21 Soft Robotics Research, Challenges, and Innovation Potential, Through Showcases

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Abstract Soft robotics, intended as the use of soft materials in robotics, is a young yet promising and growing research field. The need for soft robots emerged in robotics, for facing unstructured environments, and in artificial intelligence, too, for implementing the embodied intelligence, or morphological computation, paradigm, which attributes a stronger role to the bodyware and its interaction with the environment. Using soft materials for building robots poses new technological challenges: the technologies for actuating soft materials, for embedding sensors into soft robot parts, for controlling soft robots are among the main ones. Though still in its early stages of development, soft robotics is finding its way in a variety of applications, where safe contact is a main issue, in the biomedical field, as well as in exploration tasks and in the manufacturing industry. Literature in soft robotics is increasingly rich, though scattered in many disciplines. The soft robotics community is growing worldwide and initiatives are being taken, at international level, for consolidating this community and strengthening its potential for disruptive innovation.

21.1 Introduction: The Need for Soft Robots

Soft robotics, intended as the use of soft materials in robotics, is a young yet promising and growing research field [1]. Soft robotics stems from robotics, on one side, and from artificial intelligence, on the other side.

Robotics evolved significantly from its recent birth in the '50s and is today a solid discipline with a good wealth of knowledge and technologies. Though robotics basically evolved in the field of industrial manufacturing, service applications were soon investigated by roboticists [2]. The huge difference in the two application domains can be summarized in being the environment *structured*, in industrial manufacturing, and *unstructured* in service applications, where robots are expected to operate in a variety of scenarios, of our own world. For this reason, service robotics brought to bioinspiration, as investigating the animals that evolved and successfully live in these environments is definitely a good starting point for building like-wise successful robots [3][4]. It is then clear that soft tissues have a dominant role in animals, with respect to their rigid skeletons and exoskeletons. The use of soft deformable and variable stiffness technologies in robotics repre-

A. Verl et al. (eds.), *Soft Robotics,* DOI 10.1007/978-3-662-44506-8_21,

sents an emerging way to build new classes of robotic systems that are expected to interact more safely with the natural, unstructured, environment and with humans, and that better deal with uncertain and dynamic tasks (i.e. grasping and manipulation of unknown objects, locomotion on rough terrains, physical contacts with human bodies, etc.) [5].

In artificial intelligence, too, one of the modern views is based on the decisive role of the interaction with the environment. This interaction is not just intended as reaction to external forces and perturbations, but especially as control of movements. This means that the morphology of the body and the mechanical properties also play a decisive role in intelligent behaviour [6]. In other words, a part of movement control is not given by computation and neural processes, but by passive adaptation of body parts to the forces borne, in prevailing tasks, in so-called *embodied intelligence* and *morphological computation*.

21.2 The Challenges for Soft Robotics, Through the Octopus Showcase

Look at an octopus with a roboticist's eyes: its arms are soft and deformable, they can bend in any direction, at any point along the arm; however, they can stiffen when needed and they can grasp and pull objects with considerable strength. The octopus is undoubtedly a good model for soft robotics, and an extreme one, considering that it has no rigid structures, of any kind.

The octopus does not have a large brain, yet it can control this huge amount of possible movements and motion parameters [7]. Its soft body seems to simplify control exploiting its rich interaction with environment, which is thought to be at the base of its unexpected intelligence. The octopus then represents an ideal model for morphological computation, too.

Understanding the secrets of the octopus soft dexterity and copying some of the key principles is an effective case-study for facing the different challenges, in different disciplines, related to the development of soft robots [8]. These have been the main objectives of the OCTOPUS project.

21.2.1 Biological Insights

The first big lesson from biology is the muscular hydrostat [9][10]: a muscular structure composed of longitudinal, transverse and oblique muscles, which allows all-direction bending, by selective contractions, elongation and shortening, by contractions of the transverse and longitudinal muscles, respectively, torsion, by contractions of the oblique muscles, and stiffening, by co-contractions.

Among open questions were: how long can an octopus arm stretch? How are nervous fibres arranged inside the arm, not to be stretched and damaged? What force can each arm generate when pulling? How are longitudinal and transverse muscles arranged and anchored along the arm? What are the mechanical properties of the octopus muscular tissue? What is the density of an octopus? How are the fibres of the connective tissue arranged? What are principles of the crawling mechanism?

Biomechanical measurements on arms of specimens of *Octopus vulgaris*, with purposively designed bioengineering tools (see Fig. 21.1), gave evidence of an average 73% elongation and an average 40N force applied with one arm [11][12]. Imaging and biological analysis of the octopus arm tissue (ecography, histology, SEM) gave evidence of the helicoidal arrangement of nervous fibres in the central nerve chord [13], of the radial transverse fibres and of the anchoring of longitudinal fibres at different lengths along the arm. Mechanical tests showed a hyperelastic behaviour of the octopus arm tissue and a density very close to the water density, giving neutral buoyancy. Video analysis of the swimming and of the crawling movements outlined the mechanisms of pulsed jet propulsion and back-arm pushing for crawling [14][15].

The results have been translated into specifications for the robot design [16][17].

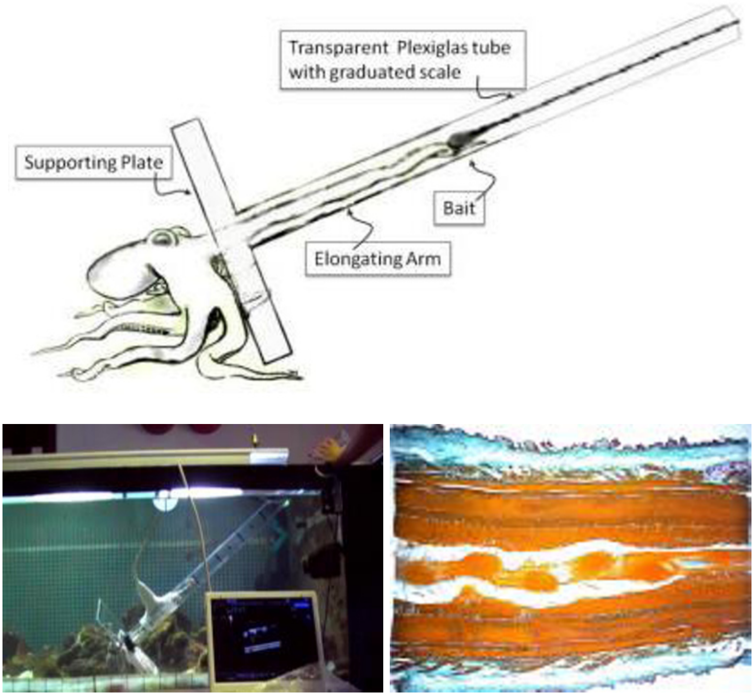

Fig. 21.1 From top to bottom, left to right: The experimental set-up for measurements and for echography of the octopus arm, and an image of corresponding histology, used for comparison.

21.2.2 Soft Actuation Technologies

The actuation of soft bodies, producing the desired deformations and desired forces, is one of the main challenges in soft robotics. In animals, analogous actuation is given by a number of muscle fibres, well distributed in the body. While artificial muscles are still an open objective for engineering, several technologies are currently being investigated to this purpose.

An important technological field, in the quest for artificial muscles, is represented by EAP, ElectrActive Polymers [18][19]. They use the property by which two layers of conductive material tend to attract when powered, by a Coulomb attraction force, thanks to the Maxwell effect, if the medium between them can be compressed. They are then well-suited to stand as soft actuators, as they can be built with soft materials like silicone, though the geometry needs to be carefully designed in order to obtain useful strain [20].

Shape Memory Alloys (SMA) are alloys that deform to an original shape when heated [21]. They are not strictly soft materials, but they are used in wires that can well serve the purpose of actuating soft materials [22][23]. Despite of their well-known drawbacks in slow deformation, difficult controllability, low strain, SMA springs stand as an effective solution for the OCTOPUS front arms, well complying with the specifications of the water environment, slow contractions, and on-off control [24].

Compressed air is a powerful actuation system for soft materials. In addition to the well-known McKibben actuators [25], compressed air has recently been used for deforming soft body parts at lower scales. In the starfish-like robot by [26], networks of channels in elastomers inflate for actuation.

21.2.3 Soft Robot Modeling and Control

New approaches are necessary for modelling and controlling soft-bodied structures. The 50-year history of robotics and of robot control is based on the assumption that robots are kinematic chains of rigid links. Robot control theories and techniques have developed on this assumption and reached today a very high level of solidity, rigour, accuracy, and progress [2]. The use of soft materials in robotics is going to unhinge these fundamentals, as most rules no longer stand. Known techniques for kinematic and dynamic modelling in robotics cannot be used, while techniques for the modelling of continuum structures are needed. Control needs a deep rethinking, as well, not only for the lack of exact kinematics and dynamics models, but also for the increased role of interaction with environment.

Most of the approaches currently in use for the direct model of continuum soft robot are limited to piecewise-constant-curvature approximation [27]. Recently, Jones et al. [28] presented a steady state model of continuous robot neglecting the actuation. In the work by Boyer et al. [29] the distributed force and torque acting on the robot are estimated but no discussion is made concerning on the actuators that could generate them. A continuum geometrically exact approach for tendon-driven continuum robot has been proposed by Renda et al. [30]. It is capable of properly simulating the coupled tendon drive behaviour of non-constant curvature manipulators, because it takes into account the torsion of the robot. The inverse model proposed in literature for controlling continuum soft robot follows different approaches. A modal approach was proposed by Chirikjian et al. [31]. A successful Jacobian method for a non-constant curvature tendon-driven manipulator is proposed and compared with a neural approach [32][33].

21.2.4 Integration and Validation of an Octopus-like Robot

The final OCTOPUS prototype is the first completely soft robot, which integrates a central body with 8 arms extending in radial directions and the main processing units (see Fig. 21.2). The front arms are mainly used for manipulation, elongation, grasping, the others are mainly used for locomotion. To optimize elongation, reaching and manipulation tasks the front arms are based on the SMA actuators, which reproduce the internal anatomical features of the real octopus arm, and thus allow to perform finely controlled and precise movements. The other arms, which are used for crawling, are based on silicone and cables, embedding the features needed to obtain an octopus-inspired locomotion. The robotic octopus works in water and its buoyancy is close to neutral.

21.3 Soft Robots at Work

21.3.1 Biomedical Applications of Soft Robotics: Octopus-derived Technologies in Surgery

Minimally invasive surgery is nowadays widely used in clinical practice and progresses are going on at a good pace. Few limitations in modern laparoscopic and robot-assisted surgical systems are due to restricted access through Trocar ports, lack of haptic feedback, and difficulties with rigid robot tools operating inside a confined space filled with organs.

The STIFF-FLOP[21] project aims at taking inspiration from biological manipulators like the octopus arm and the elephant trunk and at taking advantage of the OCTOPUS research and technologies for developing a highly dexterous soft robotic arm able to locally control its stiffness for both being compliant with the environment and accomplishing surgical tasks.

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21 www.stiff-flop.eu

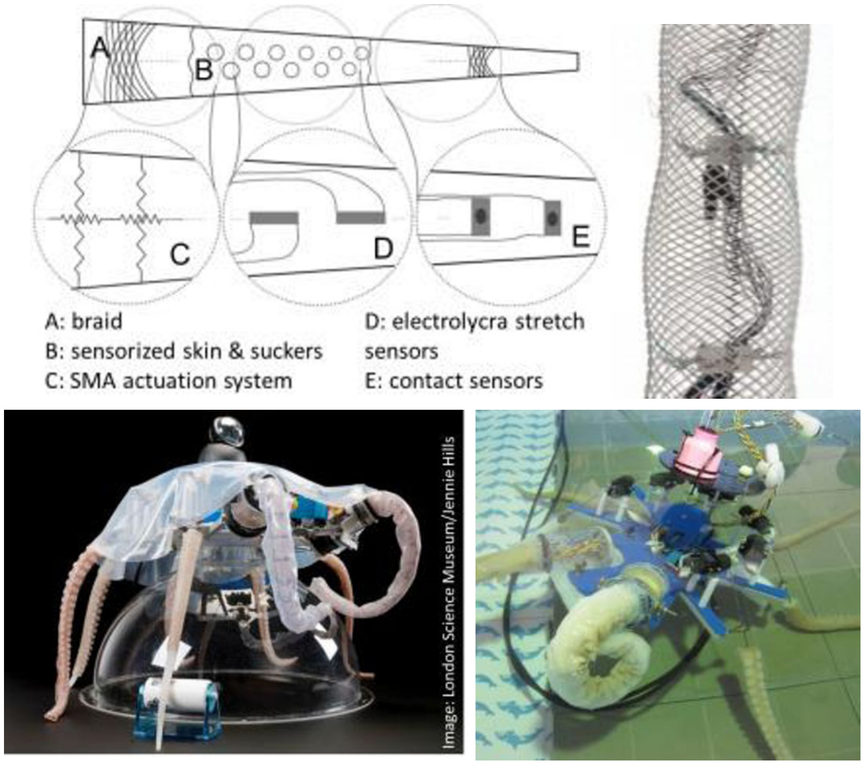

Fig. 21.2 From left to right, top to bottom: Scheme of the OCTOPUS arm components; images of the OCTOPUS arm with SMA actuators in the braided structure (credits to Massimo Brega, The Lighthouse); an image of the OCTOPUS prototype exhibited at the Science Museum in London (credits to Jennie Hills, Science Museum); image of the 8-arm robot in water, with 2 front SMA arms and 6 crawling arms.

A combination of pneumatic actuation and granular jamming led to the first prototype of a soft endoscope with controllable stiffness [34].

21.3.2 Soft Robots in Explorations: An Octopus-like Underwater Robot

Robotics has proved to be an essential tool for underwater operations. A number of tasks are today accomplished by robots, such as Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs). Standard working procedures for these kinds of vehicles envisage the robots to work at a safe distance from the sea bottom or the submerged structure upon which operation is being carried out in order to avoid the risk of damage. Instead, the introduction of soft robots in this field brings a disruptive perspective to underwater explorations and operations.

The PoseiDRONE Project aims at developing a soft robot capable of swimming, crawling over irregular and uneven substrates and perform complex manipulation tasks in cramped environments underwater. The capability to perform multigait locomotion in the aquatic environment and manipulation along with an overall highly compliant structure provide this robot with unprecedented assets [35] (see Fig. 21.3). This robot will be applicable in marine operations such as those entailed with coastal and offshore engineering, petroleum and drilling technology as well as underwater archeology and environmental protection.

Fig. 21.3 Images of the PoseiDRONE prototype, from left to right: view of the 4-arm prototype in a salt water tank, the prototype in sea water, detail of the pulsed-jet propulsion with the fluorescein dyed vortex ring (credits to Massimo Brega, The Lighthouse).

21.3.3 Soft Grippers for Manufacturing

While robotics has contributed fundamental technologies for manufacturing processes, there are still few industrial tasks that cannot be performed with current robotic grippers, requiring higher flexibility and adaptability to different shapes. For those tasks, soft robotics can be effectively applied, by producing soft grippers than can intrinsically adapt to grasp different shapes.

The SMART-e[22] Marie Curie Action aims at investigating this application of soft robotics through a European network of PhD research programmes. Specific topics are soft robotics and morphological computation, octopus-based technologies for manipulation in manufacturing, soft robotic grippers for industrial manufacturing.

21.4 Conclusions

The many challenges and the many potential applications of soft robotics involve a number of different disciplines and sectors. They also attract the interest of an increasing number of researchers worldwide and literature in this topic is growing

22 http://smart-e-mariecurie.eu/

at a fast pace: from basically no papers until 2004, to 10 papers in 2008, and 40 papers in 2012.

While this interdisciplinary nature of soft robotics is one of its main strengths for disruptive innovation, at the same time one of the possible risks to jeopardize the full development of the potential of soft robotics is the scattered community.

In 2012 a Technical Committee of the IEEE Robotics and Automation Society has been started on Soft Robotics[23], to gather scientists in this field, at least from the robotics community, with the impressive results of collecting 379 members in less than two years.

Including other disciplines, too, the scientific community of Soft Robotics is gathering around the ICT-FET Open RoboSoft[24] Coordination Action, started in November 2013. A common forum helps soft robotics researchers to combine their efforts, to maximize the opportunities and to materialize the huge potential impact of soft robotics. RoboSoft is creating the missing framework for the soft robotics scientists, regardless of their background disciplines, and enabling the accumulation and sharing of the crucial knowledge needed for scientific progress in this field. RoboSoft is aiming not only to create and consolidate the soft robotics community, but also to establish effective links with relevant scientific communities potentially interested in exploiting soft robotics as case study.

Soft robotics is not just a new direction of technological development. The use of soft materials in robotics is going to unhinge its fundamentals. Soft robotics is going to stand as a novel approach to robotics and artificial intelligence, and it has the potential to produce a new generation of robots, in the support of humans in our natural environments.

Acknowledgments These works have been supported by the European Commission with the OCTOPUS IP (# 231608, FET Proactive Initiative ICT 2007.8.5 "Embodied Intelligence"), the OCTO-PROP grant (#269477, Marie Curie European Re-integration Grants), the STIFF-FLOP IP (#287728, ICT Challenge 2), the SMART-e ITN (#608022, Marie Curie Action) and the RoboSoft CA (#619319, ICT-FET Open) and by the Fondazione Livorno with the PoseiDRONE and PoseiDRONE II projects. The author wishes to acknowledge the work of the SSSA Soft Robotics Team and of the project partners.

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