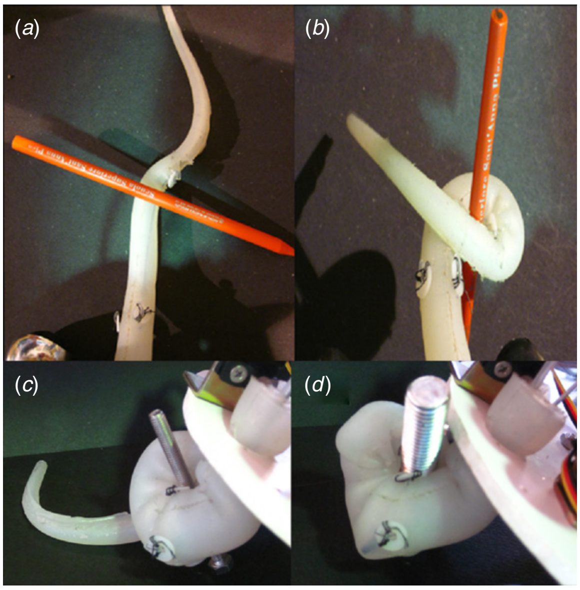

Figure 12. Some grasping examples are shown. In (*a*) a pencil has been positioned closer to the arm and by pulling just the longitudinal nylon cable the grasping was obtained ((*b*)). Also some screws with diverse diameter were tested: in (*c*) a screw with a small diameter has been wrapped around, while in (*d*) a bigger screw was held in contact with the platform.

Table 3. Tested diameters, weights and grasp results.

Diameter (mm)	Weight (g)	Wrap around	Hold
4.9	8.5	Yes	Yes
5.8	15.9	Yes	Yes
7.7	27	Yes	Yes
9.8	40	No	Yes
11.7	65.4	No	Yes
15.85	134.6	No	No

frictional grip. The length available to wrap around an object is about 90 mm, due to the difference between the length of the Dyneema® cable and the length of the steel cable, because the stiffened part of the arm is not involved in wrapping around. Table 3 summarizes the result of the grasping tests.

Finally, we tested our robot without wheels in the best configuration found. Ostensibly, if the pushing arm is the same employed for stabilizing the body, then the performance decreases. As we aimed at showing a soft arm which is able to provide movement and manipulation, we did not explore this stability problem and the solution employed by the animal. Nevertheless, this is regarded as a very interesting and profitable topic for future investigation.

6. Conclusion

In this paper, we presented a solution to locomotion and grasping for soft robots inspired by the behavioural strategies of the octopus. We used the findings of biologists to design and build a continuum soft arm capable of pushing-based locomotion and object grasping. This was made possible by a proper functional synthesis and exploiting the compliance of the soft material to obtain grasping with simple control, i.e. by pulling one cable. The soft arm built in this work is composed of a flexible steel cable that provides shortening and elongation, a nylon cable that provides bending and grasping capabilities and a soft silicone cone. The simple actuation sequence for pushing is composed of a shortening action followed by an elongating action, while the grasping motion is controlled by the longitudinal nylon cable. Both cables were actuated by servos but the strategy showed is generic and other actuation strategies could work.

Furthermore, mimicking the various stages of the single-arm pushing of the octopus, we provide a confirmation to the biological observations and also pose new questions, i.e. how the octopus stabilizes his body while crawling. We think it is the water environment that helps the animal to maintain a floating gait; thus, the pushing is more effective than the one accounted for here. Future works could be related to the underwater testing of the robot, coupled with the implementation of the stability strategy adopted by the octopus. Finally, this study showed a functional synthesis of the octopus arm structures and actuation, which enables the design of soft robots with both locomotion and manipulation capabilities.

Acknowledgment

This work was supported in part by the European Commission in the ICT-FET OCTOPUS Integrating Project, under contract no 231608.

References

[1] Robinson G and Davies J 1999 Continuum Robots—a state of the art *Proc. IEEE Int. Conf. on Robotics and Automation (Detroit, MI, May)* pp 2849–54

[2] Trivedi D, Rahn C, Kier W and Walker I 2008 Soft robotics: biological inspiration, state of the art, and future research *Appl. Bionics Biomech.* **5** 99–117

[3] Sugiyama Y and Hirai S 2004 Crawling and jumping of deformable soft robot *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (Sendai, Japan, 28 September–2 October)* vol 4, pp 3276–81

[4] Shibata M, Saijyo F and Hirai S 2009 Crawling by body deformation of tensegrity structure robots *Proc. IEEE Int. Conf. on Robotics and Automation (Kobe, Japan, 12–17 May)* pp 4375–80

[5] Seok S, Onal C, Wood R, Rus D and Kim S 2010 Peristaltic locomotion with antagonistic actuators in soft robotics *IEEE Int. Conf. on Robotics and Automation (Anchorage, AL, 3–8 May)* pp 1228–33

[6] Jung K, Koo J, Nam J, Lee Y and Choi H 2007 Artificial annelid robot driven by soft actuators *Bioinsp. Biomim.* **2** S42–9

[7] Menciassi A and Dario P 2003 Bio-inspired solutions for locomotion in the gastrointestinal tract: background and perspectives *Phil. Trans. R. Soc.* A **361** 2287–98

[8] Menciassi A, Gorini S, Pernorio G, Weiting L, Valvo F and Dario P 2004 Design, fabrication and performances of a biomimetic robotic earthworm *Proc. IEEE Int. Conf. on Robotics and Biomimetics (Shenyang, China, 22–26 August)* pp 274–8

[9] Trimmer B, Takesian A and Sweet B 2006 Caterpillar locomotion: a new model for soft-bodied climbing and burrowing robots *7th Int. Symp. on Technology and the Mine Problem (Monterey, CA, 2–5 May)* pp 1–10

[10] Suzumori K, Endo S, Kanda T, Kato N and Suzuki H 2007 A bending pneumatic rubber actuator realizing soft-bodied manta swimming robot *Proc. IEEE Conf. on Robotics and Automation (Roma, Italy, 10–14 April)* pp 4975–80

[11] Steltz E, Mozeika A, Rodenberg N, Brown E and Jaeger H 2009 JSEL: jamming skin enabled locomotion *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (St. Louis, MO, 11–15 October)* pp 5672–7

[12] Tsukagoshi H, Kitagawa A and Segawa M 2001 Active hose: an artificial elephant's nose with maneuverability for rescue operation *Proc. of Int. Conf. on Robotics and Automation* vol 3, pp 2454–9

[13] Jones B and Walker I 2006 Kinematics for multi-section continuum robots *IEEE Trans. Robot.* **22** 43–55

[14] McMahan W, Jones B, Walker I, Chitrakaran V, Seshadri A and Dawson D 2004 Robotic manipulators inspired by cephalopod limbs *CDEN Design Conf. (Montreal, Canada)* pp 1–10

[15] Calisti M, Arienti A, Giannaccini M, Follador M, Giorelli M, Cianchetti M, Mazzolai B, Laschi C and Dario P 2010 Study and fabrication of bioinspired octopus arm mockups tested on a multipurpose platform *IEEE/RAS-EMBS Int. Conf. on Biomedical Robotics and Biomechatronics (Tokyo, Japan, 26–29 September)* pp 461–6

[16] Laschi C, Mazzolai B, Cianchetti M and Dario P 2009 Design of a biomimetic robotic octopus arm *Bioinsp. Biomim.* **4** 015006

[17] Margheri L, Mazzolai B, Cianchetti M, Dario P and Laschi C 2009 Tools and methods for experimental in-vivo measurement and biomechanical characterization of an *Octopus vulgaris* arm *EMBC (Minneapolis, MN, 2–6 September)* pp 7196–9

[18] Sumbre G, Fiorito G, Flash T and Hochner B 2005 Neurobiology: motor control of flexible octopus arms *Nature* **433** 595–96

[19] Mather J 1998 How do octopuses use their arms? *J. Comparative Psychol.* **112** 306–16

[20] Gutfreund Y, Flash T, Fiorito G and Hochner B 1998 Patterns of arm muscle activation involved in octopus reaching movements *J. Neurosci.* **18** (15) 5976–87

[21] Pfeifer R, Lungarella M and Iida F 2007 Self-organization, embodiment, and biologically inspired robotics *Science* **318** 1088–96

[22] Pfeifer R, Iida F and Bongard J 2005 New robotics: design principles for intelligent systems *Artif. Life* **11** 99–120

[23] Wells M 1978 *Octopus Physiology and Behaviour of an Advanced Invertebrate* (London: Chapman and Hall) p 247

[24] Levy G and Hochner B 2010 Kinematic analysis of crawling in the octopus *The Israeli Society for Neuroscience* poster number 430

[25] Smith K and Kier W 1989 Trunks, tongues and tentacles: animal movement with muscular skeletons *Am. Sci.* **77** 28–35

[26] Yekutieli Y, Sagiv-Zohar R, Aharonov R, Engel Y, Hochner B and Flash T 2005 Dynamic model of the octopus arm: II. Control of reaching movements *J. Neurophysiol.* **94** 1443–58

[27] Huffard C 2006 Locomotion by *Abdopus aculeatus* (Cephalopoda: Octopodidae): walking the line between primary and secondary defenses *J. Exp. Biol.* **209** 3697–707