Biosystems & Biorobotics

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Soft Robotics: Trends, Applications and Challenges

Proceedings of the Soft Robotics Week, April 25–30, 2016, Livorno, Italy

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Aims & Scope

Biosystems & Biorobotics publishes the latest research developments in three main areas: 1) understanding biological systems from a bioengineering point of view, i.e. the study of biosystems by exploiting engineering methods and tools to unveil their functioning principles and unrivalled performance; 2) design and development of biologically inspired machines and systems to be used for different purposes and in a variety of application contexts. The series welcomes contributions on novel design approaches, methods and tools as well as case studies on specific bioinspired systems; 3) design and developments of nano-, micro-, macrodevices and systems for biomedical applications, i.e. technologies that can improve modern healthcare and welfare by enabling novel solutions for prevention, diagnosis, surgery, prosthetics, rehabilitation and independent living.

On one side, the series focuses on recent methods and technologies which allow multiscale, multi-physics, high-resolution analysis and modeling of biological systems. A special emphasis on this side is given to the use of mechatronic and robotic systems as a tool for basic research in biology. On the other side, the series authoritatively reports on current theoretical and experimental challenges and developments related to the “biomechatronic” design of novel biorobotic machines. A special emphasis on this side is given to human-machine interaction and interfacing, and also to the ethical and social implications of this emerging research area, as key challenges for the acceptability and sustainability of biorobotics technology.

The main target of the series are engineers interested in biology and medicine, and specifically bioengineers and bioroboticists. Volume published in the series comprise monographs, edited volumes, lecture notes, as well as selected conference proceedings and PhD theses. The series also publishes books purposely devoted to support education in bioengineering, biomedical engineering, biomechatronics and biorobotics at graduate and post-graduate levels.

About the Cover

The cover of the book series Biosystems & Biorobotics features a robotic hand prosthesis. This looks like a natural hand and is ready to be implanted on a human amputee to help them recover their physical capabilities. This picture was chosen to represent a variety of concepts and disciplines: from the understanding of biological systems to biomechatronics, bioinspiration and biomimetics; and from the concept of human-robot and human-machine interaction to the use of robots and, more generally, of engineering techniques for biological research and in healthcare. The picture also points to the social impact of bioengineering research and to its potential for improving human health and the quality of life of all individuals, including those with special needs. The picture was taken during the LIFEHAND experimental trials run at Università Campus Bio-Medico of Rome (Italy) in 2008. The LIFEHAND project tested the ability of an amputee patient to control the Cyberhand, a robotic prosthesis developed at Scuola Superiore Sant’Anna in Pisa (Italy), using the tf-LIFE electrodes developed at the Fraunhofer Institute for Biomedical Engineering (IBMT, Germany), which were implanted in the patient’s arm. The implanted tf-LIFE electrodes were shown to enable bidirectional communication (from brain to hand and vice versa) between the brain and the Cyberhand. As a result, the patient was able to control complex movements of the prosthesis, while receiving sensory feedback in the form of direct neurostimulation. For more information please visit http://www.biorobotics.it or contact the Series Editor.

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Contents

Introduction

Cecilia Laschi, Fumiya Iida, Jonathan Rossiter, Matteo Cianchetti and Laura Margheri

Soft Robotics is now considered one of the most promising frontiers for robotics research and technological innovation. The enormous growth of this field in the last few years has been evidenced by a large increase in the number of publications, special issues in journals, focused sessions and workshops at international conferences, summer schools, competitions, EU funded projects, as well as new laboratories, companies and faculty appointments.

Being "soft" is more and more a characteristics needed in robotics systems, especially in those that have to interact with humans or within particular environments. The importance of soft body parts appears clear if taking a look at many natural organisms, where softness, compliance, and embodied intelligence are useful characteristics for reducing the complexity of behaviour control [1]. The vast majority of natural organisms are soft-bodied indeed, and even those with stiff skeletons are predominantly made of soft materials. Caterpillars, octopuses, manta-ray, some fishes and snakes, birds, plants, and others, have therefore inspired engineers for the design and development of new soft technologies and soft systems, as well as for implementing new strategies for terrestrial and underwater locomotion or flying (examples can be found in [2–10]).

The field of soft robotics is highly multi-disciplinary, linking know-how from material science, mechanical/electrical engineering, control engineering, chemistry, physics, computer science, biology and many more.

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There are several cases where soft technologies and integrated soft systems could revolutionize the use of robotic devices, especially in applications where elastic versatility and safe human-robot interaction are needed.

Industrial robotic arms, agriculture robots, surgical robots, robots for search and rescue, wearable systems, exoskeletons and rehabilitation devices can benefit from the use of soft and variable-stiffness components to increase their capacities to interact safely, dependably and effectively with humans and the physical environment.

Soft robotics has the potential for allowing the development of a radically new generation of machines with better performance in the real world, and greater adaptability in a variety of tasks [11].

The interdisciplinary characteristics of soft robotics, the high number of research laboratories in Europe and worldwide that are working in its various subfields (smart materials, biomimetics, embodied intelligence, etc.) and the more recent interest of industrial stakeholders, have arisen the necessity for the creation of a common forum to help researchers to combine their efforts and to maximize the opportunities and materialize the potential impact of soft robotics.

Following this need, RoboSoft, the EU-funded FET-Open Coordination Action (CA) for Soft Robotics (http://www.robosoftca.eu/), started on October 1, 2013 to pose the basis for consolidating the soft robotics community and for enabling the accumulation and sharing of crucial knowledge needed for scientific and technological progress in this field.

RoboSoft has been running for 3 years coordinated by The BioRobotics Institute of the Scuola Superiore Sant'Anna (Italy) in partnership with the ETH Zurich (Switzerland), the University of Cambridge (UK), and the University of Bristol (UK) and it has organized a series of scientific and technical events and activities to unify and extend the community of soft roboticists, to educate a young scientific community of students, to promote the visibility of soft robotics towards stakeholders and special interest research groups and to provide opportunities for better exploiting the potential of soft robots and technologies in future ICT.

Research laboratories and institutions at European and international level working in the field of Soft Robotics have been involved and supported for taking part in the scientific initiatives of the Coordination Action as Members of the RoboSoft Community.

Their representatives are experts in various scientific and technological areas related to soft robotics (smart materials, soft actuators and sensors, control architectures, energy storage, harvesting soft devices, stretchable electronics, biology) and during the periodic meetings they participated in consultations aimed at discussing new challenges, milestones, to redefine theories and techniques, and to provide research roadmaps within a single coherent vision for soft robotics.

RoboSoft has created a large network of scientists and industries and has established strong collaborations with other initiatives worldwide that are dedicated to the promotion of soft robotics, such as the IEEE Robotics and Automation Society (RAS) Technical Committee on Soft Robotics, or education-related initiatives, such as the Soft Material Robotics IGERT at Tufts University and the Marie Sklodowska-Curie Initial Training Network SMART-E.

RoboSoft is now a pillar for the community of soft robotics because of the several events and initiatives organized for merging people, for helping the scientific discussion and for promoting soft robots.

The main events organized by RoboSoft were the annual Plenary Meetings for Community Members, the Schools for Ph.D. students, a series of workshops, special sessions and exhibitions at major robotics conferences, a number of dedicated academia-industry meetings and other initiatives for cross-fertilization with other scientific communities.

The flagship event dedicated to the soft robotics community was launched by RoboSoft in 2015 and named the "Soft Robotics Week", a week totally dedicated to Soft Robotics, featuring a unique concentration of several scientific, cultural and educational events.

International experts across multiple fields in the scientific community of soft robotics, industrial leaders, young researchers and students, met together to present current research and technologies of soft robotics, discuss the challenges and expected milestones, provide research roadmaps and identify the needed supporting actions for this field.

This book represents the proceedings of the second edition of Soft Robotics Week, held in Livorno from April 25 to 30 2016 and presents the current state of soft robotics, collecting the major research lines and novel technologies and approaches presented and discussed during the event by the RoboSoft Community.

The main themes are related to soft robot legged locomotion, soft robot manipulation, underwater soft robotics, biomimetic soft robotic platforms, plant-inspired soft robots, flying soft robots, soft robotics in surgery, as well as methods for their modelling and control.

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Soft Bionics Hands with a Sense of Touch Through an Electronic Skin

Mahmoud Tavakoli, Rui Pedro Rocha, João Lourenço, Tong Lu and Carmel Majidi

Abstract Integration of compliance into the Robotics hands proved to enhance the functionality of under-actuated hands for prosthetic or industrial applications. An appropriate design of the finger geometry with compliant joints allows the fingers to adapt to the shape of the object, and the soft and compliant skin allows for a higher contact area and contact friction. In this article, we describe how these properties were exploited for the development of compliant hands that are simple, efficient and easy to control. We also discuss integration of soft pressure and bending sensors into the digits of these hands.

1 Introduction

About a quarter of the motor cortex in the human brain (the part of the brain which controls all movement in the body) is devoted to the muscles of the hands. This shows the complexity of the human hand, which is composed of 34 muscles. It is clear that individual control of many of the hands joints and thus muscles requires considerable effort from the brain. However many of the tasks, such as grasping, is pretty instinctive for humans and does not involve a considerable brain effort.

Neuroscientists research shows that to control the complicated hand mechanism for a grasping action, the human brain does not control each joint and muscle individually, but utilizes some predefined motion pattern or synergies [1]. Therefore, as stated by Bicchi et al., all joint configurations belong to the s-dimensional manifold, where s expresses the number of synergies" [2]. This means that only a limited number of the vast possible joint configurations are used by humans.

The term synergy comes from the Attic Greek word synergia from synergos, meaning "working together". A grasping synergy, thus makes the control of the hand "easier" for the brain. On the other hand, if we consider the human hand as a rigid

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mechanical system, the limited number of predefined synergies will result in a limited number of contact points which does not comply with the range of the objects that one grasps each day. When the size and shape of the objects slightly change, using the same synergy cannot result in a stable grasp. But the key point here is that the human hand is not a rigid system. Compliance of the musculoskeletal system, of the skin and of the object combine in an overall grasp stiffness. This results in a new definition of synergy, called soft synergy [3], since the hand compliance allows several possible contact point posture with the same joint posture. Thus, the integration of compliance into the anthropomorphic hands will help in increasing the range of the objects which can be grasped.

2 Compliance in "Soft-Hands"

Compliance allows several possible contact point posture with the same joint posture.One approach for integrating compliance into the hands, is to integrate compliant joints and soft skin into the hand. Pisa-IIT Softhand [4], ISR-Softhand [5], Flexirigid [6], SDM hands [7] and the UB hand [8] are examples of recent development of soft hands that directly integrate the compliance into the joints. In Pisa-IIT Softhand several elements are interconnected with elastic elements, while in UB hand the joint compliance is achieved by integration of springs into the joints.

One development of our group was ISR-Softhand. ISR-Softhand is a low cost and highly adaptive hand system that embeds elastic joints and soft elements. For more information, readers are invited to see [5].

Figure 1 shows the first prototype of the ISR-Softhand. Except the thumb palmar abduction joint (actuated manually), all other joints are composed of elastic materials. Each finger has a single tendon, which drives the MCP and PIP joints simultaneously in order to perform the finger flexion. The PIP joint is designed with a higher stiffness compared to the MCP joint. In this way, if the MCP joint is blocked (meaning that the first contact with the object is established) the tendon force is applied to the PIP joint and thereby the PIP closes until surrounding the object. With only 3 actuators for flexion of the thumb, the index finger and the other 3 fingers, ISR-Softhand can imitate 21 out of the 33 grasp forms that humans perform in their daily activity (from the feix taxonomy [9], and for more 10 grasp posture, ISR-Softhand can perform an approximate posture to the one of the human (Fig. 1) [10].

Another example of a soft anthropomorphic hand is the UC-Soft hand (Figs. 2 and 3) [11]. The UC-Softhand is also composed of soft digits, but also benefits from an innovative twisted string actuator, which is low-cost, light weight and non-backdrivable. We modelled and developed a novel twisted string actuation scheme that can fit into the palm of a human [12]. While the number of actuators is same as the ISR-Softhand, the actuation strategy is different. Here, the thumb's Palmar abduction is actuated by scarficing the independent flexion of the thumb and index finger (coupled together).

Fig. 1 ISR-Softhand can perform 31 grasps out of the 33 grasps that humans achieve on their daily activities

In fact, this decision was the result of two independent and comprehensive analysis: on the actuation strategy of an anthropomorphic hand for a better anthropomorphism [13], and the other one on the actuation strategy for better functionality [10]. Selection of the actuation strategy for prosthetic hands is indeed one of the most important stages of optimization for the design of prosthetic hands. Therefore, in these two comprehensive analyses [10, 13], we showed how different actuation strategies can affect the functionality and anthropomorphism of the hand (in terms of grasping postures). These two benchmarks and the related analysis (anthropomorphism and functionality), helps a designer to choose the best actuation strategy for a prosthetic hand. For instance, both analysis showed the importance of the Palmar abduction in increasing both indices of anthropomorphism and functionality.

3 Soft Electronic Skin for Prosthetic Hands

For three main reasons we are interested in integration of an electronic skin into the hand.

- First, since a sense of touch is an important, but a missing factor in the today's prosthetic hands. The sense of touch, brings the feeling that the prosthetic terminal is a part of the body and not an external machine.

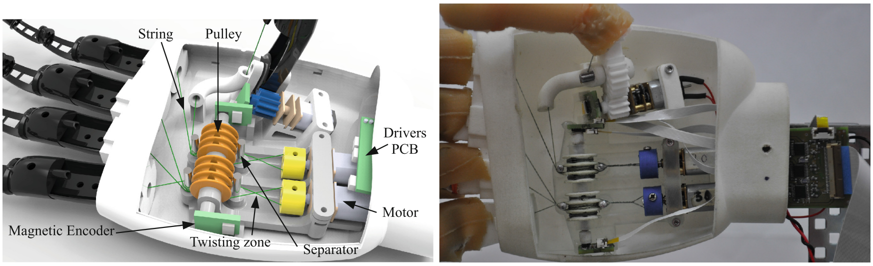

Fig. 2 UC-Softhand is composed of a twisted string actuator scheme, making it very low cost, simple and light-weight

Fig. 3 UC-Softhand has an independent actuator dedicated for rotation of the thumb

Fig. 4 Body-actuated hand with soft digits

- Second, because sensing the contact pressure, allows us to make a closed-loop control of the hand, thus we reduce the control effort from the amputee, and facilitate its usage
- Third, since the bending profile of a soft and under-actuated finger, does not always correspond to the position of its tendon/ pulley, and depends on the shape of the object. Therefore, an encoder installed on the pulley does not provide the control system, precise information regarding the bending profile of the digits. Therefore a bend sensor integrated directly into the joints of the soft fingers is very beneficial (Fig. 4)

Details of the design and implementation of the electronic skin is out of focus of this article. But as can be seen in Fig. 5, the skin is composed of pressure sensors embedded in the finger tips and bend sensors that are embedded in the joints. The sensors are made from Ecoflex-30 (smooth-on) which is a biomedical grade silicone with mechanical properties similar to those of the human skin. The conductive layers of the sensors can be made by a stretchable silicone (e.g. Sylgard 184 or Ecoflex) dopped with conductive particles (usually silver or carbon). To pattern the specific

Fig. 5 An electronic skin composed of soft pressure sensors and bend sensors are embedded on the digits of soft-hand

shape of the sensor, several methods can be used, including screen printing, Laser patterning and lifting [14].

Integration of these sensors helps to make the hand more autonomous and less dependant to the amputee. For instance, closing the control loop of the hand with the force feedback feature, makes the hand more autonomous. Furthermore, the sense of touch can be transmitted to the amputee. Finally, this is a low-cost method that does not require integration of expensive pressure sensors.

4 Conclusions

Integration of compliance into robotic hands for prosthetic applications brings many advantages which were not possible with rigid hands. First, a better adaptability to objects on underactuated digits of the hand is possible, simply by an appropriate design of the elastic properties of each of the joints. Second, a soft skin can improve highly the quality of the contact between the object and the fingers (bigger contact area and higher contact friction). Third, with the recent advances on soft and stretchable electronics, it is possible to embed low cost pressure and bend sensors into the fingers. As a result of these sensors, the sense of touch can be transferred to the amputees and the control of the hand can be simpler for them.

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Soft Robotics Mechanosensing

Lucia Beccai, Chiara Lucarotti, Massimo Totaro and Majid Taghavi

Abstract We focus on studying ways to encode mechanical information with soft sensing systems to provide future robots with exteroception and proprioception capabilities, as naturally as possible. Recently, we have shown developments on soft artificial *mechanosensing* by exploiting smart layouts in combination with soft materials, like elastomers and conductive textiles. Here, we briefly discuss some basic requirements against the significant results of state-of-the-art. Then, we report two case studies in which normal and tangential forces, as well as bending and indentation stimuli, are discriminated, respectively. The aim is to lay the ground for further discussions and investigations in order to target real applications with soft robots and wearable systems.

1 Introduction

Today, robotic scientists are experimenting a huge variety of technologies, materials and bioinspired strategies for building soft robots that in a near future will be capable of 'living' in unstructured environments [12, 13, 26]; here, the bodyware acquires the crucial role of mediating the interaction with the outside world [15]. In particular within this bold picture, soft robots should be able to sense mechanical parameters (among many others), and use such *mechanosensing* capability in adapting/reacting to unexpected situations. Hence, on one side, they should sense external mechanical cues (that can be of various types, e.g. pressure, forces from different directions, vibration, etc.) while they are dealing with exploratory movements and when performing grasping and manipulation of unknown objects. On the other side, they should reconstruct their own movements in space. This scenario is addressed in traditional robotics with a myriad of approaches that endow robots with exteroception and proprioception capabilities, and it must also be dealt in soft

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robots that conform to surfaces and distribute stresses over a larger volume. New flexible/deformable strategies have to be exploited to pursue a full integration of sensing and body, aiming for more sensing functionalities with low computational strategies.

1.1 Soft Exteroception and Proprioception

In Nature, outer mechanical information is encoded through touch sense and mediated by natural skins and underlying soft tissues: mechanical stimuli cause tissues deformations leading to tactile functions. Apart from the extensively studied human sense of touch [21], there are many biological examples from the Animal and Plant Kingdom. For example, cephalopods (like *Octopus vulgaris*) are sensitive to touch all over their body surface. Their arms embed a wide density of mechanoreceptors (in addition to chemoreceptors) in their soft tissues, allowing the animal to adaptively interact with its environment [8]. Also, plants are living beings that have evolved highly sensitive mechanisms through which they can perceive and respond to even subtle mechanical stimuli, like touch [3]. Some carnivorous plants have specific mechanosensory structures (e.g. *Venus fly trap* and *Drosera rotundifolia* have trigger hairs and tactile sensitive tentacles, respectively) capable of sensitive and selective mechanical signaling. Even plants with no specialized organs sense and respond to externally applied mechanical stimuli both in shoots and roots, by means of epidermal cells, which are the outermost layer of the plant body (i.e. the plant 'skin'). They deform upon imposed mechanical stresses and trigger a cascade of internal biochemical signals [25].

Innovative artificial tactile sensing solutions can be pursued by mimicking intrinsic characteristics of natural touch for form and function, and by exploiting the *intelligence* of smart layouts and/or of new generations of materials, i.e. soft active materials [13] that are soft since can undergo large and reversible deformations, and active because they can respond to applied stimuli. They combine conductive and non-conductive features. In particular, for a full and functional integration, it is useful to build components out of the same materials constituting a soft robot, like the stretchable platinum catalyzed silicones (i.e. polydimethylsiloxane (PDMS) or Ecoflex®). These materials are used for non-conductive parts and they have Young's moduli in the range of biological components (i.e., 10^4–10^9 Pa for skin or muscle tissues): Young's modulus of PDMS spans in the range from 360–3000 kPa, depending on the curing temperature and mix ratio of components, while Ecoflex® series have moduli up to 50 kPa [2]. Concerning the conductive part, several materials are investigated by different research groups working on artificial touch, including: conductive polymers [5, 19]; liquid metals [4, 17]; graphene [10, 35]; carbon nanotubes [18, 31]; smart fabrics and fibres [7, 16, 32], etc. Also, stretchable epidermal electronics technology has been developed, by combining conventional and advanced silicon-based technology and soft materials [1]. These, and many more, are remarkable developments, but usually either the devices are optimized as

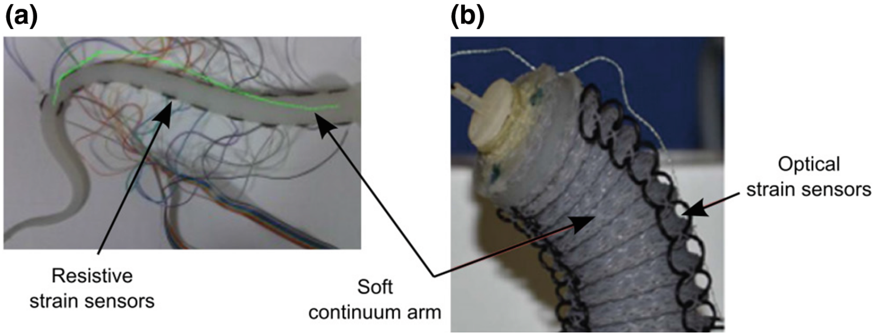

Fig. 1 Sensorized soft continuum arms. **a** Octopus-inspired continuum arm integrating resistive strain sensors. Adapted with permission from [6]. **b** Optical-based macro-bend strain sensors sewn onto a soft continuum arm. Adapted with permission from [27]

separate tactile components (single or array of sensors), because a direct integration in a soft robot is not aimed for; or they do not detect more mechanical cues simultaneously. As a matter of fact, when integrating soft sensing devices into robots made out of soft materials, some major issues arise concerning the decoupling of the mechanical solicitations. One is that soft sensors respond similarly to diverse mechanical stresses. Another is that the deformations of the body affect the sensing functionalities.

In the case of proprioceptive encoding, several works have been proposed in soft robotics. Octopus-inspired continuum arms were sensorized with resistive strain sensors (based on conductive textiles, and shown in Fig. 1a) to reconstruct the arm bending direction [6] or curvature [6]. Deflection PVDF-based sensors were used for shape tracking of a hyper-flexible beam [28]. Also, electro-conductive yarn bending sensors were integrated in a pneumatic soft manipulator for minimally invasive surgery (MIS) to detect either bending or elongation [33]. Hence, these efforts, indeed pursuing a close coupling between the sensing and robotic body, focus mainly on a single sensing function (e.g. pressure or strain) that exploits the movement of the soft body.

Recently, both exteroception and proprioception capabilities were embedded in soft artifacts by two completely different approaches. In one work, three macrobend strain sensors (based on highly flexible optical fibres) have been sewn along the periphery of a soft continuum arm (Fig. 1b) made out of Ecoflex® silicone for discriminating bending, elongation and compression solicitations [27]. The spatial configuration of the arm itself is reconstructed, while the simultaneous detection of more mechanical parameters (internally or externally applied) was not addressed.

In another work, a highly stretchable soft crawling robot was built to sense external pressures and its own deformation [14]. This work is the first (to our knowledge) in which the key aspect of merging sensing and robot body has been fully addressed by building the sensing and actuation system with materials that are perfectly mechanically coupled: the hyperelastic electroluminescent skin is fully

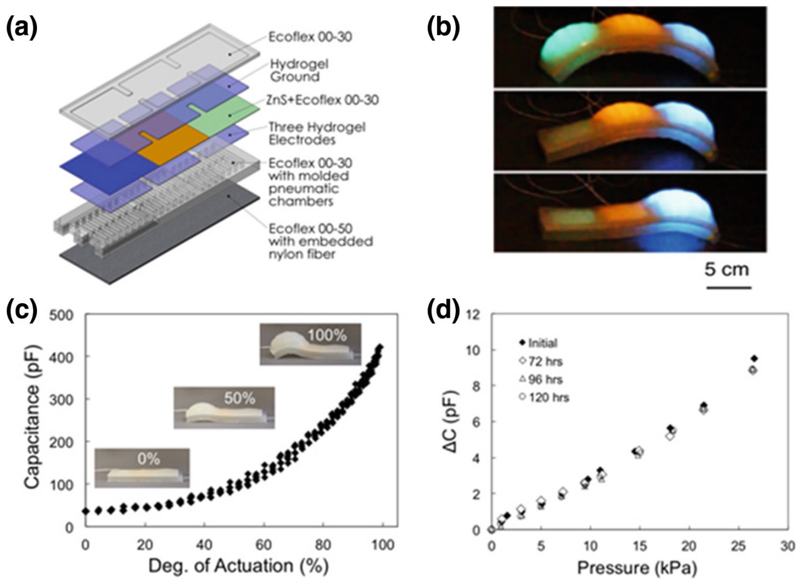

Fig. 2 **a** Schematic of the crawling soft robot having three pneumatic chambers with the hyperelastic light emitting capacitor (HLEC) embedded. **b** The actuated robot: the skin is stretched and luminescence of each chamber (each emitting a different wavelength through selective doping of the electroluminescent (EL) phosphor layer) changes accordingly. **c** Capacitance versus actuation degree, defined as the relative change in deflection between the uninflated and fully inflated states. **d** Change in capacitance versus applied pressure. All images are adapted with permission from [14]

part of the robot body itself. In particular, exploiting both capacitive and electroluminescent elements, the robot is able to either reveal the skin stretching due to its own movement or the pressure coming from an outside object (Fig. 2).

These works anticipate important milestones in soft robotics mechanosensing for which research should move in two main directions. First, the adopted sensing strategies should be able to discriminate different mechanical stimulations (i.e. capable of *multimodality*); and second, in addressing both fabrication and characterization, a symbiosis between sensing and body is a must in order to achieve a high level of functional integration. In the following, we describe two examples of soft sensing approaches that take into account the abovementioned directions, by means of different conformable materials and low computational sensing strategies.

1.2 Electrotextile Capacitive Based Mechanosensing

One of the most promising materials for soft robotics is textile that is also the main component of wearable systems [29, 32]. Indeed, textile is conformable, it can be stretched by choosing proper fibres, and it can have a wide range of mechanical characteristics, determined not only by the material employed but also by the knitting strategy adopted. In particular, conductive textiles, i.e. *electrotextiles* (*e*textiles), able to sense and respond to externally applied stimuli, have excellent electrical and mechanical properties that are opening a plethora of new perspectives for developing low-cost and efficient/robust sensing, for robotics and wearable devices [23]. Therefore, there has been a growing interest in exploiting these materials for building smart mechanosensing layouts. In the following, two case studies are described in which *intelligence* is provided by implementing a capacitive transduction mechanism with a combination of soft silicone elastomers and *e*textiles exhibiting different elastic and tensile properties in smart designs.

2 A Highly Sensitive Soft Three-Axial Force Sensor

One of the main tasks in artificial tactile sensing is to distinguish and detect both normal and tangential forces. For measuring tangential forces, several approaches and different transduction principles have been adopted [9, 11, 34]. One solution is to shape the sensor surface (e.g. with mesas) in order to enhance the shear deformation in the sensor volume causing, for instance, a resistive or a capacitive variation, according to the specific transduction mechanism. However, these solutions are more effective for rigid devices, in order to guarantee a good sensitivity in all directions. Indeed, if applied to soft structures, the deformations of the shaped surface itself become dominant for higher forces, limiting the operating range of sensors. In order to obtain a high sensitivity in a wide range, elastomers with proper mechanical and electrical characteristics were combined in a capacitive-based layout of a three axial force sensor [30].

A multilayered structure gives to the sensor a high compliance, robustness, very high sensitivity (less than 10 mg and 8 μm, minimal detectable weight and displacement, respectively) and detection range (measured up to 190 kPa, and estimated up to 400 kPa). The sensor, shown in Fig. 3, is made of two *e*textile-based electrode levels (i.e., top and bottom) of a non-stretchable (but flexible) copper/tin coated textile separated by a floating dielectric layer. The latter is a fluorosilicone film (DowCorning730, 70 μm thick) that is appealing due to its high dielectric constant and mechanical properties. Because of its low adhesion features, an air gap of around 150 μm is naturally formed during fabrication in between the two copper/tin coated textile electrodes. This air gap adds a second dielectric layer and triggers high sensitivity at very low pressures (ca. 0–2 kPa). Indeed, the woven fabric presents two main perpendicular sets of conductive yarns (i.e. warp and weft) where the warp yarn is interlaced up and down of the weft yarn creating an opening called shed. As a result, the volume of air created by the shed contributes to the formation of a third dielectric layer which plays an important role at higher pressures (>2 kPa). This unique composite structure is embedded in between two PDMS packaging layers to form a mechanically flexible and robust capacitive

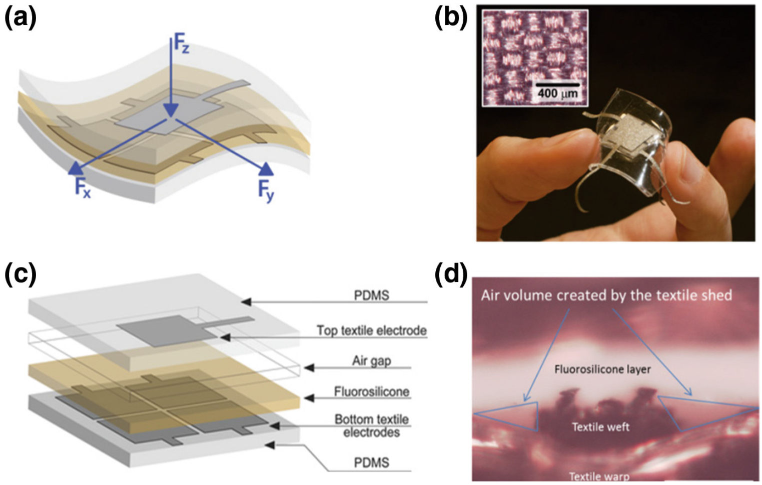

Fig. 3 The soft three-axial force sensor: **a** schematic; and **b** image with inset showing flexible copper/tin coated *e*textile. **c** Sensor layout and constituting materials. **d** Partial cross-section with textile features indicated. Adapted with permission from [30]

sensor. The design consists of four square bottom electrodes that form four unit capacitors with a larger common top electrode. The resulting overlapping of the top electrode on the bottom electrodes is the key to force detection along the three axes. In particular, the key to shear force detection is to combine the materials in a way that externally imposed tangential forces cause sliding of the top electrode with respect to the bottom layer. It is worth to mention that, in this system it is crucial to adopt a differential read-out strategy to minimize parasitic capacitance and to reduce the noise due to proximity effects; this also makes the sensor much more robust to electrode position mismatching allowing a simpler and low-cost fabrication.

3 Bending and Pressure Detection in a Soft Body

As mentioned above, *multimodality*—i.e., the ability to transduce different parameters of the applied stimulus—is one of the major issues when implementing mechanosensing in soft robots that should be solved without increasing the complexity of the overall structure (both mechanical and algorithmic).

The Plant Kingdom, and in particular plant roots are an amazing source of inspiration for this field [22]. Plant biologists [24] observed that upon bending, *Arabidopsis thaliana* roots show stretching and compression of epidermal cells, on the convex and concave wall, respectively. This enables plants to encode bending movements by detectable or non-detectable internal responses, respectively.

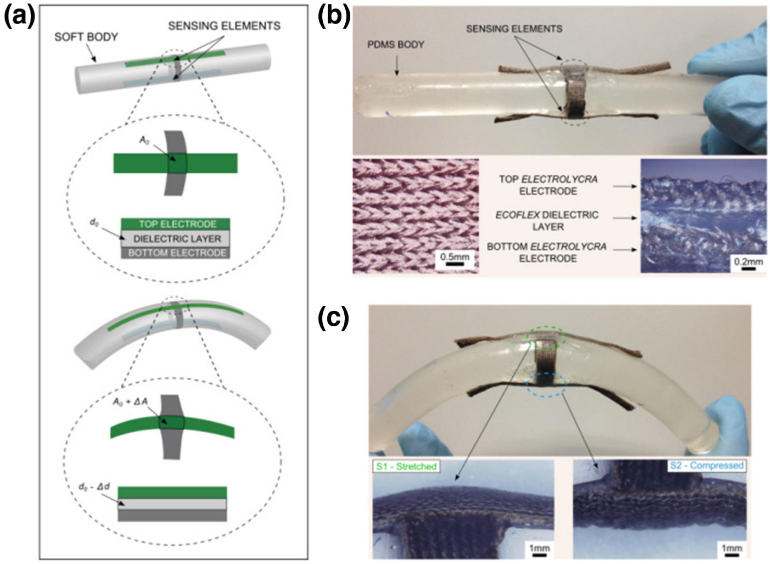

Fig. 4 **a** Schematics of the soft sensing body with focus on one sensing site, in rest (*top*) and bent (*bottom*) configurations. **b** Illustrations of the soft PDMS *cylinder* in rest condition. *Bottom*, electrolycra material and cross-section of one sensor are shown. **c** The soft sensing body in the *bent state*, with conformed sensors on convex (*stretched*) and concave (*compressed*) sides. All images are adapted with permission from [20]

Indeed, starting from the study of the plant capabilities to perceive mechanical solicitations, i.e. *mechanoperception*, in [20] a soft sensing body discriminating its convex and concave sides, as well as bending or indentation stimuli was investigated. Flexible and stretchable materials, like elastomers and *e*textiles, were used to build two hyperelastic sensing elements that intimately conform to a simple shape of a soft body in which they are built and follow its deformations. Noticeably, by comparing the responses of sensing sites, information about both bending (or maximum deflection, depending on the body mechanical configuration) and force were obtained at the same time. Figure 4 shows the cylindrical, flexible, and soft body in PDMS, and two embedded capacitive sensing elements at its opposite walls, i.e., at 180° from each other. In this case, two same sensing elements were built from two stretchable electrolycra and separated by an elastomeric Ecoflex 0010 film, acting as dielectric. The choice of such stretchable *e*textile for the electrodes of the capacitances, together with the soft dielectric that adheres to both electrodes, plus the layer-by-layer fabrication in the soft cylinder are all fundamental aspects to reveal the strain induced by the bending movement.

The capacitance variations of the sensing elements (i.e., S1 and S2) were correlated to the different mechanical stimulations applied to the soft body, such as bending and/or external force and, in particular, several mechanical configurations with the body bent in the 2D plane were analysed. It was demonstrated that, for a

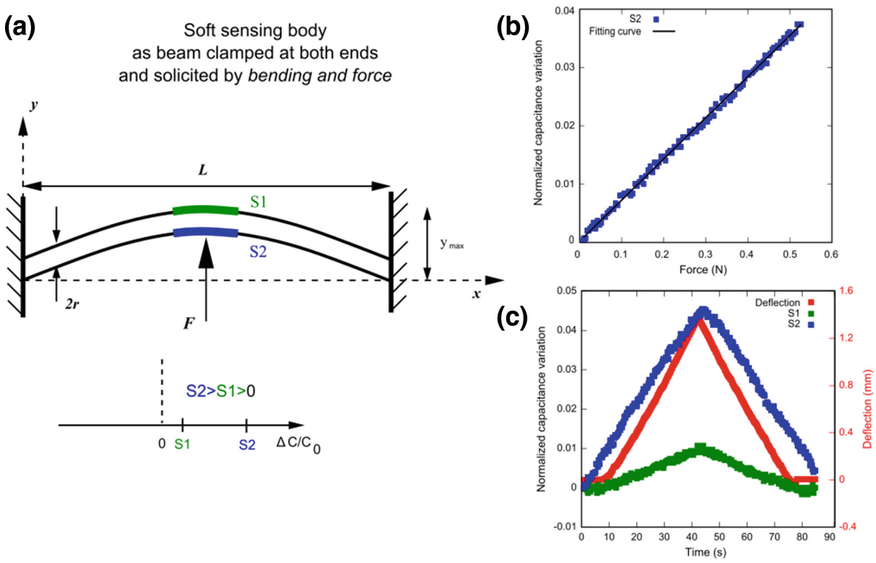

Fig. 5 **a** Schematic of beam clamped at both extremities and subjected to bending and indentation. **b** Normalized capacitance variation versus indentation force *F* on *S2*. **c** *S1* and *S2* responses, and output of an accelerometer measuring beam deflection. Adapted with permission from [20]

given configuration, the applied solicitation can be retrieved by a simple comparison of, both, amplitude and sign of sensing responses. For example, in a beam clamped at both extremities with an external force applied on one of the sensing elements (see Fig. 5), both signals have positive responses and the deflection can be retrieved (see blue curve in bottom right graph of Fig. 5). However, the amplitude of the signal on the concave side, because of the applied indentation, is much larger than that on the convex side. In contrast, when only the bending is performed (configuration not shown here, please refer to [20], the output signals have opposite sign, and the amplitude of the sensing element on the concave side is smaller than that on the convex one.

4 Conclusions

Even if at their early stages, current investigations in the soft robotics community demonstrate how some basic and well known principles can be successfully re-interpreted with new materials. For example, although the bending detection technique used by [20] is typically used in engineering for the detection of a shaft bending (but with other traditional technological approaches, e.g. strain gauges on metallic shafts), the authors got inspired from the stretching and compression mechanisms of plant cells to implement them in a soft module, and this approach triggered new results on sensing multimodality. Several open issues remain to be addressed. In particular, the reconstruction of three-dimensional movements in a soft robot should be developed, by exploiting the use of different transduction principles in combination with smart structures fully embedded in the robot body. Also, alternative and more complex shapes of the soft sensorized body (e.g. cone shape with small angle) should be investigated. Another example is given by the simple capacitive principle that (like many others) can be used thinking, not only about its electronic nature, but also at the structure and mechanical behaviour of a capacitor built with soft elements.

Today, the potentiality of merging more sensing functionalities in actuated soft artefacts has been demonstrated [14], however starting from the discussed studies, many aspects need attention in order to extend the basic concepts to real soft robotic scenarios. At any case, in future studies the soft body itself needs to be part of the mechanosensing system following a bioinspired approach, and models and reconstruction strategies will need to be developed with the lowest computational cost, in order to simplify the elaboration electronics towards reliable autonomous systems.

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Towards Behavior Design of a 3D-Printed Soft Robotic Hand

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Abstract This work presents an approach to integrate actuators, sensors, and structural components into a single product that is 3D printed using Selective Laser Sintering. The behavior of actuators, sensors, and structural components is customized to desired functions within the product. Our approach is demonstrated by the realization of human-like behavior in a 3D-printed soft robotic hand. This work describes the first steps towards creating the desired behavior by means of modeling specific volumes within the product using Additive Manufacturing. Our work shows that it is not necessary to limit the design of a soft robotic product to only integrating off-the-shelf components but instead we deeply embedded the design of the required behavior in the process of designing the actuators, sensors, and structural components.

1 Introduction

Pneumatic actuation is one of the two most used actuation techniques in soft robots [10]. This type of actuation is often realized through the inflation of channels in elastic material. These actuators are promising in soft robotics since (1) they are under-actuated and compliant, (2) they can be free of internal electronics and electric components, and (3) their performance can be tuned through the morphology of the actuated segment [3, 6, 7]. This provides a significant benefit in applications such as soft pneumatic hands [1], orthotics [9] and locomotion [11].

Previous researchers mainly used molding techniques to fabricate silicone soft robots [7, 11, 13]. However, the constraints of the molding processes limit the design freedom. As a result, in existing approaches actuators are usually oriented in the same plane or fabricated separately and later assembled into a functional structure. *Additive Manufacturing* (AM), or 3D printing, is a collection of digital

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fabrication processes that build up objects by adding material layer upon layer. AM has been used to integrate multiple actuators [5, 8] or air pressure sensors [12] with structural components. In literature, an advanced design method was developed to design the deformation elasticity of structures fabricated by AM [5]. Nevertheless, little attention was paid to the methodology of customizing the behavior of each specific actuator and sensor within a soft robotic product.

This work presents a case study in which multiple air pressure actuators, sensors, and structural components are integrated in a single body product using the AM process *Selective Laser Sintering* (SLS). To show the possibility of designing human-like behavior, an interactive setup was made realizing a handshake between a user and the hand. The air pressure-based robotic hand comprises eight actuators and two sensors without any internal electronics. The hand measures the force that is exerted upon it and squeezes back accordingly, adapting itself to the user's grip. For each part of the hand, the behavior was customized based on a given volume and function. The main technical contribution of this work is the integration of air pressure actuators, air pressure sensors and structural components that are designed for the desired behavior of this specific volume within the product.

2 Design of Soft Robotic Hand

We simplified the complexity of the human hand and subdivided it into parts with a specific function as actuator or sensor. The carpometacarpal joint of the thumb is fixed in a position suitable for shaking hands. The design of our soft robotic hand consists of four different parts (see Fig. 1 for an illustration), including (1) bending actuators, (2) a rotational actuator, (3) a bidirectional actuator, and (4) sensing air chambers, all shown and discussed below. They are designed to mimic the behavior of a human's hand.

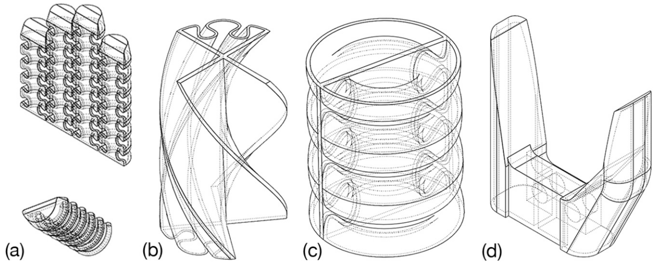

Fig. 1 An illustration of different parts used in our design—from *left* to *right*, **a** bending actuators, **b** rotational actuator, **c** bidirectional actuator and **d** sensing air chambers

2.1 Bending Actuators

The principle of a pneumatic bending actuator is based on pressurizing an air-chamber formed by an inextensible bottom layer and an extensible top layer (see also Fig. 1a). The bending range can be improved by creating a more S-shaped curve of the bellow, whereas the exerted force at a given position can be improved by increasing the bellow's stiffness [3]. This principle was used to create the difference in behavior between the fingers and thumb. Given a designed model and fabrication constraints, the following properties influenced the design process of bending actuators; we need (1) a minimum bending range of 90° of the thumb (the angle measured on tip orientation) at a pressure of less than 400 kPa, (2) a minimum bending range of 180° of the other fingers, to be achieved with the same pressure, (3) to maximize the exerted force of the thumb bellow, and (4) to minimize the radial expansion of the bellows.

2.2 Rotational Actuator

The principle of this rotational actuator was inspired by the elephant's trunk. The elephant has helical muscles in its trunk that, when contracted, cause rotation of the trunk [4]. This principle can be mimicked by sweeping a radially expanding bellow over a helical path (see Fig. 1b). Here, the design process is influenced by the following demands on properties; we need to (1) maximize the radial expansion of the bellow upon inflation, (2) minimize the lateral expansion of the bellow upon inflation, (3) maximize the structure's bending and axial stiffness, (4) minimize its rotational stiffness, (5) at least 45° of pronation to be achieved with at most 400 kPa pressure. Our design consists of a bellow swept over a helical path of 0.4 revolutions over a height of 70 mm. The bellow is encapsulated between two segments of an X-profile, and the actuator has a diameter of 50 mm.

2.3 Bidirectional Actuator

Two bending actuators that share an inextensible layer were used to mimic the antagonistic setup of a bidirectional actuator. Pressurizing one of the two bellows can be used to create palmar or dorsal flexion. Pressurizing both air chambers will inflate the bellows and therefore enhance the palmar and dorsal stiffness of the wrist. The following factors are considered in our design of the bidirectional actuator; we need to (1) minimize the palmar and dorsal bending stiffness, (2) maximize the radial and ulnar bending stiffness, (3) maximize the axial and rotational stiffness, (4) achieve minimal palmar flexion of 45° within 400 kPa pressure, (5) obtain minimal dorsal flexion of 45° with the same pressure, (6) maximize the bending stiffness upon pressurization of both actuators. Our design can be found in Fig. 1c. To increase the radial and ulnar bending stiffness, the inextensible layer of the double bellow is designed rectangular instead of following the curves of the bellows. The shape of the bellows is extensively curved to ensure self-collision to create extra stiffness when inflated. The actuator has a diameter of 50 mm and an effective height of 70 mm.

2.4 Sensing Air Chambers

The principle of our sensor was inspired by the work of [12]. Squeezing an air chamber results in an increase in air pressure, which can be measured externally from the hand. Our design incorporates the following considerations; we need to (1) mimic compliance of a human hand at contact areas, (2) provide a connection structure between fingers, thumb and wrist, and (3) minimize the air volume to maximize the sensitivity. Our design is shown in Fig. 1d. It essentially shows the palm of the hand as base to connect wrist and thumb and two extensions of the palm at which the finger-set is attached. See also Fig. 3. If these extensions are squeezed towards each other they output air pressure that can be measured and electronically processed by our control system.

2.5 Pneumatic Control System

A Freescale MP3V5010 sensor with a range of 0–10 kPa was used to measure the change of air pressure in both air chambers of the hand palm when people shake our soft-robotic hand. The sensed signal is then mapped to a 0–400 kPa pressure using a Festo VPPE-3-1-1/8-6-010-E1 proportional pressure regulator to control the gripping force of the thumb and fingers. The bidirectional and torsional actuator are manually controlled using a 3/2 valve and a pressure of 100 kPa.

3 Design for Manufacturing

The final design was fabricated on an SLS machine by Materialise [www.materialise.com] using the flexible polyurethane-like TPU92A-1 material. It took 12.5 h to print our soft robotic hand. While designing the hand, the following manufacturing factors were considered:

- Wall thicknesses: A minimum wall thickness of 1 mm was used to prevent leakages, whereas the maximum wall thickness was limited to 10 mm to prevent excessive warping.

- Removal of unused material: For each air chamber, an aperture with a diameter of at least 10 mm was required to remove the unused material. The powder was removed by inserting a flexible cable through this aperture. This cable was guided to the end of the air chamber through its internal geometry. Therefore, all sharp edges inside the air chamber were smoothened and branched air chambers were not possible. This means every finger needed to have a separate opening for airflow.
- Fittings: The apertures for the removal of support material were used to insert G1/4 threaded push-in fittings. Therefore, the aperture diameter was determined to be 10.5 mm and the depth at least 10 mm. Because of the flexibility of the material, the apertures were surrounded by a minimum wall thickness of 5 mm to create a secure connection with the fitting.

4 Results

In our design practice, various separate bending actuators of the same length and number of bellows but different shape of bellows were prototyped to find a good design for the thumb and fingers. Figure 2a shows the performance of the designs that were later implemented in the hand. For both bellow designs, the horizontal force was measured in the setup as shown in Fig. 2b. When supplying a pressure with 400 kPa, the exerted force of the thumb bellow was 7.6 N, whereas the finger bellow exerted a force of 1.8 N. The bidirectional actuator shows a bending angle of 45° when a pressure of 90 kPa is applied to one of the bellows (angle measured

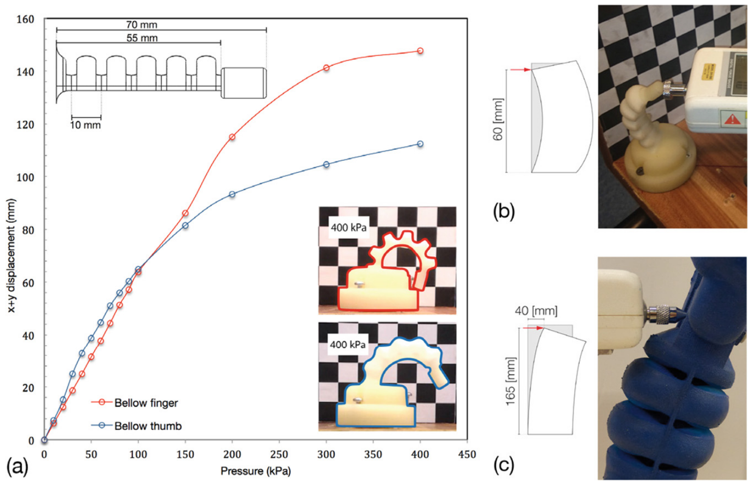

Fig. 2 **a** Displacement of thumb design (*blue*) and finger design (*red*), **b** setup for measuring the force of the bending actuators and **c** setup for measuring the stiffness of the wrist

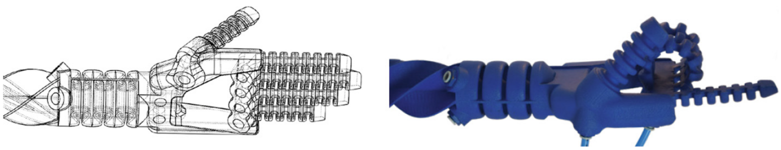

Fig. 3 The final integrated design of our soft robotic hand, the performance of which can be found in video: https://youtu.be/AdMhkIM4hwA

at top orientation). The stiffness of the wrist was measured using the setup as shown in Fig. 2c. A 0.8 N force was needed for a 40 mm displacement of the passive wrist, whereas a 2.9 N force was needed for the same displacement upon pressurization of the bellows at 400 kPa. The rotational actuator achieved a 45° pronation at a pressure of 60 kPa.

The final design of our soft robotic hand by integrating all these actuators, sensors and structures can be found in Fig. 3.

5 Conclusions and Future Work

This work shows that the design of a set of behaviors in soft-robotic products does not have to be limited to making use of existing components. In fact, these behaviors can be deeply embedded in the integral design of a robot's actuators, sensors and structures. We showed that it is possible to design bending actuators, rotational actuators, bidirectional actuators, and sensing air chambers using mono-material SLS, and create a robotic hand with it for the purpose of human-machine interfacing, in this case for interactively shaking hands.

Since the hand was created using mono-material AM, the design freedom was limited because differences in extensibility had to be created through designing the shape of the bellow's walls. In contrast, when using multi-material in AM, relative differences in behavior can also be created through compositions of complex structures of both rigid and soft materials. Thereby, a desired behavior could be addressed more easily—see [2] for an example.

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Soft Robotics in Underwater Legged Locomotion: From Octopus–Inspired Solutions to Running Robots

Marcello Calisti

Abstract This chapter reports on the conceptual design of an octopus-inspired robot. The investigation started from slow speed gaits, such as the crawling locomotion of octopuses, and was followed by faster gaits such as bipedal walking and hopping. Results envisage that this novel locomotion can be exploited to increase the mobility of underwater robots in the benthic realm.

1 Underwater Legged Locomotion

Marine robotics experienced a steady growth over last years, fostered by the increased request of underwater natural resources, as well as the number of scientific, exploration and search and rescue missions performed in collaboration with underwater robots. Although manipulation, interaction and motion are among the key system abilities requested to underwater robots, the vast majority of those vehicles move in what is called *pelagic* realm, i.e. the portion of the ocean ranging from above the seabed to the water surface, and when they need to interact with underwater structures or surfaces, for example in inspection, sampling, and manipulation tasks, the control complexity (and autonomy) drastically increases (or decreases) [11]. On the contrary there exist a category of underwater vehicles, called generically crawlers [19], which is purposely designed to explore the *benthic* real, i.e. the bottom of the sea and some sub-surface layers. Crawlers are used to track mineral resources, operates in close-contact with structure or to provide high resolution information of the benthos [16, 19]. They are usually rover-like vehicles, with wheels or tracks, and their design should take into account water-related forces, which can tilt the vehicle over and decrease the friction, resulting in reduced performance [19]. Moreover wheels or tracks can get stuck in complex, uneven surfaces, thus reducing the motion capability of the robot, or they can cause serious damages to fragile substrates. On the other hand, there is a great number of benthic animals which swiftly move onto

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the seabed or rocks, and gently interact with the environment: among them, we can recognized several species of crab, lobsters, worms, shrimps, sea cucumbers, starfish and octopuses.

Recently, octopus-inspired solutions attracted several researchers, especially in the soft robotics niche: the amazing properties of the octopus arm, which are exploited to manipulate objects and to move, have been source of inspiration for soft robotics manipulators [12] and suckers [27], in addition to mobile soft vehicles. Octopuses move in several different ways ranging from swimming by jet propulsion [25] or sculling [26], to crawling [9] and bipedal walking [5, 6]. Octopus-like robots are among the few pioneering prototypes of underwater legged machines, together with other few examples [1, 3, 20], and this chapter presents three bioinspired solutions for underwater legged locomotion. To begin with, the slowest movement of the octopus was studied, called crawling, which is mainly used in shallow waters and on multiple surfaces; then a faster locomotion, named bipedal walking, was investigated; and finally an hopping-based locomotion is formulated, inspired by punting locomotion, where the contact time is minimal and a flight (swimming phase) is clearly shown. In the next sections I will report the principles of these kinds of underwater legged gaits, while in Sect. 2 I will conclude the chapter and illustrate further developments.

1.1 Crawling

Octopus crawling appears as a cluttered sequence of pushing and pulling actions, without a timely and organized coordination [23], however recent studies demonstrated that octopus crawling relies on a few fundamental principles:

1. thrust tangential to the direction of elongation of the arm [9]
2. non-rythmical arm coordination made of instantaneous decision on which arm to recruit to move in a certain direction [21]
3. stereotyped sequences of arm motions [9]

These three principles are illustrated in Fig. 1; practically, if the octopus wants to move to the right, it elongates the arms to the left and pushes the body in the opposite direction Fig. 1a; if a target suddenly appear, a novel set of arms is recruited to push in the proper direction Fig. 1b, thus that an overall eight-arm coordination emerges from single arm recruitment; and finally it is shown how the pushing action is based on four repeated phases: a shortening motion (when the arm is shortened), an attaching phase (when the arm sticks to the ground by means of the suckers), an elongation action (when the arm elongates and pushes the body), and eventually a detaching phase, Fig. 1c. These findings significantly reduce the features required to build a soft arm devoted to locomotion: that arm should only be capable of shortening/elongating and attaching/detaching. By taking as a reference these design objectives, a conical arm made of silicone and cables was developed: the first version embedded one axial steel cable and one longitudinal nylon cable, with two different functions. Thanks to the

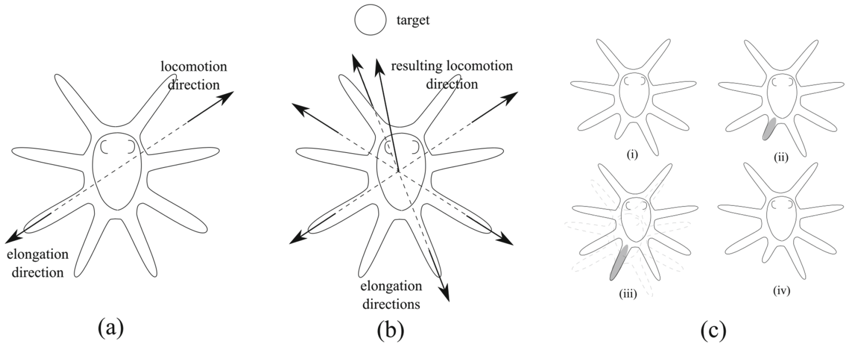

Fig. 1 Biological findings guided the development of the octopus inspired robot: **a** radial pushes, **b** multi-arm recruitment, and **c** four phases pushing action

coiling or uncoiling of the steel cable, the arm reduced or increased its length, whereas the longitudinal cable was used to bend the arm in a spiral like configuration. The bending action was used to lift the arm (or to lie it) onto the ground, thus providing a attaching/detaching mechanism, while the shortening/elongating strategy was used to push the robot. Implementation and design details are reported in [9].

Following this seminal work, a further version of the arm was developed by using the axial cable as a bar of a three-link mechanism, illustrated in Fig. 2: thanks to this design, only one motor was needed to perform the sequence of actions required to push the body forward. Moreover, a rotation in anti-clockwise direction allowed the arm to push the robot, while a rotation in the opposite direction entailed a pulling motion. By using this novel design it was possible to attach, in a radial configuration, several copies of the compliant arm on a central rigid platform, which allowed the underwater robot to move in every direction [4, 8]. Moreover, bioinspired control strategies were implemented by taking into account the non-rythmical coordination behaviour discovered in the animal. The positions of a target (balloon) on the frame of an omni-directional camera were collected as input, while the actuations of the corresponding arm were used as output of a goal-oriented sensory-motor coordination strategy which was implemented on a six-arm robotic platform. This reactive control strategy leaded to a reliable behaviour which allowed the robot to reach the target in every position of the space, and moreover a two-arm coordination emerged when the target was in between the direction of two pushing arms [22].

1.2 Bipedal Walking

The crawling solution, even if it was effective on several grounds [12], lacks the dexterity and speed desired in underwater mobile robots, hence we tried to exploit the compliant actuation mechanism developed for crawling in novel configurations, with the goal of improving the mobility of the robot. A novel platform, called PoseiDRONE, was developed for this purpose [2]: it featured only four-arms, but

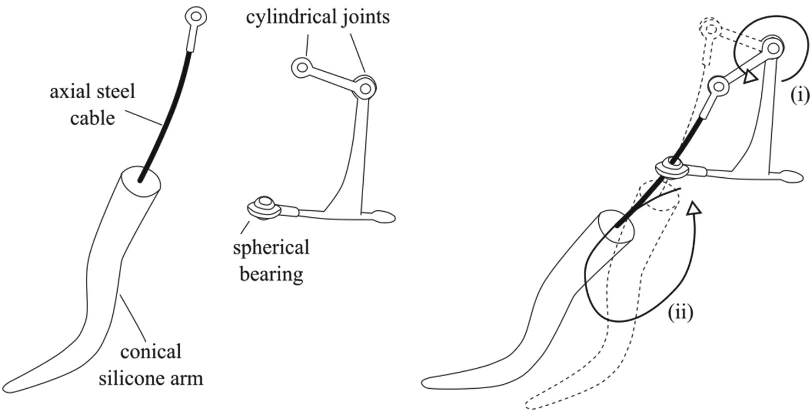

Fig. 2 The compliant arm is used as a bar of a three-link mechanism. The rotation of the crank (*i*) entails a pseudo-elliptical loop in the arm (*ii*), which allow the robot to push or pull the ground

with robot geometries optimized (via evolutionary design) to realize faster gaits [5, 13, 14]. The work was again inspired by a gait performed by the octopus: the bipedal walking. In this gait, the animal stands in a bipedal-like posture and, in a roughly coordinate action, it uses a couple of arms to push forward the body [17, 18]. By lodging over the body of the robot a controllable floating module, we tested a bipedal actuation and reported the speed the robot, which was considerably higher than the crawling one, while the behaviours was qualitatively influenced by sculling movements as well [6]. Particularly, we noticed that it was possible to exploit body/water relationships to design improved underwater legged robots [13, 14], and that the duty factor drastically decreased, due to long swimming phases after short pushing phases, as the buoyancy contribution increased. This motivates the investigation of a pushing-based motion which employed very brief, impulsive, pushing phases followed by gliding phases, as to reduce to the minimum the contact with the environment yet to increase the speed of the robot.

1.3 Underwater Hopping

Such desired dynamic motion was similar to the one-leg hopping behaviour implemented on a pogo-stick machine to study terrestrial running [24]. Similar to the terrestrial counterpart, we expected that it was possible to obtain reliable self-stabilizing running behaviours also in underwater legged locomotion, and a monopedal running model was developed to test this hypothesis [10]. The model was based on the successful Spring Loaded Inverted Pendulum (SLIP) template, which was extensively used as a reference for the control of running machines [15]. The novel model, called Underwater-SLIP (U-SLIP), included water related contributions such as the drag, buoyancy forces, and the added mass. Results demonstrate how the U-SLIP reaches a self-stabilizing periodic behaviour, even when moving over uneven terrains with random disturbances. Based on those results, a monopedal robot was design, developed and tested on several grounds, confirming the high stability of underwater robots employing such hopping locomotion [7].

2 Conclusion

Underwater legged locomotion is using tools and strategies of soft robotics to increase the interaction and motion capabilities of underwater robots. By using bioinspired design, soft solutions can be quickly developed and tested, while more focussed design methods can be used to properly exploit water/soft-body relationship. The qualitative solutions presented envision the long term goal of demonstrating quantitatively augmented capabilities related to stability of the locomotion, reduced damage to the environment and improved motion on the benthic realm.

Acknowledgments This work was funded within the framework of the EU RoboSoft Coordination Action, under the contract FP7-ICT-2013-C project # 619319.

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Underwater Soft Robotics, the Benefit of Body-Shape Variations in Aquatic Propulsion

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Abstract Aquatic organisms capable of undergoing extensive volume variation of their body during locomotion can benefit from increased thrust production. This is enabled by making use of not only the expulsion of mass from their body, as documented extensively in the study of pulsed-jet propulsion, but also from the recovery of kinetic energy via the variation of added mass. We use a simplified mechanical system, i.e. a shape-changing linear oscillator, to investigate the phenomenon of added-mass recovery. Our study proves that a deformable oscillator can be set in sustained resonance by exploiting the contribution from shape variation alone which, if appropriately modulated, can annihilate viscous drag. By confirming that a body immersed in a dense fluid which undergoes an abrupt change of its shape experiences a positive feedback on thrust, we prove that soft-bodied vehicles can be designed and actuated in such a way as to exploit their own body deformation to benefit of augmented propulsive forces.

1 Introduction

Most aquatic organisms rely on periodic oscillations of some wing-link control surface for locomotion. These may entail fins, a tail or whole-body ondulatory routines, which eventually participate in generating rotating fluids which is pushed backwards while propelling the body forwards [8, 14]. A broad degree of variability is found in the details of the kinematics of the surfaces of actuation and the associated topology of the vortices generated; however, the processes which enable vertebrate organisms to propel themselves in water manifest a remarkable degree of consistency [13].

Of higher interest within the frame of soft robotics are those mode of locomotion where body modifications don't necessarily rely on the activation of joints or the

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coordinated motion of reciprocating limbs, but rather those where the body undergoes extensive transformation of its topology or volume. In this respect, mono-cellular organisms or aggregate of these, as well as certain tunicate and cephalopods [6], are better paradigms of what a soft body, and hence a soft robot, can achieve [15]. These organisms have attracted the attention of the robotics community because they represent the perfect source of inspiration for the design of soft-bodied underwater vehicles [3, 12]. In the past, cephalopods have been studied extensively for their pulsed-jet propulsion [7], but lately their volume-changing propulsion routine has been associated with the phenomenon of added-mass recovery and the idea that this may further contribute to the thrust production [16, 17]. If confirmed, this would have a major impact both on the understanding of the biomechanics of these living organisms, as well as on the chance to exploit this principles in the design and control of innovative underwater vehicles [2, 4, 11]. Following the results of [5], we report on the phenomenon of added-mass recovery for a simplified mechanical system in order to demonstrate that shape variation can indeed act as a secondary source of thrust.

2 Added Mass Variation as a Thrust Term

When a body is accelerating in a dense medium, added mass defines an inertial term which depends on the amount of kinetic energy lost for accelerating the fluid around it. This was first postulated by Alfred Barnard Basset [1] in attempting to account for the differing frequencies experienced by a body oscillating in vacuum and in a dense fluid. Given the dynamics of a 1 dof (degrees of freedom) oscillator,

$$m^* \ddot{x} + kx = 0, \tag{1}$$

where m^*, $x(t)$ and k respectively represent the effective mass, the position and the elastic constant of the oscillator, the frequencies of oscillation in vacuum, ω_0, and in a dense medium, ω^*, are defined as $\omega_0 = \omega^* = \sqrt{k/m^*}$. However, while for the case of a body oscillating in vacuum $m^* \equiv m$, for a body vibrating in a dense fluid $m^* = m + m_a$, where m_a is the added mass of the body, thus explaining why $\omega^* \leq \omega_0$.

The added-mass is thus a force generated by the fluid acting against the acceleration of a body and, for single bodies far away from solid boundaries, it depends on the density of the fluid and the shape of the body. This term is especially important in the design and control of aquatic soft-bodied machines because these are often made of relatively light materials and added-mass effects become prominent when $\rho_s/\rho_f \sim 1$ or <1, with ρ_s and ρ_f being the density of the solid and the fluid.

The role that added-mass plays when a body undergoes shape variations such as those experienced by cephalopods has not been looked into in details. To do so we take in consideration the same mechanical system employed by Basset and expand

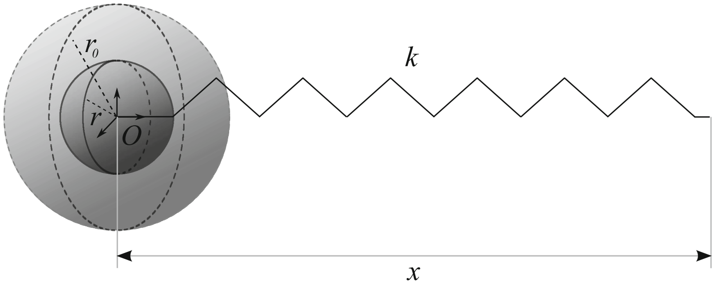

Fig. 1 Scheme of the shape-changing spring-mass oscillator. Here r represents the radius of the oscillator at time t, while r_0 refers to the mean radius of the oscillator. The distance of the frame of reference centered in O from the relaxation point of the spring is x. Adapted from [5].

on this by accounting for the capability of an oscillating body to vary its shape, and hence its added-mass, in time, see Fig. 1.

For a body immersed in a dense, viscous fluid, it has become customary to define the dynamics of such a body according to the Morison force [10], which accounts for the combined effects of added-mass and drag via their linear summation. In this case the dynamics of the 1 dof oscillator of Fig. 1 reads:

$$\frac{d}{dt}\left(m^* \dot{x}\right) = -\frac{1}{2}\rho_f C_d A \dot{x}|\dot{x}| + kx. \tag{2}$$

Where the differential sign in front of the inertial term has been retained because we are interested in accounting for bodies whose shape can be altered in time.

We perform the differentiation on the first LHS (left hand side) term while assuming the mass to remain constant (i.e. $\dot{m} = 0$) and only the shape, and hence the added-mass, to change (i.e. $\dot{m}_a \neq 0$). This situation is resemblant to the case of an oscillator being inflated/deflated by pumping a gas inside it, so that the variation of the inertia of the oscillating body is negligible. If this is the case, the buoyancy of the oscillator does vary, but since the motion of the body is purely translational along the x direction, the forces along the vertical and horizontal direction remain fully decoupled. Hence, substituting m^* into Eq. (2) and bringing the differentiation forward yields,

$$(m + m_a)\,\ddot{x} = -\frac{1}{2}\rho_f C_d A \dot{x}|\dot{x}| + kx - \dot{m}_a \dot{x}. \tag{3}$$

In the LHS term, $m_a(t)$, is the time-varying added-mass, while the third RHS term is the added-mass variation term which has the form of a thrust source. This latter form of Eq. (2) suggests that added-mass variation can indeed work as a propelling force as long as the motion has been initiated by some other effect, i.e. the elastic energy of a spring, in an oscillator, or the jet, in a freely swimming organism. The occurrence of the minus sign in front of the $\dot{m}_a \dot{x}$, proves that, in order for added-mass variation to act as a propelling term, $\dot{m}_a$ must be negative, thus requiring the body to shrink.

The best way to prove that the added-mass variation term can indeed provide a positive feedback on thrust is by rearranging Eq. (3) as follows:

$$(m + m_a)\,\ddot{x} = -\left(\frac{1}{2}\rho_f C_d A|\dot{x}| - \dot{m}_a\right)\dot{x} + kx. \tag{4}$$

This latest rearrangement highlights that, if added-mass variation can act as a propelling force, a function of $\dot{m}_a$ must exist according to which,

$$\dot{m}_a = \frac{1}{2}\rho_f C_d A|\dot{x}| \tag{5}$$

thus cancelling viscous drag and eventually driving the oscillator into the regime described in Eq. (1). This implies that, by virtue of external shape variation alone, a damped oscillator can be made to behave as an undamped one. This function can be readily derived by assuming the oscillator to be a sphere, whose added-mass is simply,

$$m_a = \frac{2}{3}\rho_f \pi r^3, \tag{6}$$

where $r(t)$ is the time-varying radius of the sphere. The time derivative of m_a thus reads,

$$\dot{m}_a = 2\pi\rho_f r^2\dot{r}. \tag{7}$$

By substituting Eq. (7) into Eq. (5), the condition for zero damping is met when,

$$\dot{r} = -\frac{1}{4}C_d|\dot{x}|. \tag{8}$$

This extremely simple formulation defines the radius variation needed for a sphere oscillating in a dense medium to cancel viscous damping effects and in this way drive the system into resonance.

A closed form for the radius variation can be found by assuming a sinusoidal velocity profile of the oscillator, i.e.:

$$x = X cos\,(\omega t) \tag{9}$$

where X is the initial displacement of the oscillator. This yields the time-varying radius profile depicted in Fig. 2 for two full oscillations and four shape-variation routines. We refer to this radius-variation routine as the "step" profile. Figure 2b reports, in the lower part, the assumed oscillator velocity and, above, the non-dimensional radius profile; Fig. 2a depicts the size of the sphere at four instants throughout half an oscillation of the body. The shape of the function $r(t)$ in Fig. 2b is extremely interesting because it qualitatively resembles the activation mode of certain pulsed-jet propelled organisms. At $t/T = 0.5$ the oscillator has zero speed when the spring is fully stretched. At this stage the sphere has a radius $r = r_0 + a$

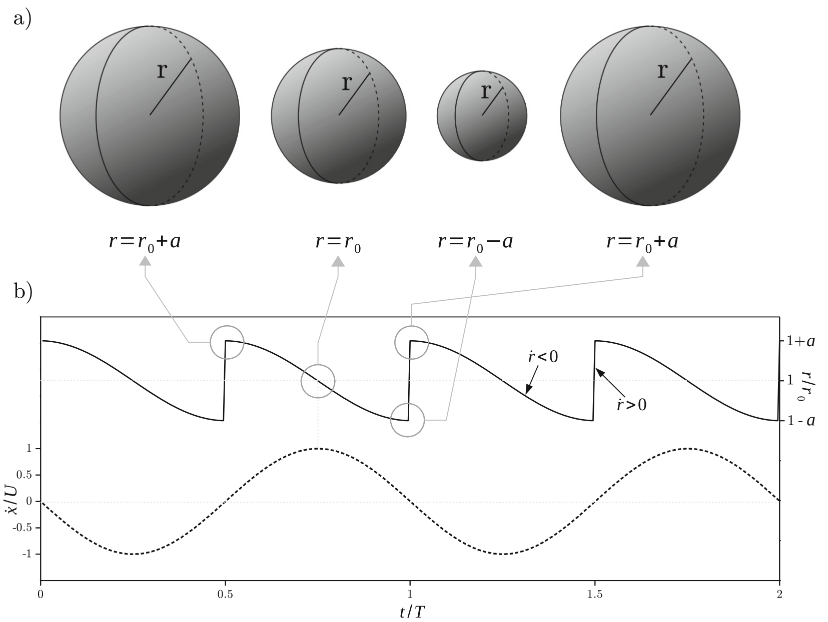

Fig. 2 Evolution in time of the shape-changing oscillator based on the "step" profile of Eq. (8). In **a**, depiction of the oscillator pulsating around the average radius r_0 at four instants during one half oscillation of the mass-spring system. In **b**, the upper part of the plot shows the profile of radius variation of the oscillator based on Eq. (8); the lower part of the plot shows the assumed velocity profile based on Eq. (9), with $U = \omega X$ being a reference velocity. Adapted from [5]

with $a = \frac{1}{4} C_d X$ being the amplitude of the radius variation of the sphere. Then the mass is released and the elastic force of the spring accelerates the sphere. Based on Eq. (8) at $t/T = 0.75$ the sphere reaches the relaxation point of the spring, where potential energy is zero, kinetic energy is maximum and the sphere has shrank to its mean value r_0. The deflation of the body continues until the end of the oscillation, $t/T = 1.0$ and $r = r_0 - a$, when the sphere stops. This is when the jump condition imposed by the absolute value in Eq. (8) forces the sphere to re-inflate abruptly to its original size. Incidentally this is the most efficient time to make the sphere inflate because if it did so during the motion, a negative thrust would be generated, slowing down the oscillation. By suddenly expanding the body when the velocity is zero, the sudden growth of added-mass has no negative impact on the propulsion. In order to verify that this kind of routine enables the oscillator to undergo resonance by annihilating viscous resistance, we perform fully coupled fluid-solid numerical simulations.

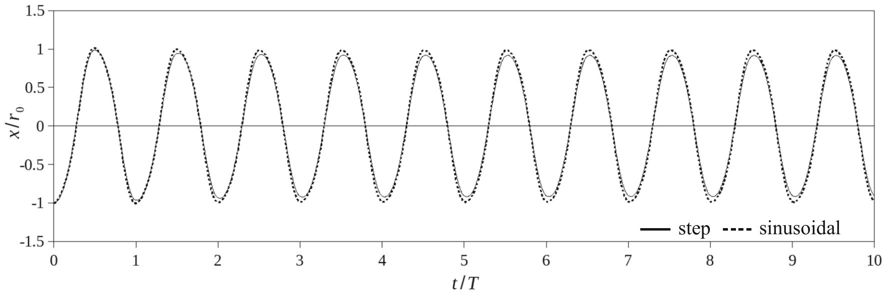

Fig. 3 Amplitude of the oscillations for the "step", Eq. (8), and "sinusoidal" shape-variation profiles obtained from the fully-coupled fluid-structure-interaction simulation. Adapted from [5].

3 Numerical Validation

To test the hypothesis formulated in Sect. 2 we use a three dimensional Navier-Stokes solver especially suited for modelling fluid-solid-interaction case studies [9, 18]. Our test case consists of a sphere in a fluid acted upon by the elastic force of a spring, Fig. 1, and a prescribed routine of pulsation based on Eq. (8) and analogous to that depicted in Fig. 2. The dynamics of the sphere is thus exclusively dependent on the spring elastic forces and the pressure forces generated by the surrounding fluid which reacts to the body displacement and body deformation.

The results, extensively discussed in [5], are briefly reported in Figs. 3 and 4a–e. The results presented in Fig. 3 confirm that the shape change of the body drives the onset of sustained resonance by acting as a propelling term or, more precisely, by cancelling the viscous damping. As opposed to the well known case of a standard weakly damped fixed-shape oscillator, where the oscillations progressively decay with time, in the pulsating case the oscillations persists while maintaining the same amplitude.

Of course, there is not one single profile of radial variation which enables recovery of kinetic energy from added-mass variation. Ideally, any pulsating mode executed at double the frequency of oscillation will drive the onset of resonance. Indeed, analogous results can be achieved by employing a "sinusoidal" radial variation profile, as demonstrated in Figs. 3 and 4f–j.

This is the first evidence of resonance being driven by the variation of added-mass, alone. These results confirm that body shape-changes can trigger an exchange of kinetic energy between the body and the fluid in such a way that it produces a positive feedback on the thrust of the body. In the case of an oscillatory system, this manifests itself in the occurrence of a resonant behaviour, but if we were dealing with a self-propelled vehicle the same phenomenon would appear as an additional source of thrust.

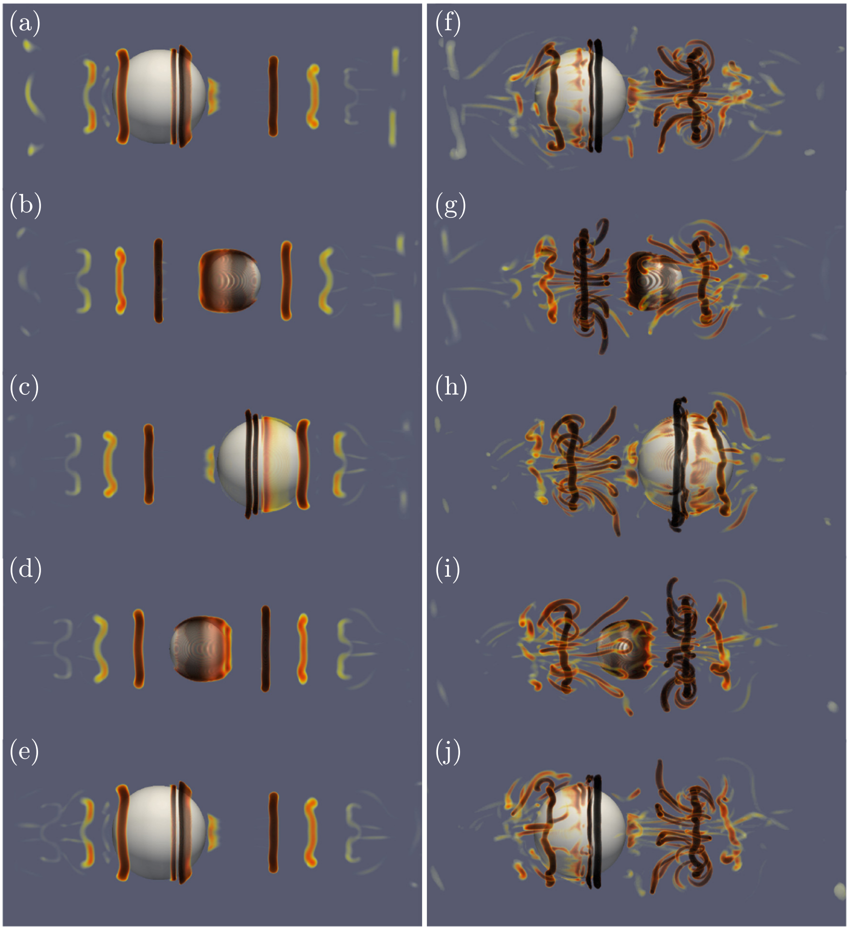

Fig. 4 Evolution of the vortical structures (λ_2 vortex criterion) during one oscillation after attainment of the zero-damping regime in response to the "step" (**a**, **b**, **c**, **d**, **e**) and the "sinusoidal" (**f**, **g**, **h**, **i**, **j**) radius variation profile at $t/T = 0.2$ (**a**, **f**), $t/T = 0.4$ (**b**, **g**), $t/T = 0.6$ (**c**, **h**), $t/T = 0.8$ (**d**, **i**), $t/T = 1.0$ (**e**, **j**). Adapted from [5].

4 Added-Mass Recovery in Self-propelled Vehicles

Evidence of the capability of a shape-changing body to benefit of thrust thanks to the recovery of kinetic energy has been demonstrated in [16]. A vehicle consisting of a rigid neutrally buoyant structure of length $L = 27\,\text{cm}$ and an elastic membrane stretched around it is used as the demonstrator. This vehicle is meant to replicate one pulsation of a cephalopod: the elastic membrane is inflated with water and, once released, the water stored inside the membrane is accelerated across a nozzle of section A_j. This jet of water pushes the vehicle forward as the elastic membrane

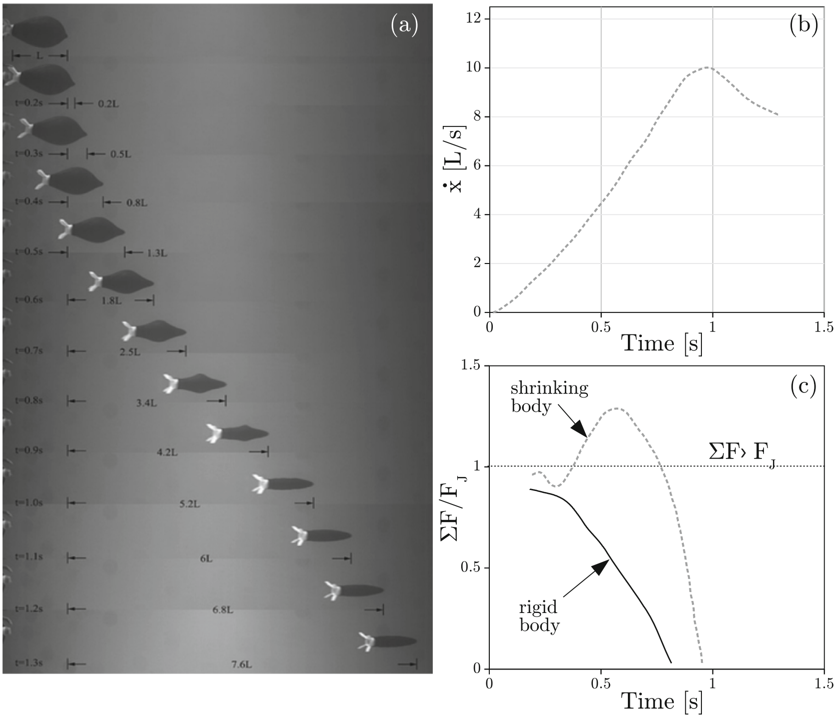

Fig. 5 Experiments performed with a shape-changing self-propelled vehicle; **a** sequential frames of the deflating vehicle, **b** speed of the vehicle as measured by tracking the center of mass of the body and **c** net thrust force non-dimensionalized by the jet force F_j for the shape-changing body (dashed gray line) compared with that experienced by a rigid 5:1 ellipsoid of revolution subject to the same jet thrust F_j. Above the $\Sigma F/F_j = 1$ line the vehicle is subject to added-mass recovery effect and the net force is larger than the jet thrust. Adapted from [16].

deflates. The experiments entail the recording of the displacement of the vehicle along with its shape deformation, Fig. 5a. Edge detection of the frames taken during this single burst of acceleration provides an accurate estimate of the membrane outline and, hence, of the instantaneous volume of the vehicle and its center of mass. From these, the ejected mass and the velocity, $\dot{x}$, of the vehicle, Fig. 5b, can be derived. The mass of the vehicle, with its payload, decreases from its starting value of $m_0 = 3.65$ kg to the point when the membrane comes in contact with the rigid frame; this yields an almost constant rate of mass expulsion of $\dot{m} = 3$ kg s^{-1}. From these quantities, the thrust generated by the jet $F_j = \dot{m}U_j$, with $U_j = \frac{4}{3}\frac{\dot{m}}{\rho_f A_j}$, and the total force $\Sigma F = \dot{m}\ddot{x}$ experienced by the shrinking vehicle are derived. The force ΣF acting over the body can be compared to that experienced by a rigid 5:1 ellipsoid of revolution subject to the same F_j. The comparison is presented in Fig. 5c. The area above the line $\Sigma F/F_j = 1$ defines the dynamics regulated by the added-mass recovery effect according to which the vehicle experiences more thrust than that provided by the jet alone.

From a conservative analysis the shrinking prototype was found to benefit of a 30 % increase in thrust associated with the shape-variation alone, with a 130 % increase in acceleration with respect to the rigid case and a 200 % increase in speed. The peak shown in Fig. 5c for the shrinking body, as opposed to that of the rigid body, can only be attributed to the term $-\dot{m}_a \dot{x}$ which arose in Eq. (3) due to the shape variation of the oscillator. The dynamics observed in the shrinking vehicle can only be justified by accounting for the shape variation effects, thus confirming the role of added-mass recovery as a source of thrust.

5 Conclusion

The purpose of this study is to underline the benefit of controlled shape modification in the frame of the propulsion of deformable aquatic bodies. While it is hard to assess the role of shape change on thrust in actual self-propelled systems, the approach used here permits to segregate the effect of added-mass variation from other sources of thrust and in this way to highlight its role as a propelling force.

We provide a rigorous formulation of the phenomenon associated with shape variation by studying a simple mechanical system consisting of a spring-mass oscillator submerged in quiescent fluid and subject to periodic changes in its volume. The study of this simplified system demonstrates that the kinetic energy associated with the shape variation can completely cancel the viscous damping of the fluid, eventually giving rise to sustained, persistent oscillations. We also present experiments performed on a shape-changing self-propelled vehicle whose peculiar dynamics can only be explained by accounting for the role of added-mass recovery hereby formulated.

The confirmation that a body immersed in a dense fluid which undergoes an abrupt change of its shape experiences a positive feedback on thrust has significant implications in the design and control of soft underwater robots that exploit shape variation as their locomotion strategy.

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Animal Models for Non-pneumatic Soft Robots

Barry Andrew Trimmer

Abstract Soft animals can be seen as "living prototypes" to inspire and inform the development of soft robots. However, soft animals are extremely diverse in their biomechanics and neural control systems. These differences should be carefully considered when selecting a biological model to guide robot design. It is also important to consider the technical advantages and limitations that affect the type of information that can be collected from different species. Aside from swimming robots, most soft robots and soft manipulator arms are inspired by annelids and cephalopod mollusks. Both groups are essentially fixed-volume hydrostats that exploit pressure differences to change shape and to gain mechanical advantage. Some robots inspired by these animals mimic their underlying mechanisms (and anatomy), whereas others produce similar movements using entirely different principles. By far the most numerous and diverse group of soft animals are larvae of the holometabolous insects. Because they contain internal air tubes, insect larvae control movements using direct actuation instead of pressure control alone. Insects also have highly stereotypical and modular anatomy and easily accessible neural coding making them excellent prototypes for non-pneumatic robot design. By mapping key features of caterpillar locomotion onto robot design a new class of robots has been fabricated from simple elastomers powered by shape memory actuators and motor-tendons. These robots have proved useful for exploring different control strategies and have the capacity to move quickly. Robots based on these design principles are expected to be useful for climbing in complex 3 dimensional structures and in low gravity environments.

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1 Animal Models for Better Robots

In the quest to make robots function in more diverse environments, many engineers have turned to studies of animal locomotion for inspiration and guidance. However, most studies of animal biomechanics have focused on organisms that have stiff, articulated skeletons such as adult insects, birds and mammals. These animals are attractive prototypes because their basic movements often can be described using simple models composed of springs, dampers and connected rods. This has led to an emphasis on the skeleton itself, largely ignoring the roles of other tissues and structures.

It is becoming increasingly clear that soft structures play an important role in producing the robust and adaptable movements that characterize animal behavior. This realization has led to increasing efforts to incorporate soft materials into robots. In trying to address the challenges of design, fabrication, and control of these robots, some researchers are attempting to build machines that are completely deformable. They have taken inspiration from a variety of soft animals but there has been relatively little attention paid to the distinctions between these different animal groups. In this chapter I will briefly summarize the major groups of soft animals and some of the robots inspired by them. I will then describe in more detail the specializations of lepidopteran larvae (caterpillars) that make them an attractive model system for the design and control of soft climbing robots.

2 Soft Animals as Model Systems

Most animal species are completely soft, or soft for a large proportion of their lifecycle. Of the more than 1 million animal species currently described [1], at least 88,000 (cephalopod mollusks, annelids, nematods, cnideria/ctenophora and platyhelminthes) generally have no stiff skeleton and over 600,000 species (the holometabolous insects) have soft larval stages. The biomechanics of locomotion in these soft animals has only been studied in a relatively small number of species and even fewer have been used as models for robot locomotion. Some of the more novel examples include jellyfish (cnideria/ctenophore) which swim slowly but can rise and descend in a column of water by controlling the way they contract their delicate bell of muscles. This has been replicated in robots with similar structures but the membranes are generally supported on a lightweight articulated frame.

Aside from these aquatic examples, the majority of soft robots have been modeled on annelids (worms) and cephalopod mollusks such as squid and octopus. Both of these major groups are hydrostats; their bodies and limbs are fixed-volume, deformable, cylindrical structures. The internal compartment of worms is largely fluid whereas the arms of cephalopods are predominantly muscular.

Worms as robot prototypes. Annelids (and nematodes) are an attractive biomechanical system because their movements are controlled by regulating the tension in longitudinal and circular muscles. Contraction of the longitudinal muscles shortens the body and increases the radius proportionately. This movement can be antagonized by contracting circular muscles to reduce body radius and increase length. This relatively simple mechanical concept has been exploited in several wormlike robots. A common feature of these devices is a wave of segment contraction from the front (head) to the back of the robot and some sort of differential friction device to promote forward crawling. Many of these modes of locomotion have been modeled mathematically.

Cephalopods as robot prototypes. The arms of the octopus (and elephant trunks) have been inspirational for developing soft manipulator arms [2, 3]. Arm musculature is complicated but in general movements are controlled in a similar way to annelid locomotion. By adjusting the local stiffness through circular and oblique muscle contraction, the arms can be bent into many configurations and the arm can assume different configurations simply by interacting with the surrounding fluid.

Worms and octopus have inspired a variety of robots using similar principles but with quite different body structures. For example, many robots have been constructed with internal body cavities that can be inflated and used as actuators [4]. Using clever combinations of materials and structural stiffness, devices have been designed with directional bending and the ability to inflate in complex shapes such as spirals. Although these pneumatic robots and manipulator arms do not directly mimic any known animals (with a few exceptions, animals do not inflate and deflate to locomote) similar structures are seen in nature, with the duck penis being a notable example. An attractive feature of pneumatic actuators is their ability to sustain very large forces and to produce large displacements [5]. However there are challenges to making pneumatic robots predominantly soft (an untethered device must carry its own compressed gas or pumps) and larger devices require volumes of gas or fluid that move too slowly for many applications.

Flatworms as robot prototypes. Although they are included here for completeness almost nothing is known about the biomechanics of platyhelminth (flatworm) movements. They possess dorsal and ventral muscle bands and are probably hydrostatic in the sense that their tissues can be displaced in all directions but they do not change in total volume in the normal time course of locomotion. Larger species propel themselves through water using waves of contraction of these body muscles but smaller species propel themselves using a ciliated ventral surface.

The remaining group of soft animals, holometabolous insects, constitute the largest number of animal species known. During their larval stages these animals have many features that distinguish them from those already described. In the following Section I will discuss the properties that make insect larvae, particularly caterpillars, useful and interesting model species for understanding soft body locomotion.

3 Insect Larvae as Living Prototypes for Soft Robots

As befitting their diversity, the larval stages of holometabolous insects vary tremendously in ecology and means of locomotion. The larvae of hymenoptera (bees, wasps and ants) in a collective hive can be legless and relatively immobile or in free-living parasitic forms can be highly mobile, digging into the tissues of their host. Dipteran (fly) larvae such as mosquitoes have an entirely aquatic larval phase with a unique wriggling method of swimming, but most fly larvae ("maggots") have rudimentary appendages and move by burrowing through their food. Together with annelids, these legless insect larvae are good subjects for identifying how to move within a supportive substrate.

The remaining major groups of holometabolous insects are the lepidoptera, (butterflies and moths) and coleoptera (beetles) that together are the most numerous species of animals. Depending on their ecological niche, the larvae of beetles and butterflies can be remarkably similar. The majority of beetle larvae have three pairs of thoracic legs but lack any locomotory appendages on the abdomen. Most of these larvae are found burrowing inside plants or underground. Although some lepidoptera larvae also live within leaves and have reduced or absent appendages, most are highly mobile climbing animals called caterpillars.

Caterpillars as robot prototypes. Because they are such ubiquitous and successful climbing animals, caterpillars are an attractive model system for understanding softbodied locomotion [6]. Through detailed studies on the 3-D kinematics of motion, by measuring ground reaction forces on each of their appendages, and through x-ray video imaging of internal tissues, it is now possible to describe caterpillar locomotion in detail. Furthermore, the material properties of the body wall and muscles have been characterized and modeled and the internal pressure changes associated with movements have been monitored. Finally, caterpillars provide a unique opportunity to understand how the central nervous system interacts with biomechanics to control softbodied movements. This is because each muscle is innervated by a single motoneuron. Therefore, by implanting electrodes alongside the muscles it is possible to record the pattern of neuronal spike activity associated with particular movements. Across multiple muscles, this neuronal spike activity constitutes the entire efferent information used to control movements.

The results of these studies can be summarized as a series of "traits" of caterpillar locomotion [7] that can be mapped onto desirable features for a soft robot that can perform similar tasks (Fig. 1). The primary traits are:

1. Caterpillars are hydraulic rather than hydrostatic. Although they have an open body plan and can alter their overall stiffness by pressurization, hydrostatic pressure does not seem to play a major role in the control their movements. This is probably because insect tissues are filled with tubes (trachea) for gaseous exchange making the internal volume variable and compressible.

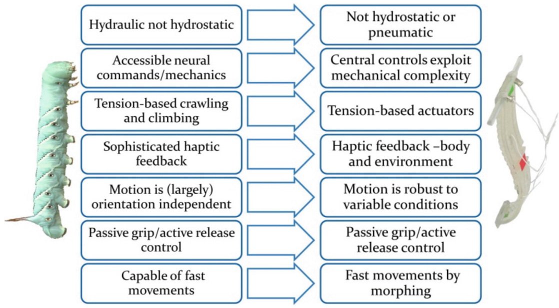

Fig. 1 Mapping caterpillar traits onto features for soft robot design

2. Most neural codes appear to be relatively imprecise; the input to each muscle can vary from moment to moment even during similar movements. This suggests that biomechanical responses are relatively robust and perhaps act as "mechanical computers" to interpret descending activity appropriately.
3. Crawling caterpillars maintain their body in tension for much of the step cycle. Forward movement is achieved by a combination of elastic recoil and active muscle contraction. This allows them to apply compressive forces to the substrate and to keep their body relatively soft and compliant. We have called this strategy the "environmental skeleton."
4. Because they lack long-range sensing, locomotion relies on feedback from mechanosensors. Caterpillars have sophisticated peripheral touch and proprioceptive organs that are accessible for studying the encoding of haptic information.
5. Although they can change their stepping pattern in response to substrate quality and orientation, caterpillars can crawl and climb using the same kinematics. This makes them useful models for robots moving in reduced gravity environments such as space or underwater applications.
6. The success of caterpillars in scansorial environments is largely attributable to their impressive grip. The abdominal prolegs passively attach to substrates and actively release their grip. This appears to be a self-compensating system controlled by a single neuron for each proleg.
7. Although most terrestrial soft animals are slow-moving, caterpillars can exploit shape-change to produce fast movements. They can quickly roll into a circular shape and propel themselves ballistically. This remarkable trait has been replicated in a soft caterpillar-like robot.

4 The Design and Control of Caterpillar-Like Robots (*Softworms*)

With these caterpillar traits in mind we have designed, fabricated and tested, a wide variety of caterpillar-like robots called Softworms [8]. These designs can be 3D printed as molds into which different soft polymers can be cast or printed directly using a multi-material 3-D printer. Direct printing produces robot bodies of any complexity without increasing fabrication difficulty. The body is composed of a soft elastic polymer and stiffer materials can be printed in the same build for motor housings and other components. Most of these devices are tethered so that electrical power and control can be delivered from remote equipment. We have also built an untethered Softworm carrying batteries and a radio receiver. Most of the robots are elongated structures but we have also constructed devices with three, four and six limbs to test hypotheses about the scalability of control structures.

Although it is possible to add actively controlled gripping systems to these robots, we have instead followed the design principles derived from caterpillars and minimized the number of actuators controlling behavior. Softworm grip is achieved by feet each end of the body made of TangoPlus®, a soft and sticky material. When the body bends it changes the substrate contact angle and, beyond a certain threshold, transfers contact to a smooth slippery material allowing the foot to slide. This principle has also been exploited in multi-limbed Softworms and is a key design element for some control systems.

Shape-memory alloy actuated Softworms. For research purposes, the smaller Softworm robots are actuated by shape-memory alloy (SMA) coils attached at specific locations within the body. Passing current through these coils causes resistive heating and contraction strains as much as 100 %. As the SMA cools it is restored to its resting length through elastic recoil or by activating a nearby SMA. This type of actuation resembles muscle in that active force can only be generated in tension and the restorative force comes from other actuators or from stored elastic energy. Different actuators can be placed in the body for steering and 3 dimensional bending [9].

A primary motivation for developing the Softworms is to explore strategies for controlling locomotion in deformable machines. We have explored two approaches that are only briefly summarized here and explained in more detail in several publications [8, 10, 11]. Both methods avoid modeling the physics of the body or its interaction with the environment. The first method is based on autonomous decentralized control. Movements are generated by the interaction of oscillators and feedback adjusts the phase of these interactions. This feedback can be from sensors that monitor tension or a mechanical response through interactions with the environment. The second control approach is based on control primitives in which movements are discretized into simple states (*e.g.*, high or low friction). A series of transitions between these states defines locomotion gaits and the effectiveness of these transitions can be learnt. The system can be described using map based methodologies and by optimizing periodic control sequences. We have shown that different caterpillar gaits such as crawling and inching can be mathematically defined using this approach. One advantage of this model-free method is that multi-limbed robots can still be controlled when one of their limbs is disabled. The large map of possible nodes and transitions of a multi-limbed robot reduces to a much smaller set of effective simple cycles. It remains to be seen how well the method applies to very complex multi-limbed robots or movements in other contexts.

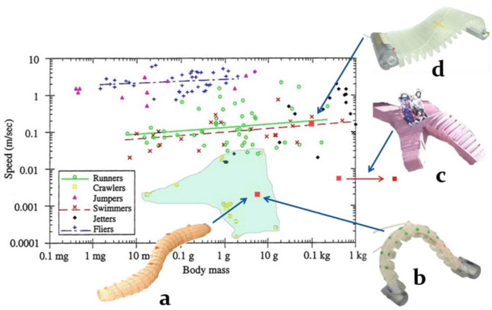

Fig. 2 Soft robots are typically very slow for their size. Most devices (*e.g.*, **a** and **b**) perform similarly to crawling and burrowing animals shown in the *shaded area*. Current pneumatic robots (*e.g.*, **c**) can be made impressively large but they are not faster. The motor-tendon drive robot, M-Bot (**d**), moves ten times faster and is comparable to running and swimming animals of similar size. Adapted from [13], **a** from [14], **c** from [5] and **b** and **d** from [8]

Motor-tendon actuated Softworms. Although the SMA-actuated robots are simple and effective research devices, they are too inefficient, underpowered and slow for most practical applications. As an alternative, we have built Softworms powered by electric motors pulling on tendons [12]. To maintain the flexible and conformable advantages of soft robots the heavy and stiff motors are housed separately from the deformable parts of the robot. A key design aspect of these robots is defining the location and path of tendons. We have shown that the effects of different configurations can be modeled using relatively simple methods and that tendons can be placed to optimize translation or rotation of the robot. We have also demonstrated that these robots can crawl very quickly compared to soft robots powered by other mechanisms. For example, M-Bot, a simple block-like Softworm powered by two rotary motors and employing the simple friction switching mechanism already described, can crawl at half a body length per second (about 10 cm/s). This is an order of magnitude faster than most other flexible crawling robots using SMAs, servos or pneumatic actuators. It is also gratifying to see that this velocity exceeds that of most crawling animals and is comparable to the speed of running or swimming animals when scaled for body size (Fig. 2).

5 Concluding Remarks and the Future

Although the design, fabrication and control of entirely soft robots are relatively new fields, there have been many dramatic advances. The recent Grand Challenge in Soft Robotics competition (sponsored by the RoboSoft Consortium) was an opportunity to see the variety of early-stage conformable machines. Most of these machines are still relatively slow and difficult to control but soft materials are finding their way into hybrid robots that combine the advantages of traditional robot

Fig. 3 The Softworm motor-tendon technology has been applied to power a large (60 cm) robot constructed from plastic foam. A living caterpillar is shown in **a** together with motor housings and the body. **b** shows the robot lifting its "head" and **c** and **d** show stages of a single "step" during the RoboSoft Grand Challenge Competition. Photos curtesy of the Tufts RoboSoft Team

components with the morphability and robustness of deformable structures. From our own research we have been able to demonstrate that caterpillar-like structures, combined with motor-tendon actuators, can be made quite large (60 cm long or larger) and are capable of crawling and navigating through obstacles. These robots can be fabricated from a huge variety of materials including elastomers and compressible foams (Fig. 3).

Although there are still enormous challenges to address, we can now foresee the development of useful and deployable devices. It is important that soft robots are developed for applications that make use of their unique combination of capabilities. Robots based on borrowing animals such as worms and some insect larvae can expand our ability to explore underground and to search for survivors in the debris of an emergency situation. Similarly, robots based on the remarkable climbing ability of caterpillars will help in exploring complex three-dimensional environments such as forest canopies, agricultural applications and electrical wiring. They will also be extremely useful in low gravity situations.

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Plant-Inspired Growing Robots

Barbara Mazzolai

Abstract Plants have conquered almost all surfaces on our planet; they were the first settlers in hostile environments, making way for habitats that could then be settled by nearly all living beings. Plants, as sessile organisms, spend their entire lives at the site of their seed germination. Consequently, they require a suite of strategies to survive extremely diverse environmental conditions and stresses. Some may think that plants do not actually move unless they grow; however, this is incorrect. Plants move a great deal, although they typically move in a different time frame than animals. Plants are able to move their organs, often in response to stimuli, and they have developed a variety of motion systems, primarily as a result of water absorption and transport. Despite their exceptional evolutionary and ecological success, plants have rarely been a source of inspiration for robotics and artificial intelligence, likely due to misconceptions of their capabilities and because of their radically different operational principles compared with other living organisms. This chapter will describe several plant features that can be translated to technological solutions and, thus, open up new horizons in engineering by offering inspiration for developing novel principles to create growing, adaptable robots and smart-actuation systems.

1 Biological Principles

One of the fundamental characteristics of plants is the correlation between growth and movement. The growth process is mostly associated with development in animals, although growth can occur for both development and movement in plants. Movements in plants can be classified on the basis of reversibility or irreversibility; of their active (presence of a metabolism) or passive (primarily based on already dead tissues) nature [3]; of their independency from (nastic response) or influence

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by (tropic response or tropism) the spatial direction of stimulus; or of the different timescales of water transport in the cellulosic wall [5].

Tropisms play a crucial role in plant fitness because they allow plants to use limited resources and avoid unfavourable growing conditions. In tropic responses, the direction of stimulation is extremely important and can either be positive (i.e., towards the stimulus) or negative (i.e., away from the stimulus; [6]). There is a wide range of tropisms in plants, including phototropism (light), gravitropism (gravity), thigmotropism (touch), thermotropism (temperature), chemotropism (chemicals) and hydrotropism (water/humidity gradient).

Behaviour in plant roots. To fulfil its primary needs and survive, an organism must exhibit adequate behaviour with respect to the environment. This behaviour is the result of the interaction between an organism and its environment. To understand the behaviour, specific attention should be paid to morphological properties: interaction is primarily guided by the morphological characteristics that define a certain range of movements and the ability to explore the environment. Morphological adaptation, also empowering morphological computation [9], plays a primary role in plant fitness, in particular, the (i) modularity and redundancy of structural and functional units, (ii) shape alteration in the root tip, (iii) rich and distributed sensing, which are the basis of high-performance exploration, and (iv) dynamic interaction between root morphology, sensory-motor control, and environment.

The root system architecture of plants varies substantially between species and also shows extensive natural variation within species. As a consequence, the extension in space and time of the root system is governed by genetically driven developmental rules, which are modulated by environmental conditions. As a result, genetically identical plants can have extremely different root architectures. A general plant root system consists of a primary root, lateral roots, adventitious roots and root hairs. Plant roots perform multifaceted roles, of which two functions are foremost: (i) firmly anchor the plant into the soil, and (ii) supply water and nutrients to the aerial parts of the plant.

Living roots are capable of penetrating a variety of soils, including rocks and dense ground, because of their peculiar growth strategy: roots penetrate the soil by elongating the meristematic area (the region situated a few mm behind the tip) by cell mitosis and cell expansion [2]. In this way, plants avoid generating high pressures associated with high-energy consumption, which would be necessary for a penetration system operating from the surface, and prevent damage due to friction processes, which would occur during advancement. The cell expansion in the elongation region produces an axial pressure, which is dissipated when the soil cavity expands and from the frictional resistance of the soil during the root advancement.

Another important characteristic of the plant root growth is the reduction in the soil-root friction by producing mucus and releasing cells from the tip. In addition, plant roots grow by extending hairs into existing pore spaces into the soil and moving soil particles aside in the radial direction, increasing the anchoring capabilities of the root to the soil.

Actuation in plants. The most familiar *biological actuator* is the muscle. Muscle movement results from an arrangement of micro-metric contractile filaments. However, muscles are not the only actuators in nature. Plants perform a variety of movements despite lacking muscles. The lack of muscles has led plants to exploit alternative strategies to perform movements essential for their survival. Plant cells are surrounded by a thin, stiff cell wall made of cellulose microfibrils embedded in a pectin matrix. This stiffness is the basis of the capability of plant cells to sustain a large, internal hydrostatic pressure, known as turgor. This pressure originates from an osmotic gradient between the cell cytoplasm and environment [5]. Osmosis plays an unquestionable, key role in plant actuation systems. In particular, cell turgor is generally responsible for slow, small-scale movements. In fast, large-scale movements, osmosis acts more as a "trigger" of a cascade sequence of elastic instability movements of smart, natural engineered structures. An analysis of these mechanisms reveals that the engineering of soft, non-muscular, hydraulically actuated systems for rapid movement requires either a small size or enhanced motion on large scales via elastic instabilities [15]. Thus, the elastic release of energy acts as a "speed-booster". A few examples of these fast and slow movements include the rapid ($\sim$100 ms) closure of *Dionaea muscipula* (Venus flytrap), partly actuated by an abrupt decrease in internal tissue pressure [3]; leaves that close by touch stimuli in *Mimosa pudica*, which occurs within 20 ms from when they are touched [11]; the impressive pollination mechanism of Stylidium, in which Gynostemium flips rapidly ($\sim$25 ms) to hit and pollinate insects [7]; and the remarkable 4.5-MPa actuation pressure exhibited by stomatal guard cells during the closing phase, whose objective is to prevent water loss [7].

An improved understanding of these movements will push developments forward, both in applied sciences and engineering and, in particular, in creating novel biomimetic actuation strategies characterised by high-energy efficiency and low power consumption [3, 11].

1.1 Bioinspired Systems

Robotic solutions inspired by plant roots. The development of robotic artefacts capable of moving autonomously and efficiently exploring an environment in a non-destructive way, as plant roots do, poses new and bold challenges in robotics and materials research. The mechanical properties of plant roots and the morphology of their structure have been considered in developing the first artificial plant-inspired robotic systems. As a first attempt, we developed a robotic system inspired by low-friction penetration strategies in plant roots. Cell growth at the root tip deforms soil, while sloughing cells in the cap create an interface between the root and soil to reduce root-soil friction during penetration. A simple prototype, inspired by these root features, is based on a tubular shaft and a soft continuum skin [12]. The skin slides from the inner to the external part of the shaft. This outward movement of the skin opens soil in front of the tip and penetrates it. The skin embeds soft hairs at its surface that provide the prototype with self-anchorage capabilities. The performance of this robotic system was characterised during penetration in granular soils. The skin-soil interaction was fundamental for (1) displacing the soil in front of the tip and (2) preventing backward movements of the robot by anchoring the posterior body to the soil. An increased hair density (0.012 hairs/mm^2) resulted in a higher penetration depth of the robot (approximately 30 %).

Taking inspiration from the root-growth ability at the apical region, we developed a device that grows at its apical area by addition of new material [13], which represents a totally new approach in robotics, embodying *artificial growth*. The system embeds a *growing zone*, which is based on an additive layering mechanism that generates a force for penetration in soil by transferring a filament (made in Polypropylene-PP) from an external system (i.e. a spool) to the tip (see Fig. 1). The prototype was tested at different depths and penetration conditions (Elongation from the tip-EFT and No-EFT penetrations). The results of the experimental trials demonstrated that, for all the initial depths tested, the energy required for penetration was lower with EFT than with No-EFT, with a reduction in energy consumption with EFT ranged from 45 % at 100 mm depth to 70 % at 200 mm depth (see [13]).

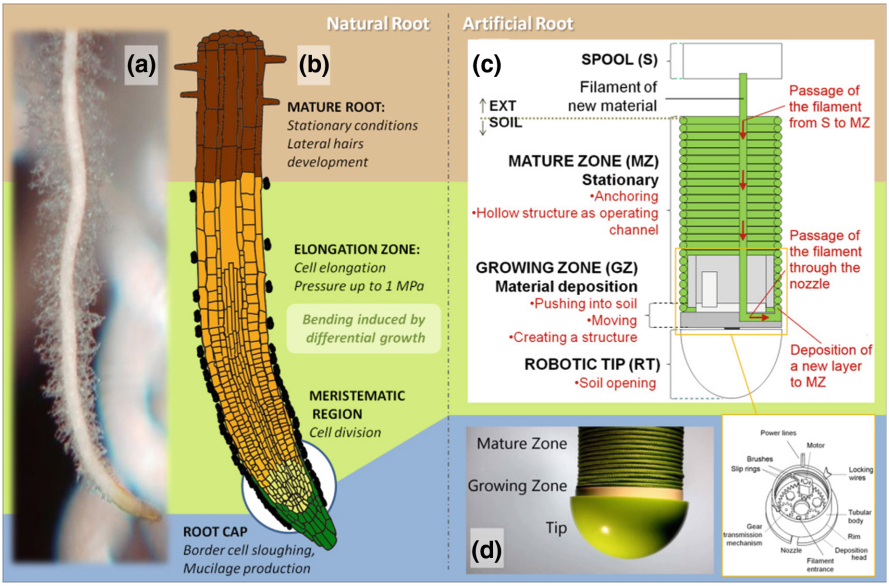

Fig. 1 An overview of a *Zea mays* root and the artificial root-like growing robot. **a** An apex of a *Zea mays* root. **b** A schematic view of a root: growing from the tip (cells sloughing); bending by differential elongation and growing; root anchorage by lateral hairs. **c** Prototype of an artificial root with growing capabilities. The sketch shows the mechanisms inside the robot that allow the growing at the tip level (also visible in the zoomed scheme): a rotating deposition head; a guiding nozzle on the deposition head; a motor and a transmission mechanism (i.e., a gearset). **d** A picture of the growing device showing the tip, the growing and mature zones

From these initial achievements the basic principles learned from the natural root behavior is validated and, by adding flexibility, the system can be designed to change the direction and navigate around the obstacles [14].

Plant-inspired actuators. Actuation represents a bottleneck in many current engineering applications, including bio-robotics. The available actuators are primarily electromagnetic, and their performance is far from that achieved by natural actuators. The main limitations involve inertia and back-drivability, stiffness control, and power consumption. Nevertheless, new and promising technologies are emerging taking inspiration from living organisms, which offer new possibilities to fill the gap between natural and artificial solutions. Among these biological models, several plant features, such as hydraulic movements (driven by osmotic or humidity gradients) and the material properties and geometry of the cell wall, have already been proposed as innovative solutions to create new actuators characterised by remarkable energy efficiency and high-actuation force [15]. Starting from modelling a new concept of an osmotic actuator based on an adequate understanding of plant osmotic-driven actuation strategies [15], we designed, developed and tested a plant-inspired actuator based on forward osmosis [16]. The obtained results show that our actuator exhibits a very low power consumption (below 1 mW), short characteristic times (approximately 2–4 min), and remarkable actuation forces (above 20 N). The remarkable merits of the proposed osmotic actuator (including its energy density and thermodynamic efficiency, which are superior to those of many existing low-power actuation technologies) suggest that it might be effectively used in bioinspired robotics and in other applicative fields, as in drug release. We also showed, using our plant cell-inspired device, that osmolyte complexes, rather than single osmolytes, permit to obtain higher turgor required by plant movements. We provided quantitative cues for a deeper investigation of osmolyte transport for plant movement, and reveal the possibility of developing osmotic actuators that exploit a dynamically varying concentration of osmolytes [1].

The observation and investigation of plant movements has revealed a plethora of physical and mechanical principles that are extremely interesting for creating smart actuators. The imitation of the hierarchical structure of the cellulose layer in cell walls allowed us to implement movements that are primarily driven by changes in environmental conditions and, thus, do not require further control and energy supply [17]. This mechanism is based on reversible adsorption and desorption of environmental humidity. It combines the possibility to achieve active and passive actuation with a single composite material, i.e. poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT:PSS), which is a well-known conjugated conducting polymer that exhibits a unique water absorption capability (due to the hydrophilic PSS). Actuation can be obtained by coupling an ultra-thin film of PEDOT:PSS (a thickness of several hundreds of nm) with a passive thick elastomeric layer (i.e., poly-dimethylsiloxane-PDMS, which acts as a structural material) in a bilayered fashion. If the humidity in the ambient air increases, then the PEDOT:PSS layer adsorbs water vapour and increases in volume, which results in bending of the structure due to the constraints of the passive layer [17].

2 Conclusive Remarks

The study of plant features can lead to the development of new soft plant-inspired robots that are able to grow by adding new materials while they search for specific targets. These robots require the development of new actuation solutions for steering and elongation of the robotic root, soft sensing, control and robotic architectures (distributed control, coordination of many degrees-of-freedom), and kinematics models. Interestingly, concerning the plant root behaviour, it seems that root apices, which includes sensing mechanisms, act as decision-making centres, which is supported by the observation that the growth pattern of the root system (e.g., root swarming or proliferation in favourable patches) is not random and is actually coordinated and efficiently shaped to exploit soil resources and to avoid hazards [4]. Within this perspective, a group of apices in a given plant could be considered as a "colony" whose individual elements work for the benefit of the colony, akin to colonies of social insects. Similar to a flock of birds, it has been demonstrated that roots can be influenced by their neighbours and can align their growth directions [4]. The occurrence of this swarming behaviour may be an advantage for exploratory purposes. Thus, because plant roots address multiple mechanical, sensory, and communication constraints as they grow and react to the environment, future directions in science and engineering will be in the development of novel, bio-inspired methods of sensor fusion and collective decision-making in decentralised structures with local computation, simple communication, and a high-level of control of a new generation of growing, soft robots inspired by plant roots.

Applications for technologies inspired by plants include soil monitoring, penetration and exploration in on-earth and extra-terrestrial environments and could also include medical and surgical applications. For example, new flexible endoscopes, able to steer and grow, could be envisioned for safer operations on delicate structures, such as the central nervous system.

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Bio-inspired Soft Aerial Robots: Adaptive Morphology for High-Performance Flight

Sina Sareh, Robert Siddall, Talib Alhinai and Mirko Kovac

Abstract The application of soft architectures in robotics offers the potential to reduce control complexity while increasing versatility, performance and robustness of robot operation. However, current aerial robots tend to have rigid body structures, and rely predominantly on abundant sensing and dynamic closed loop control to fly. In contrast, flying animals combine sensing and control with adaptive body designs, exploiting fluid dynamic and biomechanical effects to achieve very high levels of operational robustness and multiple functionalities. This paper provides an overview of several examples in which softness is used in aerial robotics, outlining instances where inspiration from biology can be taken to develop next generation aerial robots which selectively use soft materials and adaptive morphologies to achieve high-performance flight behaviours. For illustration we describe three case studies where soft structures have been used in aerial robots: (1) to enable multi-modal mobility across terrain interfaces and fluid boundaries, (2) for robust perching in complex environments and (3) to repair and manufacture infrastructure components. These examples show the benefits that can be gained through the application of soft technologies and they outline how the bio-inspired approaches can be used to develop the next generation of flying robots.

1 Soft Structures in Nature

Biological systems have high degrees of controlled flexibility in their bodies which enhances their mobility and makes them highly adaptable to the environment [1–3]. For example, the wings of many birds are adapted to morph into a wide range of configurations, from extended and rigid planforms for gliding flight to highly morphed shapes during flapping and dynamic flight manoeuvres (Fig. 1a, b). This adaptive morphology of the wings can improve the animal's energy consumption,

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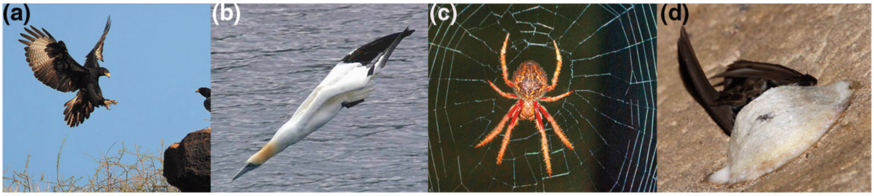

Fig. 1 Soft structures in nature: **a** Perching manoeuvre of a Verreaux's Eagle, during which the bird morphs its wings and uses its feathers as passively adapting aerodynamic structures to enable a robust deep stall manoeuvre; **b** diving gannet (*Morus bassanus*) folding its wings to dive into water; **c** an orb-weaver spider (*Eriophora transmarina*) creating an aerial web using soft tensile structures; **d** a nest created by a swiftlet (*Aerodramus fuciphagus*), using its saliva as both a structural material and adhesive. Images used under a Creative Commons license from **a** Steve Garvie, **b** Mike Pennington, **c** Adam Inglis and **d** Marcel Holyoak

wind resistance, increases the range of speeds at which they can fly, and improves their robustness to aerodynamic disturbances [4–6]. It is not only the active change of morphology of the wing that contributes to increased performance. For example, it has been shown that wing elasticity in bats allows for robust flight through highly cluttered environments, such as the caves and forests which they inhabit [6].

The flexibility of wings in insects and birds has demonstrated importance in enabling high performance flight. For example, the deformability of insect wings during flapping flight helps to keep leading edge vortices stably attached to the insect's wing even at high angles of attack, enhancing force generation and allowing the animal to hover or manoeuvre [4]. In birds, e.g. the steppe eagle (*Aquila nipalensis)* wings are adapted to reconfigure their various shapes, allowing a broad range of flight modes, from efficient soaring, to dynamic deep stall manoeuvres. The feathers of the bird's wing also contain integrated aeroelastic elements to maintain control authority in different flight regimes [5], as shown in Fig. 1a.

Adaptive body morphologies are also key for multi-modal mobility. Many animals have evolved secondary modes of locomotion, even across multiple fluid media, which allows movement through varied terrain, escape from predators or increased access to prey. A recurring example of multimodality in nature is jump-gliding, a behaviour exhibited by many animals including several species of arboreal lizards, squirrels and primates, flying fish, and jumping insects [7]. These animals almost universally rely on soft deployable structures for flight, which are normally retracted when not airborne so as not to impair mobility, and to protect fragile lifting surfaces. Another example of multi-modal mobility are birds that are capable of propelled flight and also underwater diving. They adapt their morphology when entering the water from air allowing it to move effectively and robustly in the denser, more viscous fluid. A notable example is the common guillemot *Uria aalge,* a seabird which utilizes the same fundamental flapping mechanism in both air and water, morphing its wings to deal with changing force generation in water and air [8]. Other aquatic birds, in particular the members of the

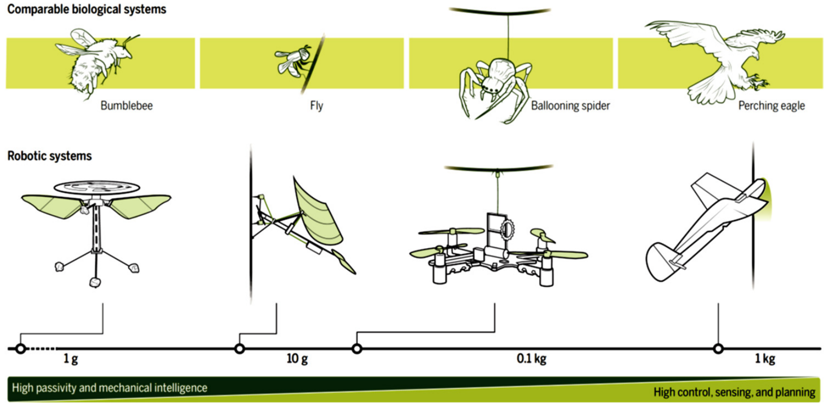

Fig. 2 Perching strategies in flying animals change as size increases: For smaller flying bodies, both in nature and robotics, perching exploits the mechanical intelligence of the body morphology; larger systems rely on more complex control, sensing, and planning. The top panel illustrates different perching approaches in nature: Bumblebee Bombus ruderatus; housefly Musca domestica; ballooning spider genus Stegodyphus; and Verreaux's eagle (Aquila verreauxii). In the bottom panel, examples of perching of aerial robots are shown, with robot masses indicated on a logarithmic scale: The Perching Robobee of Graule et al.; the École Polytechnique Fédérale de Lausanne Perching Microglider; the Imperial College String-Based Percher; and the Stanford Univ. Scansorial Unmanned Aerial Vehicle Figure reproduced from [11].

Sulidae family, dive directly into the water at high speeds (Fig. 1b), using flight momentum to reach depth. These birds are able to collapse their wings into a highly slender, streamlined shape to mitigate the large impact forces, and use soft air filled structures in their face and neck for protection during impact [9]. The efficacy of aerial-aquatic locomotion is not restricted to escape or prey capture; recent studies suggest that jump-gliding locomotion between air and water may be an energy saving strategy for pelagic flying squid [9, 10], which glide on wings formed by the arrangement of soft tentacles normally used for predation into an aerodynamic planform. The breadth of these multimodal behaviours is a fertile resource for the inspiration of new solutions expanding robot locomotion, increasing accessibility, endurance and performance.

Soft structures are also employed for the transition to solid surfaces from flight, both through aeroelastic mechanisms to maintain control during low speed flight (Fig. 1a) and through elastic mechanical elements which ensure robust attachment [11–13]. Many birds stall completely at the moment of attachment to a perch, and exploit an arrangement of tendons in their claws to ensure attachment to the perch whilst arresting the motion of the body [11]. At a much smaller scale, common houseflies are able to land without reducing their flight speed, instead relying on soft, compliant legs to passively damp the impact [13], which reduces the need for complex sensing and control to reliably attach to a perch (Fig. 2).

Table 1 The three prominent soft technologies for high performance mobility and manipulation in nature

Mechanism	Examples in nature	Engineering systems
Multi-modal mobility	Aerial-aquatic mobility in flying fish and squid, jumpgliding squirrels etc.	AquaMAV [34–36], Multi-MoBat [52], EPFL jumpglider [53]
Attachment	Perching onto elevated structures by birds to save energy or stand against wind and storm	NAV percher [37], RoboBee [54], SCAMP [55]
Creating support structure	Nesting by birds to lay and incubate their eggs, webbing by spider to enable aerial mobility	NAV constructor [37], 3D printing UAV [39]

Operating at a similar scale, spiders are able to create soft and flexible structures to enable both perching and aerial mobility [14–16]. By trailing fine 'gossamer' threads of silk small spiders are able to generate sufficient forces for flight allowing the animal to move large distances rapidly, a behaviour termed 'ballooning' [14]. The same silk spinning process is then used for construction of a perch for prey capture and protection (Fig. 1c). These silk webs are perhaps the most famous natural soft structure, and are used for a broad array of purposes by the many arachnid species, employing spider silks of varying strength and elasticity, with some spiders able to produce up to 8 distinct materials, including adhesives [17]. The ability of spiders to build variegated softness into their structures means that webs can resist damage during use, cope with mobile attachment points (such as tree branches), and be built in many locations.

Versatility is an essential feature of construction in an unstructured environment, something that can often be achieved not by having a broad variety of construction material but application of a single material with multiple properties. The swiftlet *Aerodramus fuciphagus,* a small bird weighing 15–18 g, creates nests out of solidified saliva [18], which functions as both a structural element and an adhesive, and is viscous enough to be formed into thin elements as it hardens, allowing creation of complex nests from amorphous material (Fig. 1d).

Many complex multi-modal mobility and manipulation mechanisms in nature are difficult or costly to replicate using conventional rigid robotics. Hence, creating bio-inspired robotic systems that exploit the compliant, elastic and flexible properties of biological mechanisms is a major focus of robotics research [1–3, 19]. In Table 1 we have summarised three prominent systems for high performance locomotion in nature, from which we have abstracted principles into the design of engineering systems which expand robotic capabilities, the details of which are expanded upon in Sect. 2.

2 Soft Robotic Technologies for High Performance Flight

Soft robotics is an emerging research field employing novel compliant and adaptive technologies for engineering, robotic systems and medical devices. In particular, soft robots become more unique solutions for applications that require access to hard to reach areas, safe and comfortable human-robot interactions, and where high degrees of miniaturisation, light-weight design, and flexibility is needed. To enable this, roboticists employ a number of core sensing and actuation technologies including smart materials, e.g. electroactive polymers [19–22] and memory materials [23, 24], fibre-optics [25], soft-matter electronics [26], conductive textiles [27], cable and pneumatic actuation [1, 25]. In order to design soft robotic mechanisms and morphologies, a number of methods are used including formal design methods for creating fold and bend patterns such as origami [28–30], kirigami [22, 31], morphological computation [32], bio-inspired engineering (such as abstraction of active mechanisms in nature [2]), and biomimetics [33].

In this paper, we describe a number of robotic technologies, developed at Aerial Robotics Lab, that exploit adaptive and reconfigurable mechanisms to enhance mid-flight performance for aerial-aquatic mobility [34–36], perching and construction [11, 37, 38] and 3D printing [39] with aerial robots.

2.1 *Multimodality: Adaptable Wings, Mechanisms for Transition Across Fluid Boundaries*

Animals able to both swim and fly are excellent examples of mobility across fluid boundaries achieved using multifunctional locomotory modules. These animals adapt their structures and behaviours to address the changing requirements of movement needed in air and water and to reduce the energetic costs of locomotion [34]. Aerial-aquatic robots face similar challenges, and must accommodate the increased structural loads, fluid inertia and drag encountered underwater, without compromising the weight and lifting area requirements of flight. To achieve this, we have developed a novel robot, called the Aquatic Micro Air Vehicle (AquaMAV) that is capable of aerial and aquatic locomotion (Fig. 3).

A unique example of aerial-aquatic mobility can be found in the species of squid which can perform gliding leaps, taking off using pressurised jet of water [40]. While often less efficient than conventional propeller propulsion, a water jet can provide very high power densities, and importantly produces similar thrust in both air and water, which allows a vehicle to escape the water and accelerate when airborne, where drag is dramatically reduced [41]. Taking inspiration form the flying squid and other aerial-aquatic animals [34], we have created a water jet propulsion system, powered by the expansion of compressed gas [35], or water reactive combustion chemical [42] which allows the AquaMAV to rapidly escape the water, reaching speeds over 11 m/s in under 0.5 s.

Fig. 3 **a** AquaMAV launching out of the water using a burst of water jet thrust. **b** Timelapse of a launch from water, with wings deployed in final snapshot. **c** CAD Renderings of the AquaMAV, all images reused from [36]

When leaving the water, both flying squid [40] and flying fish [41] keep their wings folded until they are clear of the surface. There are large differences in fluid forces between the two media, and doing this protects wing structures from large hydrodynamic loads, reduces drag, and may also have stability considerations. Reconfigurable wings have also been shown to have advantages in jumpgliding [43], and are features of almost all aerial aquatic animals [41]. We have implemented this type of adaptive morphology into the AquaMAV, which has wings which can deploy into a high aspect ratio configuration for gliding, and can retract into a narrow, low drag configuration for movement underwater. This facilities rapid aquatic escape using a powerful burst of thrust, in which the robot keeps its wings retracted during acceleration, deploying them when at the apex of a jump, where it has reached an altitude and velocity sufficient for gliding flight [36].

2.2 *Energy Management: Robotic Perching for Energy Saving and Enhanced Access*

The typical flight times of rotary-craft MAVs are in the order of 10–20 min [44]. In order to prolong their endurance a number of studies have investigated perching as a viable power management solution. Prominent examples include mechanisms to perch to vertical surfaces and ceilings using magnetic adhesion [45], micro spines [38], electrical adhesion [46], adhesive pads [47], and hot-melt adhesives [48].

We have created a perching system to enable multirotor MAVs across a wide range of scales to maintain and control their relative altitude whilst perched upon an external structure (Fig. 4), [37]. Our method requires no active attitude control while perched, and the use of only a single motor. In order to enable the application of this technology in tightly constrained environments, we focused on subminiature multi-rotor MAVs or Nano Aerial Vehicles (NAVs), hereby proposing an NAV as a robot with a total mass of no more than 30 g and a span of less than 10 cm.

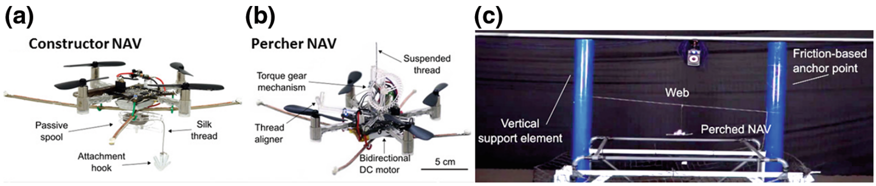

Fig. 4 **a**, **b** Nano aerial vehicles equipped with construction and perching payloads, respectively, weighing 26 g each. The constructor payload is made up of a spool of string designed for building a tensile web structure. The percher payload consists of a hook at the end of a connecting string designed to latch on to an overhanging support element. **c** The constructed web structure with an NAV perched for an extended duration

2.3 Aerial Construction: 3D Printing with Flying Robots

A number of research groups have proposed approaches for construction with aerial robots, usually making use of pre-fabricated components and connectors. This has included the assembling of a beam-based structure by flying robots relying on magnetic connectors to join construction elements [49], the creation of a rope structure between two previously placed parallel elements using a mid-sized quadrotor [50]. In [51], an off-board circular motion wax 3D print deposition strategy for potential integration into aerial robots is proposed.

In order to improve the versatility of construction with aerial robots, we have developed an aerial 3D printer capable of depositing polyurethane foam to create structures during flight (Fig. 5), [39]. This allows the printing of complex 3D structures in areas which are hard to access using ground or climbing robots and enables a variety of maintenance and repair applications. The flying 3D printer has a great potential for ad-hoc construction of first response structures in search and rescue scenarios, and bridging gaps in discontinuous terrain.

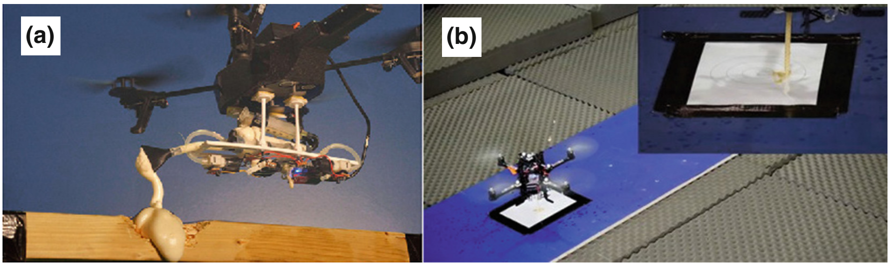

Fig. 5 Aerial construction with amorphous materials: **a** Static deposition of foam material on a damaged wooden beam. **b** Precise aerial 3D printing on a planar target from a hovering UAV

3 Conclusions

In this paper, we describe a number of examples where softness is used successfully in the animal kingdom to enhance flight performance, improve robustness and increase adaptation capabilities to complex environments and varied terrains. We also outline how these principles have been transferred to aerial robots with emphasis on adaptive and reconfigurable mechanisms to enhance mid-flight performance (AquaMAV), or perching and printing mechanisms for flight time prolongation and enhancing multi-modal mobility in flying robots (NAV percher and 3D printing UAV).

A future direction can be to investigate the integration of soft materials, passive aerodynamic structures, morphing body elements and embedded sensing and control into aerial robots. Combining novel soft technologies with traditional aerial robotic engineering approaches can substantially increase functional capabilities and flight performance for UAVs. Interdisciplinary work, at the interface of soft materials, biology, aerodynamics, smart mechanism design and control engineering, as outlined through the examples in this paper, can be the stepping stone towards a new generation of aerial robots for a wide variety of applications.

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Soft Robots in Surgery

Matteo Cianchetti and Arianna Menciassi

Abstract Minimally Invasive Surgery (MIS) represents the gold standard in the majority of abdominal operations, although some fundamental limitations are still present and are far to be really addressed despite emerging robotic solutions. Flexible endoscopes can exploit their high flexibility to reach the surgical target while being inserted remotely or by a natural orifice. However endoscopes may lack stability that rigid tools normally provide. Novel surgical instrumentation is being developed in order to provide higher dexterity and flexibility to the surgeon, but unlike traditional surgical manipulators, here we report the approach followed in the development of the STIFF-FLOP manipulator. The main idea is based on the exploitation of soft materials to be intrinsically flexible and safe while combining different fluidic actuation technologies to enable high dexterity and selective stiffness variability. In this chapter, the functional evolution of the robot is reported highlighting advantages and drawbacks that steered the development of a manipulator which in the end demonstrated to be effective in overcoming mobility limitations experienced with standard rigid tools.

1 Flexibility and Dexterity in Surgical Robotics

In the second half of the 20th century, Minimally Invasive Surgery (MIS) started replacing traditional open surgery laying the foundations of a real revolution in operative medicine. The main shortcomings of open surgery (e.g., patient discomfort and pain, costs associated with the procedures, complications, hospitalization duration and cosmetic effects) pushed the advancements of minimally invasive surgical techniques [1]: in particular, the reduction of intervention trauma represents the key feature of MIS [2]. Although the advantages of MIS for the patients are undeniable, from surgeons' point of view additional technical hitches and difficulties are introduced due to the minimal access. The use of instrumentation

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suitable for MIS often results in limiting the surgeon's capabilities of maneuverability and dexterity, and his/her visibility of anatomical structures via the mono-dimensional endoscope.

Exploiting the strengths of robotics, in terms of accuracy, teleoperation, integration of multiple sensing sources, holds the potential to again revolutionize the MIS scenario [3].

On the other hand, a target which seems still difficult to achieve even if with the integration of the most advanced robotics technologies, is the possibility to operate in robotic MIS with the same flexibility and dexterity typical of the human hands: differently from any robotic surgical tool, the human hands (under the human control) can manipulate, palpate, dislocate organs with an excellent dexterity and adaptability to different tissue conditions. Reaching the same level of flexibility and dexterity is a challenge for the academia and the industrial community. The authors have identified in the state of the art three different trends for enhancing dexterity and flexibility in MIS:

- Reconfiguration of "bricks" in MIS and laparoscopic surgery (i.e. minimally invasive techniques in the abdomen).
- Deployable structures for MIS with an "origami" architecture.
- "Soft" exploration of the internal organs, both in an endoluminal fashion (e.g. through the gastrointestinal tract) and in the abdominal cavity in MIS.

As regards the possibility to increase flexibility and dexterity by reconfiguration, some seminal proposals to build up a reconfigurable robot to be used in heart surgery appeared in Japan in the 80 s. Taking inspiration from swarm robotics, from rescue and field robotics, and from the possibility to generate an advanced robotic device starting from simple bricks with minimal functions and docking capabilities, the Paolo Dario team proposed different concepts and prototypes for gastrointestinal applications and abdominal surgery [4, 5]. The idea is to set up—by magnetic docking or dedicated mechanisms—a large internal robot with the ability to achieve different configurations and different manipulation abilities. The robot should be composed by thin and slim pieces to be swallowed or to be introduced by surgical access ports (no more than 15 mm in diameter). All modules are provided with a couple of miniature motors which can be used for pitch and roll of end-tools or for executing real tasks (e.g. taking a bioptic sample).

The problem of reaching the wall of the abdominal cavity or exploring the wall of large diameter organs (such as the stomach) is extremely challenging from the kinematic viewpoint, especially when all tools that can be introduced have a limited diameter. In this scenario, origami architectures represent a valid opportunity for achieving a large operating workspace by starting from tiny (and lightweight) structures. Few examples have been proposed for surgical applications, but the potential of adding origami-enabled degrees of freedom into traditional surgical tools has been already demonstrated [6, 7].

A third kind of approach (connected to the second one in terms of materials exploitation) makes use of soft matter to build devices and tools with high compliance and dexterity. Soft robots are often based on continuous structures and this high degree of mobility can be used to enrich the motion capability. Soft robots are also intrinsically safe (due to their passive compliance) but can count on technologies which are able to vary their stiffness and allow to generate relatively high forces. This chapter is aiming at reporting the main results obtained with this last approach in the STIFF-FLOP manipulator. The historical development led by failures and achievements will underline the limitations and the advantages of such an approach.

2 A New Paradigm in Endoluminal and Endocavitary Surgery

By combining the different needs in minimally invasive and endoluminal surgery, ranging from improving flexibility, enhancing dexterity and—last but not least—preserving the maximum safety, soft-bodied robots emerge as the elective choice. In comparison with highly articulated—yet rigid—robots, soft-bodied robots can adapt passively to external environments and can be collapsed to enter small access ports.

The development of a soft bodied system is usually a very difficult and long process. Mechatronic devices usually follow an integrated design, so that each component (sensors, actuators, mechanisms, electronics and power supply) are studied from the very beginning for being integrated in a single system. This entails a design which takes into consideration functionalities together with the interface among the parts. In the area of Soft Robotics, a platform based on soft and compliant materials cannot follow a "simple" integrated approach. The new paradigm for soft mechatronics is to consider and design a single all-in-one system. Each part affects all the others, from an active but also from a passive point of view: a soft actuation system supported by a flexible structure loses its main characteristic if a bulky rigid sensor is necessary on board. This approach can show all its potentiality only if all the components are contextually taken into consideration as fused together, going even beyond the biomechatronic approach in terms of integrated design.

This is the reason why in this discipline the development of simplified mockups has a central role. The basic functionalities (and flaws) of a chosen combination of technologies are easily highlighted by simplified platforms. Of course they have to embed all the parts, but they can be inserted one by one, allowing the assessment of the single contributions in terms of overall functionality.

This approach has been followed in the design of the STIFF-FLOP manipulator, where two different actuation technologies, the support and the power supply have been contextually taken into consideration in a series of prototypes (conventionally divided into three generations—Fig. 1).

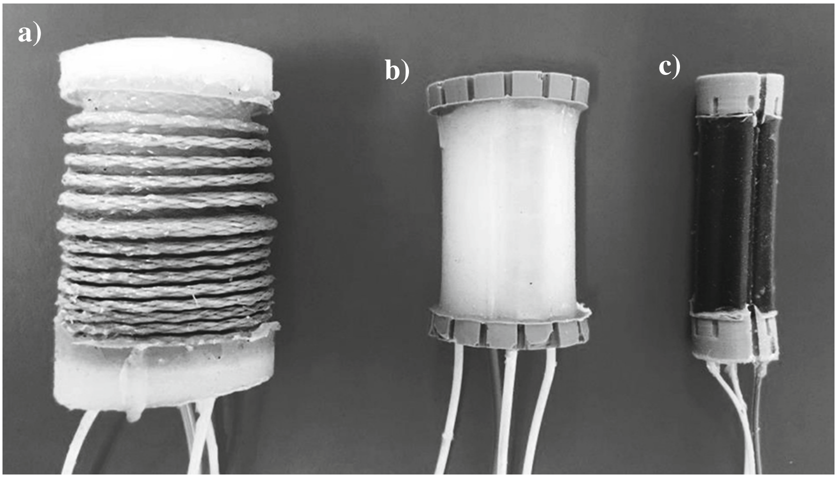


Fig. 1 The evolution of the STIFF-FLOP manipulator: the first (**a**), the second (**b**) and the third (**c**) generation

3 STIFF-FLOP Manipulator Evolution

The STIFF-FLOP manipulator has been conceived to present the following functionalities:

- ability to pass through standard MIS access ports (trocar);
- a flexible, but articulated and functional length of 100–300 mm;
- 30 % of elongation capability;
- 1–20 N of force at the tip and in other relevant points along the arm;
- controllable stiffness.

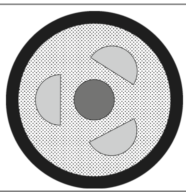
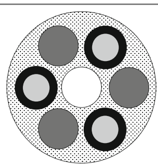
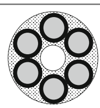
A modular architecture was adopted from the very beginning: each module showing high dexterity and stiffness tunability. The embedded technologies were thus selected among several possibilities which also met the soft requirements [8]. For the actuation system a combination of fluidic technologies has been selected. Flexible fluidic actuators (FFA) for enabling omnidirectional bending and elongation, while granular jamming (GJ) based chambers to include variable stiffness capability. Being based on fluidics, the power supply was decided to be maintained externally placed. This eased the development, but tubing had to be carefully taken into consideration anyway. In particular dimensions and flexibility of the tubes used for inflation represented a potential threat limiting the system flexibility. Soft structural material (silicone Ecoflex™ 0050, 0030—Smooth-on Inc.) has been used to support, embed and drive the actuation system.

3.1 First Generation: Converging into Working Modules

FFAs are known to be very simple but effective soft actuators. They can exploit the vast knowledge already available in driving fluidic systems and they are very versatile. They can be shaped in the most convenient manner, enabling different morphing possibilities. Being based on the inflation of elastomeric chambers, this kind of actuator often requires a restraining system to limit and lead deformations along preferential directions. In literature different approaches have been used like patterning [9], folded paper [10], wrapped-around threads [11] or high elastic modulus materials [12]. In our first generation of the STIFF-FLOP manipulator an approach derived from the McKibben actuators have been preferred. McKibben actuators are a special class of FFA that are based on a braided sheath which contains the internal balloon inflation. The braided sheath guides the actuator deformation and in particular the braiding angle. This also leads to the main limit of such actuators: the braiding angle is physically constrained to range between 54.7° to almost 90° that translates in an elongation capability which rarely exceeds 50 %. In order to exploit the same principle, but with an enhanced elongation the braided sleeve has been modified through a peculiar thermo-mechanical treatment [13]. As a result it shows circumferential folds which still have a containment effect, but increased elongation capabilities since the folds are first flattened and then the braiding angle starts to change (Fig. 1a).

The internal arrangement of the actuation components are showed in Table 1—first column. The FFA have a semicircular section to optimize space allocation and

Table 1 Different design approaches used in the three development generations of the STIFF-FLOP manipulator

Generation	I	II	III
External diameter	35 mm	25 mm	14.7 mm
Module length	50 mm	50 mm	55 mm
FFA shape	Half cylinder	Cylinder	Cylinder
Containment method	External with braided sheath	Internal with helicoidal threads	Internal with helicoidal threads
Tubing	Through the silicone body	Inside the inner channel	Inside the inner channel
GJ position	Inside the inner channel	Between FFAN	N/A
Free space in the inner channel	Not usable	Lodging tubes	Lodging tubes
Cross section sketch			

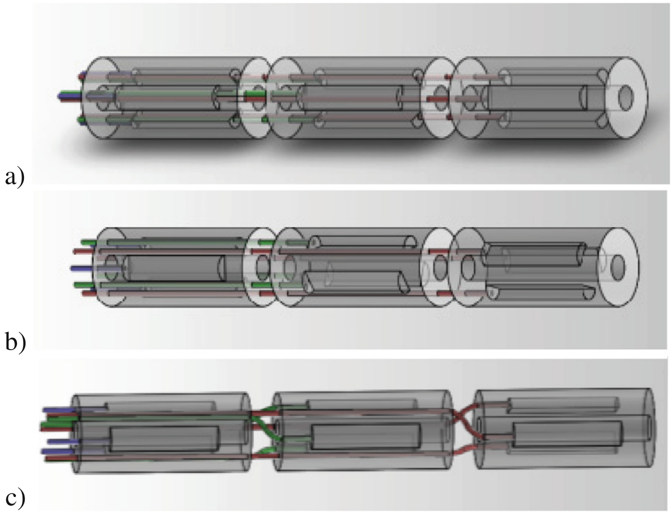


Fig. 2 Different solutions for tubes arrangement: chambers and tubes aligned (**a**), tubes aligned and chambers rotated (**b**), tubes rotated and chambers aligned (**c**)

they are arranged longitudinally at 120° to enable omnidirectional bending while the granular jamming is hosted in a cylindrical central channel. The length of a single module was set to 50 mm, but several versions of 2- and 3-module manipulator have been developed too, reaching a final length of 135 and 190 mm respectively (additional space is requested to create a flexible silicone-based joint between the modules).

The development of multi-module manipulators required to cope with a very important issue: how to arrange the tubes so that inflation and/deflation can reach all the chambers (including the GJ system)? Several possibilities have been evaluated and while for the GJ system an in-series solution has been adopted (the three modules stiffened all together) for the FFA different solutions have been evaluated:

- In a first possible solution the chambers of the modules are aligned (Fig. 2a). Nine tubes, three for each chamber, pass through the first module. Focusing on a single chamber, one tube stops at the base of the chamber for its actuation, while the other two pass into the same chamber up to the second module, in correspondence of the aligned chamber. One tube stops at the base of the chamber, while the last one pass into the chamber and stops at the next chamber of the third module. Features of this solution:
  - The chambers are aligned: the trajectory of the manipulator is more intuitive;
  - There is more free space: it can be used for the integration of the sensory system or it can allow for a further reduction of the module diameter;
  - The chambers are perforated in bottom and top area: there can be more leakages, but solutions to reduce leakages are under testing;

  - The chambers in the first module have an effective volume smaller than in the second and in the third modules. This could produce different performance among modules.

- A second solution is based on an axial-symmetric design for the disposition of the chambers and the corresponding tubes (Fig. 2b). The chambers and the respective tubes are placed at 40°. Nine tubes are located in the first module: three actuate the chambers while the others six pass through the module, externally respect to the chambers and each one in a dedicated duct, up to the second module where the location of the tubes is the same. Features of this solution:
  - The chambers are perforated only at the base where the supply tube is located: the leakages are reduced;
  - There is a little free space: low possibility to insert other components in the same structure or to reduce the dimensions;
  - The chambers are not aligned: the inflation of the chambers respect to the trajectory of the manipulator is less intuitive, especially on bench tests during the first evaluations of the manipulator performances;
  - The ducts of the tubes are very close to the chambers: the chambers could break during their activation or in the fabrication process.

- In the third solution the chambers of the modules are aligned (Fig. 2c). Nine tubes are placed in the first module: three actuate the chambers while the others six pass through the module, externally respect to the chambers and in a single duct, up to the second module and so on to the third module. Features of this solution:
  - The chambers are aligned: the trajectory of the manipulator is more intuitive;
  - The chambers are perforated only at the base: the leakages are reduced;
  - There is free space: it can be used for the integration of the sensory system or it can allow the reduction of the module diameter;
  - Not straightforward fabrication process especially in correspondence of the junctions between two modules.

3.2 Second Generation: Optimizing Spaces

After functionality tests carried out to assess the performance of the manipulators composed of first generation modules it was quite clear that despite the promising results from a mechanical point of view there were issue related to the inflation of the chambers: the external braided sheath limits the radial deformation directed outwards, but chambers tend to extend also inwards. In principle thus does not represent a problem until the GJ system is not deformed too much, but there is an issue related to the actuation system: when inflated singularly the chambers are very much precise and with high repeatability, but when two or more chambers are combined to generate intermediate plane bending and/or elongation the interference between the chambers makes not univocal the relation between chamber activation and tip position. The motion becomes sensible to the order of chamber inflation and the amount of pressure used. Moreover the use of the external braided sheath poses limit also from the scalability point of view. Theoretically the structure would work at any scale, but the manufacturing becomes prohibitive.

To overcome this issue a new method for confining the chambers' expansion has been introduced [14]. A chamber with a thread helicoidally wrapped directly around it has minor shape possibilities, but represents a much more compact solution (Fig. 1b). In this way each chamber is singularly limited to extend only and any other interference is avoided. While this solution allowed the removal of the external braided sheath, on the other side it imposes strong limits in the chamber's shape. In the first generation the half-circle cross section was used to optimize the exploitation of the internal space, but with the new approach the circular cross section is the only possibility (any other shape will tend to a circle under pressurization, implying a lateral deformation).

A general reconfiguration of the actuation system has thus been implemented. The necessity of using cylindrical chambers reduced the diameter of the internal channel leading to the choice of moving the variable stiffness system to a more external position. This implies a more efficient stiffening (the area moment of inertia of the system varies much more if the GJ is placed at higher distance from the center) without increasing the number of tubes. In fact, the three GJ chambers were locally connected, so that one single tube is sufficient to create vacuum in all the 3 chambers. Moreover leaving the central channel free, this can be used to lodge fluidic tubes or flexible instruments and tools. This solution is showed in Table 1—central column.

3.3 *Third Generation: Going Thin*

The diameter of the first two generations of the STIFF-FLOP manipulator was almost suitable for single access (single-port laparoscopy) or for natural orifice translumenal endoscopic surgery (NOTES), but not compatible with standard trocar ports usually used in MIS. This pushed a further development of the device in reducing its overall diameter (Fig. 1c). The third generation is still under study for further improvements but gaining on the experience deriving from the previous extensive use of the fluidics technologies, some thinner manipulators have been already manufactured and tested.

In particular a 2-module manipulator has been proposed with the specific aim of being used as a soft vision tool thus equipped with a miniaturized camera. The arrangement of the fluidic chambers resembles the previous version, but a substantial modification has been introduced from the actuation view point. For its specific task the variable stiffness capability has been neglected since very limited interaction with the surrounding environment is expected. Without the GJ system, the FFA chambers have been doubled, so that the effectiveness of the bending motion has been enhanced. 6 chambers (coupled in pairs) have been embedded in each module and the central channel is used to lodge tubes and electric connections necessary for the camera.

4 Main Achievements and Results

The first generation of the STIFF-FLOP manipulator was quite handcrafted and this was visible from an esthetic (due to a mostly manual fabrication) and a functional point of view (asymmetries), but already demonstrated to meet the basic functionalities listed in Sect. 3. The single module have been fully and accurately characterized [13, 15] and the results proved that this approach represents a breakthrough in surgery. Elongation, omnidirectional bending and variable stiffness were combined in a compact system completely made of soft materials. Moreover the two-module version paved the way to a new surgical scenario: it is possible to exploit the modular structure of the manipulator to carry out different tasks with different sections of the manipulator. For example, while the proximal module (at the base) is retracting and stabilizing an organ/tissue, the distal module (at the tip) can freely interact with other targets by bending and elongating independently from the first module.

The second generation of the STIFF-FLOP manipulator is characterized by a much more reliable and accurate manufacturing process which led to improved performances in a more compact size. The new restraining approach allowed to reduce the overall dimensions without affecting the overall strategy too much. But the most important result achieved with this version is the possibility to maximize the modularity of the system. The new method, indeed, leaves free the inner channel (previously occupied by the GJ system) and allows lodging tools and/or let tubes pass through the modules without hindering motions.

The third generation of the STIFF-FLOP manipulator was aimed at achieving dimensions more compatible with MIS constraints. Despite the first two versions of the manipulator were squeezable and resilient to high deformations, they suffered from limitations in dealing with standard trocar ports. This thinner version has been also tested with human cadavers. A surgeon used the manipulator equipped with a miniaturized camera as a vision tool to perform a Total Mesorectal Excision (TME). Its high dexterity and mobility demonstrated to acquire superior angles of vision of the surgical field (respect to the standard laparoscopic vision) while neither intra-operative complications nor technical failures were registered during the two hours of continuous work necessary for the procedure [16].

Recently the manipulator has been also integrated in the daVinci surgical robot and has been invited as finalist to the 2016 Surgical Robot Challenge (event connected to the Hamlyn Symposium of the UK Robotics Week) demonstrating the possibility to be completely functional as a MIS tool. The integration was full since the surgeon was enabled to intuitively control the STIFF-FLOP motion directly from the master console of the daVinci robot.

5 Conclusions

The development of the STIFF-FLOP manipulator highlighted the possibility to exploit technologies based on soft materials in the surgical field, but also it underlined that the exploiting soft mechatronics technologies still present many threats. Manufacturing techniques, for example, are still far from being suitable. There exist many possibilities (like multi-step molding processes), but several fabrication phases are still manual. This usually undermines the robustness and the repeatability of the system or at least introduces structural weaknesses. Also the very recent and promising 3D printing techniques are not able to fully satisfy soft robotics requirements. The printed materials are usually soft enough, but the low tensile strength limits the elongation at break to unsuitable values.

Another limit which should be seriously taken into consideration in the development of soft robots based on FFAs regards tubing. The integration of a pressurized fluid source is currently not compatible with size and mechanical properties of commercially available pumps, thus lodging tubes inside the robot is mandatory to use an external pump. But while the dimension of the chambers is not constrained, tubes have to guarantee structural stability thus their diameter is hard to be reduced as well as it is difficult to decrease the hardness of the material they are made of. This is especially difficult in two cases: if pressure drops become too high and if the tubes are used to create vacuum in the chambers. Moreover the connection of the tubes to the chambers represents a discontinuity point which needs to be curated to guarantee reliability.

Despite this, the experience of the STIFF-FLOP manipulator demonstrates that the introduction of novel technologies for tools and instrumentation such as soft and flexible robotic devices may aid in overcoming the technical challenges of difficult laparoscopic procedures based on standard, rigid instruments. Soft robotics represents a design methodology with the potential to change the perspective of traditional robotics and traditional application scenarios. On the other hand, it can be challenging to radically substitute existing robotic devices with soft robot architectures. The experience of the authors in developing the STIFF-FLOP manipulator can be a paradigmatic example of a successful methodology aimed to a concrete take up of soft robotic technologies. First of all, the soft robotic architecture should be tuned in a pragmatic way in order to obtain first early prototypes which immediately demonstrate the possible advantages of the soft robotic technologies. Only in this way users can provide useful hints for further improvements. As a second step, the soft robotic technologies must be completely dominated for integrating the most adequate solutions for the targeted applications, by trying to merge traditional functionalities with more advanced functionalities, specifically enabled by soft technologies. Finally, the users and the soft robotics engineers should test their results in the field, for an objective benchmarking on well-known and familiar applications. For doing this, it is crucial to identify the soft features that could be relaxed and the soft features to be maintained for an effective translation into the selected application scenario.

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Design Principles for Soft-Rigid Hybrid Manipulators

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Abstract In nature, manipulators have evolved into different morphologies with varying rigidity to accomplish different tasks. Soft and continuum tentacles of the octopus, rigid and strong pincers of the crab and ligamentous jointed fingers of the human demonstrate the relationship between the complexity of a host's task space and the design of its manipulator. Thus, the purpose of use a robotic manipulator should be considered as an important design parameter which governs the choice of appropriate materials and design rules. For tasks which require delicacy and strength at the same time, such as human-machine interaction, agriculture or robotic surgery hybrid soft-rigid manipulator designs should be investigated. Here, we present four design principles for building hybrid robot manipulators which incorporate soft and rigid materials and demonstrate each principle with working examples.

1 Introduction

Interaction with the environment is essential for the survival of intelligent life in nature. Especially animals have developed a great variety of manipulators with different morphology and rigidity which yields the necessary functionality to achieve life sustaining, interaction based tasks. For example, an octopus thrives in its habitat by utilizing its highly deformable soft octopus arms [1], whereas in comparison, a lobster has rigid dexterous pincers with thick strong exoskeletons [2]. Human hands lie in the middle of this spectrum in terms of the rigidity of their structure. The rigid bone phalanges and the soft ligamentous joints contribute to the overall strength while also providing the necessary flexibility of the human fingers [3].

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For decades robotics research has focused on the design of robotic manipulators with rigid structures for use in industrial applications which require high precision, large force exertion and low mechanical flexibility [4]. Commonly used two or three fingered manipulators have led to the development of more anthropomorphic robotic manipulator designs such as Utah/MIT Hand [5] and DLR/HIT Hand II [6] which utilised rigid body links and fixed degree of freedom (DOF) joints. Recently there has been a shift towards bio-inspired manipulator designs which behave like or consist of continuum body soft materials. Advancing from Hirose's rigid link manipulator which behaves like a soft arm [7], later examples started using soft materials and continuum bodies. Manipulators such as Ilievski's soft gripper [8], the Octopus Arm Project [9] and RBO Hand 2 [10] are successful examples to manipulators with soft materials which exercise large deformations and structural conformity due to their high DOF.

2 Hybrid Manipulator Definition

By definition, hybrid is the combination of two different elements and it is typically used to define manipulators which combine parallel and serial mechanisms in robotics [11]. However, we are using hybrid to describe manipulators which combine soft and rigid materials. Figure 1 is an overview of the manipulator design

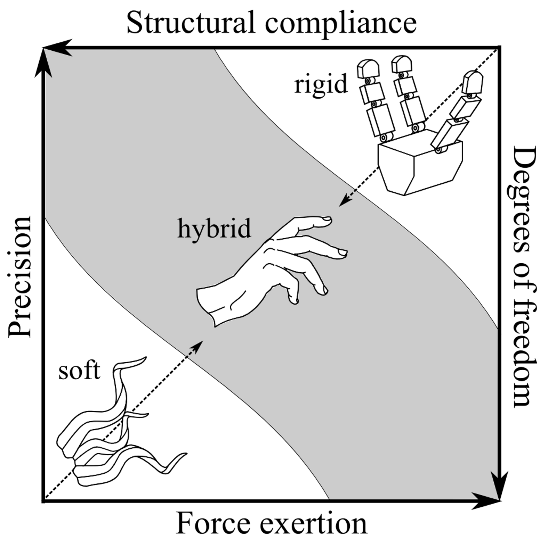

Fig. 1 The position of *soft*, *hybrid* and *rigid* manipulators in the 2D design space. Quantitative change of the four important manipulator features: *precision*, *structural compliance*, *degrees of freedom* (DOF) and force exertion are shown on the axes. *Hybrid* manipulators lie on the fairly unexplored diagonal design space (*grey* coloured)

space according to the choice of materials. Soft continuum body manipulators exploit large deformation capacities; demonstrating features such as higher DOF and structural compliance. Conversely, manipulators with interconnected rigid body links utilise rigid body dynamics and inverse kinematics enabling precise motions and exertion of higher magnitudes of forces.

The hybrid manipulator lies in the middle of the design space as it is a combination of soft and rigid materials. Manipulators built this way can benefit from a sufficient proportion of all the features granted by both of the material types as shown in Fig. 1. A key example found in nature would be the human hand which demonstrates impressive dexterity. Inspired from human fingers' ligamentous joints which connect rigid bones with soft tissues, robotic platforms such as Pisa/IIT Hand [12], iHY Hand [13] and the derivation of the ACT Hand [14] have been developed. Hybrid manipulators built similar to human hands can be promising candidates for achieving dexterous tasks in human-machine interaction (e.g. caretaking and rehabilitation), agriculture (e.g. planting and harvesting), invasive surgery and tactile exploration (e.g. sea/ocean bed and planetary surface investigations). However, human hand design is still very complicated and cannot be replicated with a top-down approach. That is why in the next section, we are going to present a bottom-up approach and list four design principles which can be utilised to build hybrid manipulators.

3 Design Principles of Hybrid Manipulators

In this section we present four design principles which are essential for the design of hybrid manipulators in order of increasing complexity with an example of a robotic manipulator given for each. Each manipulator design builds upon those presented previously, with the final manipulator encompassing all four principles.

3.1 Articulated Link Structure

Being able to generate form and force closure on objects enables manipulators to achieve complex interactions [15]. While the form closure guarantees the immobilisation of an object via geometric enclosure, the force closure allows in-hand manipulation. Articulated links with a hybrid usage of rigid and soft materials can allow a manipulator to be flexible and generate both types of closures simultaneously, as the soft articulation enables the rigid links to enclose the object and exert forces. Counter examples, such as the universal gripper [16] with an impressive grasping adaptivity through mainly form closure, cannot perform in hand manipulation due to its lack of articulated links. Similarly, the industrial manipulators without deformable link structures [4] can maintain a large scale of force closures, but cannot enclose objects which hinder their flexibility of grasping.

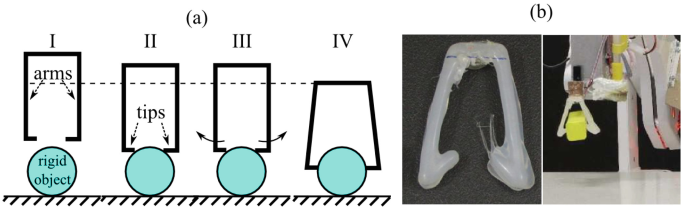

Fig. 2 The simple design of the passive soft gripper allows the fingers to bend outwards when pushed against a rigid object to exploit the elasticity of the articulated link structure (**a**). Hot melt adhesive (HMA) is used to fabricate this simple design [17] and a robotic arm is used for pick and place tasks exploiting the environmental niche [18] (**b**)

The passive gripper shown in Fig. 2a is a simple demonstration of articulated links. The arms are fabricated thinner and softer compared to the denser, more rigid tips, making the manipulator structurally hybrid as seen in Fig. 2b. This allows the gripper to elastically enclose the object while exerting forces at the tips.

3.2 Soft Actuation—Tendon Driven Links

It is necessary to have low inertia for a hybrid manipulator to achieve delicate and soft interactions. This requires the actuation mechanism to transfer forces to the target actuation point without hindering the softness of the manipulator. There are two types of candidate mechanisms which can meet this requirement. Pneumatic-hydraulic soft chambers bend continuum link structures by inflating, and merge links and joints together which may not be preferred in hybrid manipulators. In comparison, our preferred solution tendon drive systems allow transfer of force from a distant actuator over manipulator's rigid links, keeping the moment of inertia low. The tendon cables (e.g. kite lines) have a very high tensile strength on their longitudinal axis, but they are easily bendable on other directions, allowing complex routing over a hybrid manipulator structure. As tendons generate only pulling

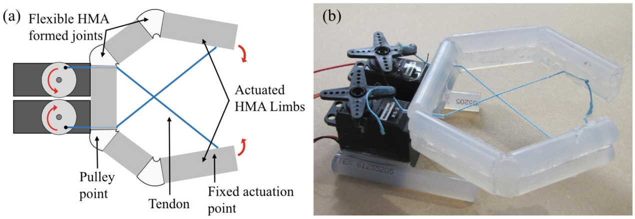

Fig. 3 An improved version of the passive gripper design allows the usage of simple tendon actuation to perform finger flexion operation (**a**). Fingers are cold HMA blocks glued together with the melt HMA creating soft-joints which do not have a fixed axis of rotation such as hinges or gimbals (**b**)

Fig. 4 In this design, links are made of wood which carry the pulleys that allow the translation of actuator force through the fingers (**a**). Wood links are connected to each other with soft HMA material to form soft joints and contribute to the overall flexibility of the manipulator. Finger pads are covered with soft sponge materials to assist form closure (**b**). By repeating the same finger design, a hybrid manipulator that resembles the human hand is created. Palm is reinforced with rigid materials for the fingers to apply necessary forces during grasping (**c**)

forces, counteracting forces can be achieved by using antagonistic tendon pairs or through the inherent elasticity of the joints.

Figure 3 shows the addition of tendons to a manipulator constructed from HMA material. Tendons allow the actuation source to be away from the gripper ends without distorting the soft body. Tendons are pulled to flex the links and relaxed to let the joint elasticity to bring the links back to their original resting position.

3.3 Differential Stiffness via Multi-material Usage

The hybridity of soft and rigid sections can also be achieved through combining materials with differing mechanical stiffness. When exposed to an internal or external stimulus, a hybrid manipulator's lower stiffness parts will generate a larger motion compared to the higher stiffness parts. In other words, we can define the motion of a manipulator by using materials with differing stiffness. In biology, mechanical properties of every tissue are special for the functions they take part in. Similarly, in hybrid robotic manipulators, high tensile strength cables can be used as tendons, durable and flexible materials as joints, and strong materials as links.

Differential stiffness is demonstrated in the hybrid manipulator design in Fig. 4. Tendons with high tensile strength are routed over the wooden links through the frictionless pulley tubes. The flexibility of the soft HMA joints contributes to the structural compliance and the high DOF motion of the fingers during interactions within the workspace. Additionally, the wooden links and the pulleys allow the transfer of actuator force carried by the tendons to the fingertips and generate successful grasping of objects.

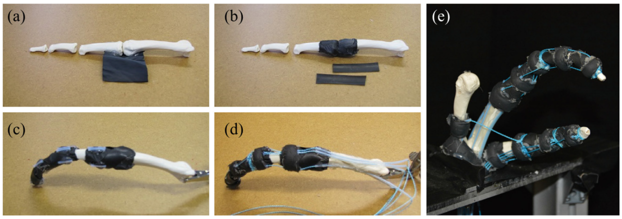

Fig. 5 In this hybrid manipulator design [19] anatomically correct human finger bones are used as rigid parts and are connected to each other by two types of soft and elastic rubber elements to form the ligamentous structure of human finger joints (**a**–**b**). Tendon pulleys are attached on the rigid links and strong tendons are routed through the finger structure from these pulleys (**c**–**d**). The overall hybrid manipulator design uses 14 tendons to actuate the thumb and index finger for flexion, extension, abduction and adduction motions (**e**)

3.4 Guided Soft Joints

Typical hinge and gimbal mechanisms are compliant only on the axes of their fixed degree of motion. Although these joints are easy to actuate and control, they provide little to the overall adaptability of the manipulators. Therefore a soft joint which can move in multiple directions would be suitable for improved structural compliance. However it is challenging to design such a joint by only using soft and deformable materials. Soft materials have infinite DOF which will make joints bend in undesired directions during force exertion and impossible to fully actuate with finite number of actuators. However, guiding soft joints with the geometry of the link end regions and the routing of the tendons can establish a controlled actuation. Links with guided soft joints can move and exert forces in predefined axes, but they can flex and adapt to the environment when disturbances are larger than a certain threshold. This makes the manipulators more adaptive and durable.

The manipulator shown in Fig. 5 is the last example of a hybrid manipulator design. In addition to the embodiment of the previously shown principles, this anthropomorphic design uses the geometry of the bone cavity and the tendon routings to guide the soft joints [19]. The soft joints are made of two types of elastic rubber materials which resemble the ligamentous structure of the human finger joints.

4 Discussion

Hybrid manipulators are going to be central to the future development of safe, highly functional and adaptive systems which can work in environments which require safe and compliant interactions as shown in Fig. 6. Clear applications for both soft and hard manipulators already exist, and the hybrid approach would not only solve problems that are not currently solved by these two, but would also

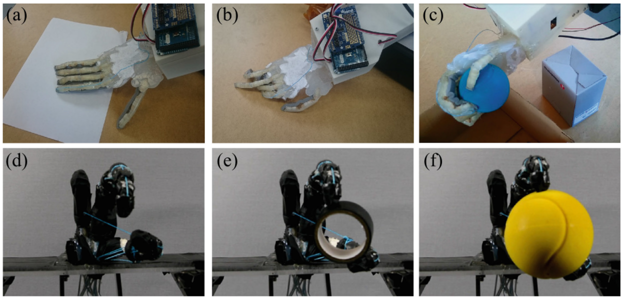

Fig. 6 The structural compliance of the hybrid manipulators will allow them to use environmental niches to assist their tasks (**a**) and increase their durability in unexpected interactions (**b**). By using rigid structures and flexible joints, these manipulators can apply the necessary forces while adapting to the shapes of the objects they are handling (**c**–**f**)

overlap with these in some areas by offering additional precision/compliance due to the variable rigidity of the system. With the gradual automation of industrial and agricultural processes, a higher degree of compliance will enable a safer handling of delicate products, while current soft solutions can benefit from the advent of hybrid manipulators to improve their intrinsic speed/precision.

Our better understanding of hybrid manipulators is dependent on a stronger academic push which addresses the challenges associated with soft and hard materials. Soft materials' inherent ability to deform in virtually infinite DOF can be useful in achieving highly deformable and adaptable manipulators. However, estimating the body state of these manipulators with a finite number of sensors has theoretical boundaries. Using guided soft joints [19] or custom sensor morphologies [20] may reduce the number of necessary sensors to detect soft deformations; however a deeper investigation is still very crucial. Additionally, assembly of multiple materials in a continuous way is a unique challenge for hybrid manipulators. With the increase of complexity and inclusion of more materials, the fabrication method switches from automation to assembly by hand as can be seen from the examples given. However, with the projected usage of hybrid manipulators in a large range of applications, automated manufacturing methods which combine multiple materials must be explored. These methods need to produce hybrid manipulators ensuring continuum connections between rigid and soft parts. This will require an interdisciplinary research on manufacturing and material science.

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Eating, Drinking, Living, Dying and Decaying Soft Robots

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Soft robotics opens up a whole range of possibilities that go far beyond conventional rigid and electromagnetic robotics. New smart materials and new design and modelling methodologies mean we can start to replicate the operations and functionalities of biological organisms, most of which exploit softness as a critical component. These range from mechanical responses, actuation principles and sensing capabilities. Additionally, the homeostatic operations of organisms can be exploited in their robotic counterparts. We can, in effect, start to make robotic organisms, rather than just robots. Important new capabilities include the fabrication of robots from soft bio-polymers, the ability to drive the robot from bio-energy scavenged from the environment, and the degradation of the robot at the end of its life. The robot organism therefore becomes an entity that lives, dies, and decays in the environment, just like biological organisms. In this chapter we will examine how soft robotics have the potential to impact upon pressing environmental pollution, protection and remediation concerns.

1 Soft Robots in a Wasteful World

Modern technology is driving our society ever further from a state of environmental equilibrium. Throughout animal evolution the driving force has, perforce, been to fit in with the environment. As competing species grow in population, or as climates change, animals have adapted to re-establish the status quo. In contrast, since the start of the industrial revolution the drive has been technology advancement and

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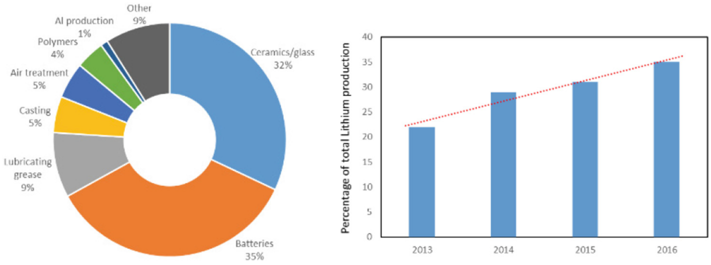

Fig. 1 (*Left*) Lithium use in 2016, (*right*) lithium use in batteries 2013–2016

the growth of the human race. The newer information technology and robotics revolutions have taken this to an extreme. Now the advancement of society is precariously out of balance with the environment. Technology has the potential to drastically and negatively affect the environment and yet is more and more dependent on the natural world to deliver crucial resources for its sustenance. It is with these environmental and resource pressures that we can turn to soft robotics to provide novel and timely solutions.

The pressure on natural resources from technology growth is huge and it is striking how soon the modern world is heading for critical events. Semiconductor components and electronic circuits, for example, use significant quantities of rare and exotic materials [1]. What happens when these resources dwindle? Another example is the lithium polymer battery, a staple of modern portable electronic devices and the enabler of new home power initiatives and future electric transport systems. Figure 1 shows the current proportion of world lithium production used for batteries (35 % in 2016) and the rapid rise in this value over the last four years [3]. This is in advance of the full impact of the Tesla Powerwall [2] and Gigafactories which are set to consume massive quantities of lithium. The planetary supply of lithium is finite and these new technologies are putting an increasing demand on the raw material [4]. What happens to our tech when lithium resources reach critically low levels? Experts are even starting to talk seriously about ‘peak X’ where X is almost any naturally occurring chemical, much as we talk about ‘peak oil’ [5]. When we reach ‘peak lithium’ we will have to carefully examine how we can sustain the burgeoning robotics revolution.

Even more immediate environmental catastrophes are looming which are driven by our rapid industrial, domestic and agricultural development. These include the widespread pollution of our lands and oceans with chemicals, fertilizers and plastics [6–8]. These may be result of industrial accidents (chemical release) or farm run-off (nitrate fertilizers). Nitrate run-off is a slow-burn pollution. These chemicals accumulate in the water courses and, when conditions are right, feed the growth of harmful algal blooms. These blooms have multiple deleterious effects: their rapid growth uses up all dissolved oxygen in the water, causing both aquatic flora and fauna to die; and they can release harmful toxins, some of which are extremely dangerous for humans.

The negative effects of the technology described above all have in common a lack of balance with the environment and natural resources. There is a danger with future robotics that we will make the same mistake again, that is, we will develop effective but unsustainable technologies that are out of balance with the environment. We argue that this need not be the case with careful choice and development of sustainable, bio-compatible, environmentally-benign and biodegradable robotics. Unfortunately, conventional robotics is hampered in this endeavor by the prevalence of toxic and non-biodegradable materials used in their rigid metal and plastic bodies, their silicon processors and their electromagnetic drive systems. In contrast soft robotics offers a new and high-potential set of technologies that can readily be made environmentally neutral and sustainable. In fact, by rethinking the concept of a robot and moving towards a more bio-integrating model of a *soft robotic organism* we can envisage how soft robots can radically change, and improve, our interactions with the natural environment and our management of natural resources.

2 Taking Inspiration from Nature

A soft robotic organism will need to work in harmony with organisms in the environment. We can study these organisms and take inspiration from their life cycle in order to construct an environmentally sympathetic robotic life cycle. Natural organisms go through a continual cycle of birth, life and death. When they are living, organisms must operate in homeostasis both within their bodies and in interaction with the wider environment [9]. For example, during daily living the organism may go through a cycle of resting, thinking, moving and eating. This cycle helps to maintain short-term homeostasis. When the organism dies it decays and fragments into elementary components which are, in turn, consumed by other organisms in the environment. This biological recycling maintains large scale and long-term environmental homeostasis.

If we are to move to fully sustainable robotics we must: 1. Work with the natural forces and conditions of environmental homeostasis, including biodegradation and resource re-use; and 2. Mimic per-organism homeostatic processes including feeding, metabolism and movement. Soft robotic technologies are highly suited to meet these challenges head on.

One important consideration is the scale of the robot. Biological organisms extend from micrometer scale bacteria to the 30 m/180 tonne blue whale. This range gives us the flexibility to design small, simple robots that operate collectively or to design larger complex robots that operate intelligently and independently. Given current soft robotic technologies, and especially the low level biomimetic technologies discussed here, a large number of small simple cooperating robots is more appropriate than one large complex robot.

We now consider how one might make a simple soft robot that could potentially operate safely, efficiently and with no negative impact within the natural environment. To do that we will consider both short-term and long-term homeostasis.

3 Soft Robots as Organisms

In order for a soft robotic organism to mimic its biological counterpart, and to maintain continuous homeostasis it needs to have two abilities: it must be able to feed itself and it must be able to move. Although feeding could be taken in its broadest sense as the absorption of energy, and hence could include conventional photovoltaics or direct electrical charging, we assume a more specific biomimetic view of feeding. Let us assume therefore that the robotic takes in the same biological material that its natural counterpart consumes and that it metabolises this material in its own ‘stomach’. While we do not have the ready technology to exactly copy the breakdown and utilisation of organic materials in their chemical form as biological organisms do, we can mimic this effect using a microbial fuel cell (MFC), which has already been implemented in the field of robotics with the EcoBots [10]. The MFC takes in organic material and live microbes (bacteria and algae) within the structure break this down and consume it. A by-product of this action is the release of electron-proton pairs. These charges are separated in the two-chamber microbial fuel cell, akin to a conventional H_2-O_2 fuel cell, and their movement through the cell circuit generates useable electrical energy. This energy can be stored in a capacitor for later use. It is has been shown that the microbial fuel cell is able to digest harmful algae [11] and that microbes can also consume crude oil and even long-lived plastics such as poly(ethylene terephthalate) (PET), a common material for plastic drinks bottles [12]. These capabilities mean that MFC-based robots have the potential for use in waste and pollution remediation activities.

The MFC provides a bio-mimetic, environmentally friendly energy source that, because it exploits the actions of naturally occurring microbes, encourages large-scale environmental homeostasis. Having satisfied the above stated requirement for a robot that can feed, we now need to satisfy the requirement for mobility. Biological organisms use movement to search for and gather food. Working towards a fully environmentally-integrated robot, the RowBot has been developed [13], which differs from EcoBot in terms of design, material compliance and environment (Fig. 2a). RowBot mimics the movement of the water boatman *Hesperocorixa castanea*

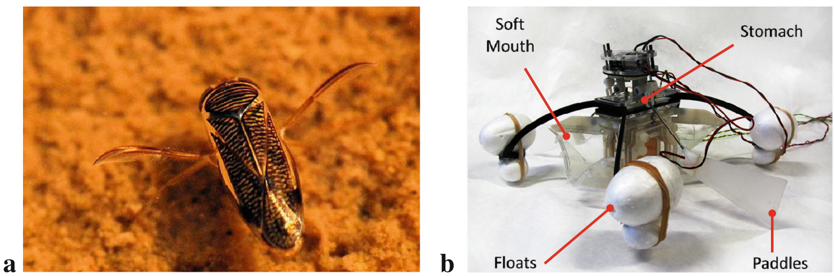

Fig. 2 **a** The RowBot environmental robot with soft mouth and MFC stomach [13], **b** the water boatman (James Lindsey, *Hesperocorixa castanea* from Commanster, Belgian High Ardennes, April 11, 2009 via Wikipedia, Creative Commons Attribution)

(Fig. 2b) and the feeding mechanism of the basking shark. It has a microbial fuel cell stomach and employs a soft robotic compliant mouth mechanism to control feeding and waste evacuation. When the RowBot is running low on energy it opens its front mouth and rear waste gate and rows through water to gather a fresh load of nutrient-rich water. It then waits for some hours for the nutrients to be consumed by the microbes in the MFC stomach. The resulting electrical energy is stored in a capacitor ready for use in operating the mouth and rowing mechanisms. The RowBot shows that the energy inequality $E_{metabolise} > E_{rowing} + E_{mouth\_operation}$ can be achieved, where $E_{metabolise}$ is the energy extracted from consumed organic material in the MFC stomach, E_{rowing} is the energy used in locomotion and $E_{mouth\_operation}$ is the energy used in opening and closing the soft mouth and waste gate. Other methods for extracting energy from organic chemicals for soft robotics include combustion of organics volatiles [14] and hybrid soft robots utilising cardiac muscles [15].

So far we have predominately considered how a robotic organism can maintain short-term, small-scale homeostasis through movement and feeding. Now let us consider the existence of the robot in the wider environment and the longer-term and larger-scale homeostasis of the environment itself. In this case the robot must have one crucial capability: it must be able to *decompose* and *biodegrade*. In this way there will be no build-up of persistent or toxic matter and environmental stability will be maintained.

It has recently been shown that soft robotics is particularly suited to the development of biodegradable and decomposing robots [16]. Conventional rigid and electromechanical robots all face limitations with respect to their decomposition, due to complex component integration, and their degradation, due to the prevalence of non-biodegradable materials. In contrast, biodegradable soft robots can be fabricated from naturally occurring biopolymers such as agar, natural rubber [17] and gelatine/collagen [18]. These materials have been shown to act as electroactive polymer actuators (Fig. 3) and can therefore form the compliant body and ‘artificial muscles’ of a soft robotic organism. Combined with MFCs, they constitute the fundamental blueprint of a wide range of soft robots that live by feeding on freely available organic material, die when they come to the end of their life, and safely degrade to nothing in the environment. The materials that make up the robot are consumed by competing organisms with negligible overall impact. It has also been shown that MFCs themselves can be made biodegradable [19, 20]. Such a low environmental impact means that we can also take radically different approaches to robot deployment. Instead of releasing and recovering a small number of non-biodegradable robots which must be recovered at the end of their productive

Fig. 3 Electrical actuation of biodegradable gelatine. Frames 4s apart

lives, we can speculatively release hundreds, thousands or millions of biodegradable robots, safe in the knowledge that they will degrade to nothing in the environment.

We have seen here that soft robots have the potential to revolutionise environmentally-interacting robotics. Like their biological equivalents they can live, die and degraded in harmony with the natural environment. The use of natural biopolymers also opens up radical new areas of robotics, including edible robots. What could be more natural when you have a stomach pain to eat a robot which could diagnose the problem, provide on-the-spot treatment and then be consumed by natural digestion within the body or in normal waste treatment once it leaves the body? As we have seen, eating, drinking, living, dying and decaying soft robots may assist in solving many of our most pressing natural and man-made problems.

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Soft Robot Modeling, Simulation and Control in Real-Time

Christian Duriez and Thor Bieze

Abstract This chapter presents new real-time and physics-based modeling methods dedicated to deformable soft robots. In this approach, continuum mechanics provides the partial derivative equations that govern the deformations, and Finite Element Method (FEM) is used to compute numerical solutions adapted to the robot. A formulation based on Lagrange Multipliers is used to model the behavior of the actuators as well as the contact with the environment. Direct and inverse kinematic models are also obtained for real-time control. Some experiments and numerical results are presented.

1 Introduction

Soft robots have a highly deformable structure, similar to organic materials, and the motion of these robots is created by deformation in the same way as the muscles in animals. Soft-robots have a theoretical infinite number of degrees of freedom and the robot deformations could be partially driven by the collision with its environment. Consequently, the standard methods used to control robots are inadequate and the modeling and control methods are an open problem in soft robotics. In this work, we demonstrate the feasibility of using real-time model of deformable solid mechanics based on Finite Element Methods. The method is developed for both simulation of the robot in its environment and inverse kinematic control.

1.1 Mechanical Deformable Models for Real-Time Computation

In this work, the non-linear deformation of the soft robot is computed using FEM. The method integrates the constitutive law of the deformable material over the whole

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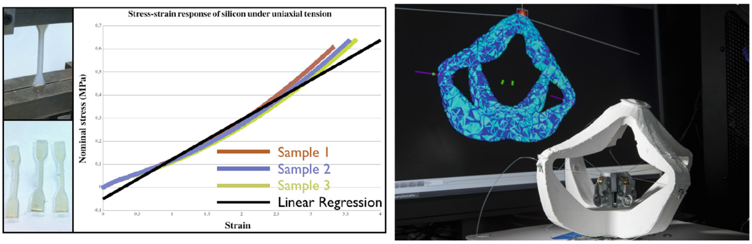

Fig. 1 Mechanical experiments to obtain the constitutive law on a silicone sample and Finite Element Method applied on a soft robot (*Left*) Photos of the uniaxial tension experiment (*Middle*) stress/strain response of the silicon. (*Right*) FEM model and the corresponding soft-robot

structure. The constitutive law describes the stress/strain function, which can be obtained empirically, as shown in Fig. 1. This kind of measure is quite standard but the result could exhibit more complex constitutive laws (non-linear hyperelasticity, anisotropic formulation...).

In this study, the choice of large strain but small stress with a corotational formulation [4] provides a good compromise between performance and accuracy. Of course, more sophisticated FEM models could be proposed in the future, according to the constitutive law and solicitation of the material employed (i.e. large stress). Moreover, for meshing the shape of the robot, we use linear tetrahedral elements, but the same method could be use with other element and shape function. The method requires a fast computation of the FEM model with numerical stability; to this end, we use a C++ implementation, freely available in the open-source framework SOFA [3]. Finally, the main hypothesis of this work is that the robot moves at low velocity and quasi-static modeling of the deformation is relevant[1].

During each step i of the control, based on the simulation, the equilibrium between external and internal forces is linearized:

$$\mathbf{f}(\mathbf{x_i}) + \mathbf{p} + \mathbf{J}^T(\mathbf{x_i})\boldsymbol{\lambda}_\mathbf{i} = 0 \quad \approx \quad \mathbf{f}(\mathbf{x_{i-1}}) + \mathbf{K}(\mathbf{x_{i-1}})d\mathbf{x} + \mathbf{p} + \mathbf{J}^T(\mathbf{x_{i-1}})\boldsymbol{\lambda}_\mathbf{i} = 0 \qquad (1)$$

where $\mathbf{f}$ provides the volumetric internal stiffness forces at a given position $\mathbf{x}$ of the nodes, $\mathbf{p}$ represents the external forces (e.g. gravity) and $\mathbf{J}^T\boldsymbol{\lambda}$ gathers the loads of boundary conditions on the end-effector, actuators and contact with $\mathbf{J}^T$ that gives the direction of these loads and $\boldsymbol{\lambda}$ their magnitude. $\mathbf{K}(\mathbf{x})$ is the tangent stiffness matrix that depends on the actual position of the nodes. The lines and columns that correspond to fix nodes are removed from the system to obtain a symmetric positive matrix in $\mathbf{K}$.

Two types of actuators, tendons and pneumatic cavities, are considered in this work. We thus have 4 possibilities to fill the lines of matrix $\mathbf{J}$. For each line i, we will define a function $\boldsymbol{\delta}_i(\mathbf{x}) : \mathscr{R}^{3n} \rightarrow \mathscr{R}$ for which we have $\mathbf{J}_i = \frac{\partial \boldsymbol{\delta}_i(\mathbf{x})}{\partial \mathbf{x}}$.

[1] We can easily extend the direct simulation to the dynamics of the robot in Sect. 1.3, using implicit method like in [3]. But the formulation of the inverse model Sect. 1.4 would change.

- End effector: For the 3 lines e that corresponds to the end-effector, $\boldsymbol{\delta}_e(\mathbf{x})$ measures the shift along x,y and z between the end effector position and its desired position. In the case of end-effector constraint $\boldsymbol{\lambda}_e = 0$.
- Tendons (Cable): One possible actuation is to place cables inside the structure of the robot to pull at certain points to create a deformation. We have one line per cable and the function $\boldsymbol{\delta}_a(\mathbf{x})$ measures the length of the cable which is modified by the actuation. $\boldsymbol{\lambda}_c$ is the force applied by the cable on the structure.
- Pneumatic: The other type of actuation considered in this study is pneumatic; a change in pressure is used to activate a deformation. In such case $\boldsymbol{\delta}_a(\mathbf{x})$ is a measure of the volume of the cavity. $\boldsymbol{\lambda}_c$ is the pressure inside the cavity.
- Contact: when contact appears on the robot, $\boldsymbol{\delta}_c(\mathbf{x})$ measures the interpenetration between the robot and the obstacle at the contact point. $\boldsymbol{\delta}_c(\mathbf{x}) \geq 0$. $\boldsymbol{\lambda}_c$ is the contact force.

1.2 Computation Process

From Eq. (1), at a step $\mathbf{i}$, the equation on the right has two unknowns: $d\mathbf{x}$ which is the difference between positions $d\mathbf{x} = \mathbf{x_i} - \mathbf{x_{i-1}}$ and $\lambda_\mathbf{i}$, which is the intensity of the actuators and contact loads. Consequently, the solving process will be scheduled in two steps.

The first step consists of obtaining a free configuration $\mathbf{x}_{\text{free}}$ of the robot that is found by solving Eq. (1) while considering that there is no actuation and no contact applied to the deformable structure.

$$-\mathbf{K}(\mathbf{x_{i-1}})d\mathbf{x}_{\text{free}} = \mathbf{p} + \mathbf{f}(\mathbf{x_{i-1}}) \tag{2}$$

$$\mathbf{x}_{\text{free}} = \mathbf{x_{i-1}} + d\mathbf{x}_{\text{free}} \tag{3}$$

To solve the linear Eq. (2), we use a LDL^T factorization of the matrix $\mathbf{K}$. The size of matrix $\mathbf{K}$ is often very large so an optimization in the motion space would be computationally very expensive. Given this new *free* position $\mathbf{x}_{\text{free}}$ for all the nodes of the mesh (i.e. position obtained without load on actuation or contact) we can evaluate the values of $\boldsymbol{\delta}_i^{\text{free}} = \boldsymbol{\delta}_i(\mathbf{x}_{\text{free}})$, defined in the previous section.

The second step is based on an optimization process, that provides the value of $\boldsymbol{\lambda}$. In the following sections, we will define two cases of use:

- *Direct modeling* of the robot in its environment: we impose the actuator values (either δ_a or λ_a) and the model gives the displacement of the effector. The optimization process provides the contact response λ_c.
- *Inverse modeling* of the robot: we provide a desired position on the effector of the robot and the optimization gives the force or the motion δ_a or λ_a that needs to be applied on the actuators in order two minimize the distance with the effector position. In such case, we do not consider contact.

In both cases, the approach relies on an optimization process and its output is the value of the Lagrange multipliers. To perform this optimization in real-time we propose to project the problem in the constraint space using the Schur complement:

$$\boldsymbol{\delta}_i = \underbrace{\left[\mathbf{J}_i \mathbf{K}^{-1} \mathbf{J}_j^T\right]}_{\mathbf{W}_{ij}} \boldsymbol{\lambda}_j + \boldsymbol{\delta}_j^{\text{free}} \tag{4}$$

This step is central in the method. $\mathbf{W}_{ij}$ provides a measure of the mechanical coupling between the boundary conditions i and j, whether they corresponds to effector, actuator or contacts. In practice, this projection allows to perform the optimization in the smallest possible number of equations. It should be emphasized that one of the main difficulties is to compute $\mathbf{W}_{ij}$ in a fast manner. No precomputation is possible because the value changes at each iteration. But this type of projection problem is frequent when solving friction contact on deformable objects, thus, several strategies are already implemented in SOFA [2].

After solving the optimization process described in the two following sections, we get the value of $\boldsymbol{\lambda}$, and we can compute the final configuration of the soft robot, at the end of each time step:

$$\mathbf{x}_t = \mathbf{x}_{\text{free}} + \mathbf{K}^{-1} \mathbf{J}^T \boldsymbol{\lambda} \tag{5}$$

1.3 Direct Kinematic Model and Contact with Environment

As explained above, using the operator $\mathbf{W}_{ea}$, we can get a measure of the mechanical coupling between effector and actuator, and with $\mathbf{W}_{aa}$, the coupling between actuators. On a given configuration, $\mathbf{W}_{ea}$ provides a linearized relationship between the variation of displacement $\Delta\boldsymbol{\delta}_e$ created on the end-effector and the variation of the effort $\Delta\boldsymbol{\lambda}_a$ on the actuators. To get a direct kinematic link between actuators and effector point(s), we need to account for the mechanical coupling that can exist between actuators. This coupling is captured by $\mathbf{W}_{aa}$ that can be inverted if actuators are defined on independent degrees of freedoms. Consequently, we can get a kinematic link by rewriting Eq. (4):

$$\Delta\boldsymbol{\delta}_e = \mathbf{W}_{ea} \mathbf{W}_{aa}^{-1} \Delta\boldsymbol{\delta}_a \tag{6}$$

This relationship provides (in the most condensed way) the displacement of the effector given the displacements of the actuators. Matrix $\mathbf{W}_{ea}\mathbf{W}_{aa}^{-1}$ is equivalent to a jacobian matrix for a standard, rigid robot. This corresponds to a local linearization provided by the FEM model on a given configuration and this relationship is only valid for *small variations* of $\Delta\boldsymbol{\delta}_a$.

In order to add the modeling of the environment, we need to deal with contact mechanics, and find the value of $\boldsymbol{\lambda}_c$. For that, we will rely on a formulation of the complementarity problem using Signorini Conditions [2]:

$$0 \leq \boldsymbol{\delta}_c \perp \boldsymbol{\lambda}_c \geq 0 \tag{7}$$

$$\boldsymbol{\delta}_c = \mathbf{W}_{cc}\boldsymbol{\lambda}_c + \mathbf{W}_{ca}\boldsymbol{\lambda}_a + \boldsymbol{\delta}_c^{free} \tag{8}$$

$$\boldsymbol{\delta}_a = \mathbf{W}_{ac}\boldsymbol{\lambda}_c + \mathbf{W}_{aa}\boldsymbol{\lambda}_a + \boldsymbol{\delta}_a^{free} \tag{9}$$

If the effort values on the actuators is known directly, the vector $\mathbf{W}_{ca}\boldsymbol{\lambda}_a$ is known and the problem is a Linear Complementarity Problem (LCP) with Eqs. (7 and 8). If imposing $\boldsymbol{\delta}_a$, the motion of the actuators, is preferred, then $\boldsymbol{\lambda}_a$ is unknown but there is a supplementary linear relationship between $\boldsymbol{\delta}_a$, $\boldsymbol{\lambda}_c$ and $\boldsymbol{\lambda}_a$ and we have a Mixed Complementarity Problem (MCP). This approach can be extended to friction contact with the method described in [2].

1.4 Inverse Model by Optimization

The goal of the optimization is to find how to actuate the structure so that the end effector of the robot reaches a desired position. It consists in reducing the norm of $\boldsymbol{\delta}_e$ which actually measures the shift between the end effector and its desired position. Thus, compute $min(\frac{1}{2}\boldsymbol{\delta}_e^T\boldsymbol{\delta}_e)$, can be done by setting a Quadratic Programming (QP) problem:

$$min\left(\frac{1}{2}\boldsymbol{\lambda_a}^T\mathbf{W}_{ea}^T\mathbf{W}_{ea}\boldsymbol{\lambda_a} + \boldsymbol{\lambda_a}^T\mathbf{W}_{ea}^T\boldsymbol{\delta}_e^{\text{free}}\right) \tag{10}$$

$$\begin{aligned} &subject\ to \text{ (course of actuators) : } \delta_{min} \leq \boldsymbol{\delta}_a = \mathbf{W}_{aa}\boldsymbol{\lambda_a} + \boldsymbol{\delta}_a^{\text{free}} \leq \delta_{max} \\ &and \text{ (case of unilateral effort actuation) :} \boldsymbol{\lambda_a} \geq 0 \end{aligned} \tag{11}$$

The use of a minimization allows to find a solution even when the desired position is out of the workspace of the robot. In such case, the algorithm will find the point that minimize the distance with the desired position while fulfilling to the limits introduced for the course of the actuators.

The matrix of the QP, $\mathbf{W}_{ea}^T\mathbf{W}_{ea}$ is symmetric. If the number of actuators is equal or less than the size of the effector space, the matrix is also definite. In such case, the solution of the minimization is unique.

In the opposite case, i.e., when the number of actuators is greater than the degrees of freedom of the effector points, the matrix of the QP is only semi-positive and the solution could be non-unique. In such case, some QP algorithms are able to find one solution among all possible solutions [5], but an additional criterion can be added to regularize the quadratic cost function and force the QP matrix to be definite.

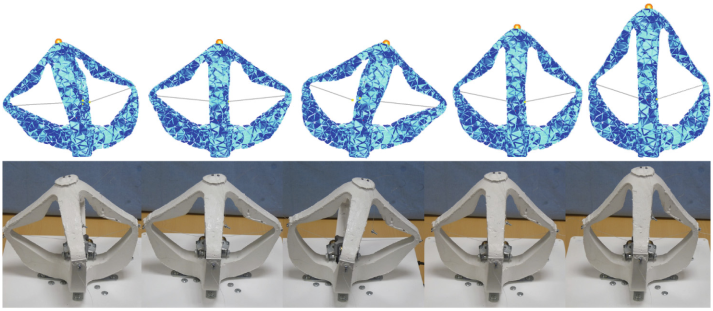

Fig. 2 Screenshots of the inverse kinematic model and the corresponding configurations of the real robot

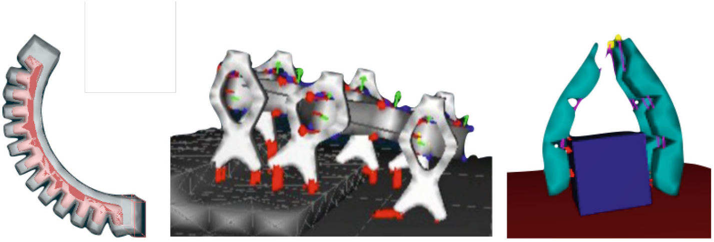

Fig. 3 Screenshot of interactive FEM simulations of soft robots in their environment

1.5 Results and Conclusions

In this chapter, we present a generic method for direct and inverse modeling of soft-robots. The method has been applied for interactive control of a real 3D soft robot made of silicone with an analysis of the precision. The results, shown in Fig. 2, are presented in more details in [1]. The computation time for each step is below 30 ms on a 2.5 GHz Intel Core i7 for a mesh of 1628 nodes.

Other examples demonstrate the interactive FEM simulations of the PneuNets bending actuators, a soft robot in locomotion on a rigid ground and the simulation of grasping using a soft gripper, see Fig. 3.

The modeling method presented in this chapter is generic and can be applied to soft and deformable robots. We demonstrate the real-time feasibility of inverting the model and simulating the robot in its environment. In future work, we will investigate a better trade-off between computation time and size of the mesh in order to keep real-time performance on more complex robots. Future work will also investigate more advanced control methods based on FEM models.

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Evolutionary Developmental Soft Robotics: Towards Adaptive and Intelligent Soft Machines Following Nature's Approach to Design

Francesco Corucci

Abstract Despite many recent successes in robotics and artificial intelligence, robots are still far from matching the performances of biological creatures outside controlled environments, mainly due to their lack of adaptivity. By taking inspiration from nature, bio-robotics and soft robotics have pointed out new directions towards this goal, showing a lot of potential. However, in many ways, this potential is still largely unexpressed. Three main limiting factors can be identified: (1) the common adoption of non-scalable design processes constrained by human capabilities, (2) an excessive focus on proximal solutions observed in nature instead of on the natural processes that gave rise to them, (3) the lack of general insights regarding intelligence, adaptive behavior, and the conditions under which they emerge in nature. By adopting algorithms inspired by the natural evolution and development, *evolutionary developmental soft robotics* represents in a way the ultimate form of bio-inspiration. This approach allows the automated design of complete soft robots, whose morphology, control, and sensory system are co-optimized for different tasks and environments, and can adapt in response to environmental stimuli during their lifetime. This can be useful for several purposes, from the evolutionary design of soft robots for practical applications, to the study of general properties of soft bodied creatures, which could help realizing the full potential of this field.

1 Introduction

Researchers in the field of biologically inspired robotics [1] (which includes soft robotics [2]) take inspiration from the natural world in order to distill effective mechanism observed in animals and plants into new engineering solutions. Although this procedure has a number of positive effects (e.g. a deeper comprehension of

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biology–"*understanding by building*", the possibility to overcome technological barriers by finding alternative solutions to complex problems, etc.), there is an aspect of conventional bio-inspired design that deserves to be highlighted.

Researchers in this field take inspiration from the *products* of a number of natural processes (most notably, *evolution*) that occur in the natural world. This has a number of important consequences. First, the creatures that populate our world are the result of a single evolutionary trajectory, determined by continuous incremental adaptations that allowed them to survive in a changing environment, facing the opponents that happened to compete for the same resources at a given time. Therefore, they are not necessarily optimal in general terms, as we would like machines to be in the engineering field. Secondly, animals and plants are optimized for the biological substrate that was available on earth (e.g. bodies are made of cells, which require specific conditions to survive). In robotics, however, we are not limited to that. Humans have invented sophisticated technologies (e.g. robust and lightweight materials, high-speed computation and communication technologies, all sorts of sensors and actuators, etc.) that cannot be found in nature, and could not be, therefore, exploited during natural evolution. Third, animals and plants are "designed" to cope with challenges such as survival, foraging and reproduction. Although a parallelism can be made among these tasks and those that robots are (or will be) required to accomplish (e.g. surviving = avoid being destroyed in a hostile environment, foraging = harvest energy and resources in order to self-sustain), robots are not in general required to solve tasks that are of paramount importance in the natural world (e.g. they do not need to mate and reproduce), which shaped natural evolution.

These observations entail a paradigm shift in bio-inspiration: despite the solutions that we observe in the natural world being clever and astonishing, what is really special about them is, more than each specific mechanisms, the *processes* that produced them, and the fact that they managed to do so with neither guidance, nor goals. This justifies fields such as *developmental robotics* [3] and *evolutionary robotics* [4], in which inspiration is taken from biological *processes*, that are generalized and applied to artificial systems. In some cases, this also allows moving from the study of "*life-as-we-know-it*" to that of "*life-as-it-could-be*" [5]. For example, with algorithms inspired by natural evolution (*evolutionary algorithms*) it is possible to set up sophisticated simulations that allow us to observe different evolutionary trajectories (as opposed to the single one that we can observe on earth) and perform all sorts of evolutionary study by changing the environment, the starting conditions, and the elements that evolution can manipulate.

In what follows some examples will be briefly described in which evolutionary algorithms are applied in soft robotics, combined, in some cases, with developmental paradigms. This research area can be broadly referred to as *evolutionary developmental soft robotics* (*evo-devo-soro*), a subfield laying at the intersection between artificial life and robotics, in which entire soft robots—both their morphology and control systems—are automatically evolved and grown instead of being manually designed. As the reported examples will point out, this can be done with several different purposes in mind: from the design and optimization of real robots for specific tasks, to the study of general properties of soft bodied creatures.

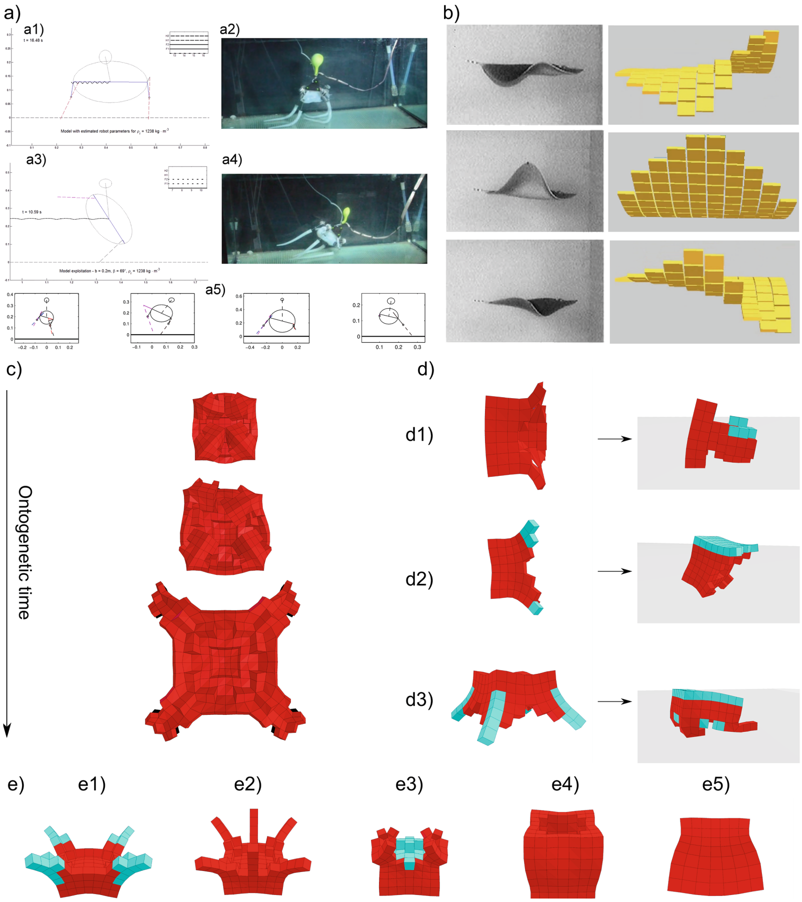

Fig. 1 Examples of *evo-devo-soro*. **a** Evolutionary algorithms have been extensively applied in the design of the PoseiDRONE robot. Shown are examples of a successful transfer from evolutionary simulations (*a1*, *a3*) to the real robot (*a2*, *a4*), entailing in some cases substantial performance improvements. In (*a5*) a subset of alternative designs suggested by evolution are shown. **b** Evolutionary simulations have been adopted to study specific animals too, such as *batoid* fished (e.g. the manta ray). Pictures show the qualitative match between the animal and a simulated compliant wing, that was evolved to study the emergence of oscillatory dynamics involved in the locomotion of these fishes. **c** A growing soft robot whose morphology and developmental processes were co-evolved in order to reach out four light sources (not depicted) placed at the four corners. **d** A study focused on the effect of environmental transitions water $\leftrightarrow$ land on morphological evolution. Robots evolved to swim (*left*) are moved to land and further optimized in order to study exaptation phenomena (e.g. tentacles become legs in (*d3*) and the relationship between swimming and walking. **e** A set of soft robots evolved to swim. A wide array of life-like morphologies and behaviors emerged. See all these evolved robots in action at https://goo.gl/ka3clE

2 Examples of Evolutionary Developmental Soft Robotics

Figure 1 summarizes the examples that will be briefly described in this section.

2.1 Evolutionary Design of Real Robots

Evolutionary algorithms have been extensively applied in the design of the PoseiDRONE robot, an octopus-inspired soft underwater drone (Fig. 1a). They were first used to achieve a faithful dynamical model of the robot (*genetic parameters identification* [6–8]) (Fig. 1a1, a2), then to explore its design space and suggest alternative configurations [9–11] (Fig. 1a3–a5). Many insights were gained from these studies, and in some cases evolved behaviors (Fig. 1a3, a4) correctly transferred to the real world, with a significant improvement of locomotion performances.

2.2 Studying Specific Properties of Soft-Bodied Animals

In another work [12], evolutionary simulations were employed to study the emergence of oscillatory phenomena involved in the locomotion of *batoid* fishes such as the manta ray (Fig. 1b), and to identify the key morphological traits for the adaptation of such a morphology to different environments (e.g. fluids with different density). The tools and the insights developed with these studies could be useful both to evolutionary biologists and robotic engineers.

2.3 Studying General Properties of Soft-Bodied Creatures

A recent article [13] starts investigating the properties of morphologically-plastic soft robots, i.e. soft robots that are able to adapt during their lifetime in response to environmental stimuli (*environment-mediated development*). This aspect (also referred to as *developmental plasticity*) could be key to realizing the huge potential of soft robots in terms of morphological adaptation. Several technologies already allow soft robots to adapt some aspects of their body during their lifetime, but this adaptation is usually controlled by humans and is rarely triggered by environmental stimuli, as it happens in nature. In order for soft robots to be effective and adaptive in the face of changing environmental conditions, insights should be gained regarding when and how such phenomena occur in nature.

This is particularly important if we take into account *embodied intelligence* [14], which postulates that effective behavior is often the result of the dynamic interplay of many factors (not only control, but also morphological structure, material properties, passive dynamics, interaction with the environment etc.). In robotics, these aspects are often carefully tuned by the human designer, in order to have the robot behaving in a desirable "sweet spot". It is clear that if the environment happens to change (as it does, in the real world), that sweet spot can only be maintained if the robot is able to recognize that change, and control a suitable adaptation, that can of course happen in the control system, but could leverage body properties as well. This is also related to the concept of *morphosis* [9, 11] (see the related chapter in this volume).

Motivated by these observations, growing soft robots are evolved in [13] to perform a simple phototaxis task, elected as case study (Fig. 1c). Preliminary results show that artificial evolution is able to find effective morphologies and associated developmental processes, often exploiting passive dynamics and *morphological computation* [15]. It is shown, however, that material properties have a dramatic effect on evolution's ability to exploit such beneficial phenomena, that are quantified in information-theoretic terms. This further highlights the importance of morphology, and shows how evolutionary simulations can be used to investigate the conditions under which adaptive and, ultimately, intelligent behavior emerge.

2.4 Answering Evolutionary Biology Questions Through Evolutionary Simulations

Another recently introduced setup [16] allows the evolution of swimming soft robots. Despite a very simplified fluid model, it is remarkable how artificial evolution came up with a wide arrange of life-like morphologies and behaviors (Fig. 1e). This setup is currently being used for several studies, concerning the role of softness in (underwater) locomotion, the relationship between underwater and terrestrial locomotion and, particularly, the effect of environmental transitions (e.g. water $\leftrightarrow$ land) on morphological evolution (Fig. 1d). This kind of studies have the potential to contribute not only to robotics and soft robotics, but also to fields such as evolutionary biology.

3 Conclusions

In this chapter some considerations in favor of evolutionary developmental soft robotics have been discussed, presenting four different application scenarios. It is expected that the adoption of such automated procedures will become more and more necessary in order to optimize increasingly complex robots that, with progresses in fields such as smart materials, will soon embed massively distributed sensing and actuation systems. A tight integration among different subsystems will be more and more required: the unique ability of evolutionary algorithms to co-optimize all aspects of a robot could be extremely useful in that. In addition to representing a viable way to design and optimize complete soft robots for specific tasks and environments (even more so with advances in digital fabrication and in techniques aimed to preserve the effectiveness of evolved behaviors into the real world), it has been suggested that evolutionary simulations can be used to investigate general properties of soft-bodied creatures, contributing to a deeper understanding of the phenomena and the conditions that lead to the emergence of adaptive and intelligent behavior, possibly unleashing the full potential of this field.

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Morphosis—Taking Morphological Computation to the Next Level

Helmut Hauser and Francesco Corucci

Abstract Morphological Computation is a concept used in robotics that sees physical bodies of robots as means to carry out computations that are relevant for their successful interaction with the environment. It is inspired by observations in nature where we can see that the morphology (i.e. the shape as well the dynamic properties of the body) of biological systems is playing a crucial role for the emergence of intelligent behavior. Although there are a number of successful implementations of this concept in robotics, there are still challenges to overcome. One is that any functionality implemented in a morphology is deemed to be fixed. However, truly autonomous robots should be highly flexible and are expected to be able to adapt to changes in the environment and to new tasks. In case of morphological computation, in order to change the desired computation to be carried out, the underlying morphology has to be altered. A solution is to introduce mechanisms that enable the robot to make these changes online, often referred to as *morphosis*. We introduce and discuss a general notion of morphosis from the view point of dynamical systems theory, highlight the concept by examples from robotics, and elaborate on the wide-reaching implications with respect to the design of highly autonomous robots.

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1 Introduction

There are numerous robotic examples that apply morphological computation as design principle. They all use the robot's body dynamics to carry out (implicitly, or explicitly) relevant computational tasks including nonlinear processing, transforming, and transmitting information. Successful implementations include highly robust locomotion, like running [17], swimming [7, 22], flying [18], as well the combination of different locomotion modes [2–4]. It has also been shown that morphological computation is useful in the context of grasping [1], sensing [13], as well facilitating communication [15, 16] and control [14]. Although morphological computation has been successfully applied, and, theoretically, there is almost no limitation with respect to which computations can be carried in morphological structures [9, 10], there are still a number of challenges that have to be addressed. One is the limitation that once a computation is implemented in a certain morphology, it will be fixed. This is a problem if we want to build highly autonomous systems that are able to adapt to changes in the environment or to new tasks. Recently, there has been an effort to incorporate mechanisms that overcome this limitation by enabling the robot to dynamically reconfigure its morphology. Often referred to as *adaptive morphology* or *morphosis*, this concept has strong implications regarding the possibility to build highly robust systems, simplifying control, and implementing hierarchical control structures that might form the basis for higher cognitive functions.

2 Morphosis from the Perspective of Dynamical Systems Theory

A number of mechanisms have been proposed to vary morphological parameters online. These include simple variable impedance and damping systems that can help to increase the range of conditions in which a robot is able to work properly, e.g. as in [20]. Some robotic systems go beyond that by allowing a reconfiguration of the morphological structure that results in a qualitative change in the behaviour of the robot [5, 6, 21]. Both approaches implement the idea of morphosis. To better understand this concept, we propose to look at it from the dynamical systems' point of view.

For the sake of simplicity, let's consider an arbitrary stable one-dimensional dynamical system (note that the underlying concepts are scalable). The left part of Fig. 1a (i.e. behaviour A) shows an example of the attractor landscape of such a system with one stable equilibrium point located at the bottom of the "valley". If the system is perturbed, its own body dynamics will bring it automatically back to this point (blue arrow). By changing the parameters of the dynamical system (i.e. changing morphology), we can get a different response. For example, we can make the valley steeper if we make the mechanics stiffer. If the dynamics of the body are complex enough, we can have two (or more) equilibrium points, representing

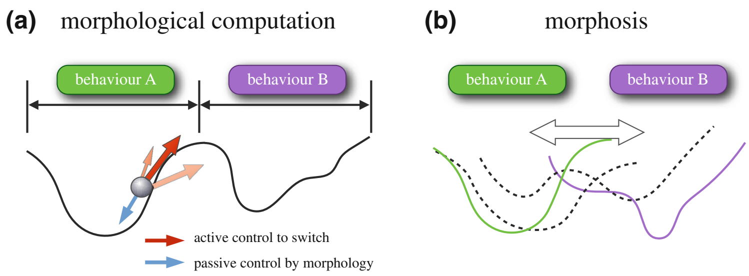

Fig. 1 Dynamical systems view of morphological computation and morphosis. **a** Two fixed behaviours implemented in one morphology. **b** Morphosis enables smooth switching between two behaviours by reshaping the attractor landscape

different (locally) stable behaviours, see both sides of Fig. 1a. The question is how can we move from one equilibrium point (i.e. one behaviour) to another? As it turns out this is very simple: The system has to get pushed into the right direction to get over the energy hump between them. Note that the required control is low-dimensional and it can be rather imprecise. The direction of the force can vary (compare red arrows in Fig. 1a) and the amplitude just needs to be big enough to overcome the hump between the two valleys. The rest is done by the attractor landscapes of the local equilibrium points. Also, energy is only required during the change. While this is very promising and has a great potential (see [10, 11] for examples), this is not morphosis yet. Now, instead of having a fixed attractor landscape we can imaging morphosis as a way to dynamically reshape the attractor landscape online (see Fig. 1b). By reshaping ("reprogramming") the body, morphosis enables the robot to easily switch among a set of different behaviours. As before, the control can be low-dimensional, imprecise, and is typically very energy efficient. Morphosis therefore further simplifies the control problem by outsourcing parts of the control to the morphology in form of attractor landscapes. It also provides a form of abstraction that implements implicitly a control hierarchy. As a consequence, building upon morphological computation and morphosis might lead us the way to achieve higher cognitive functions. Having discussed the notion of morphosis in the context of dynamical system theory, we are now ready to look at three robotic examples to underline the idea and to demonstrate its potential.

Example 1: Morphosis to achieve energy efficient locomotion

The most straightforward implementation of morphosis in locomotion consists in changing leg stiffness. A number of different variable compliant mechanisms have been proposed for that. One of them, MESTRAN [19], was used in the knee joint in the hopping robot leg shown in Fig. 2a. The idea of this setup was to mimic a behavior observed in humans and other animals, which adapt their leg stiffness depending on ground conditions in order to locomote in an energy efficient manner. The experimental setup in Fig. 2a allowed to vary systematically the stiffness of the ground. The robot leg was driven by a simple sinusoidal control signal applied at the hip motor. The knee joint was passive, but it was possible to adjust its stiffness. It was shown that there exist one optimal stiffness for each of the explored different ground stiffness values, resulting in minimal energy consumption [20]. This points to the great potential of morphosis to increase energy efficiency and versatility of robots over a wide range of environmental conditions.

Example 2: Morphosis to change gait

Locomotion in different environments (slopes, steps, roughness of the terrain, etc.) calls for different leg and foot trajectories. Vu et al. [21] developed a robot platform to explore this idea with the help of morphosis. The basic leg design was a crank-slider mechanism translating a simple control signal (i.e., constant rotational velocity) into two-dimensional leg trajectories (compare Fig. 2b). The morphosis mechanism changed the way the rotational movement was translated, while the control remained unchanged. The result was a range of different end point trajectories (see Fig. 2b) that can be useful for different terrains. Note that morphosis only takes place when there is a need for a change as opposed to the continuously running, rotational hip motor. As a result, the morphosis motor could be small, not very demanding, and could even be switched off during stable locomotion. This robotic prototype demonstrates how morphosis can help to increase the number of possible behaviors (gaits, in this case) within one robot design.

Example 3: Automated evolutionary design targeting morphosis

A complete design pipeline targeting morphosis was introduced in [5]. The case study is the locomotion of a soft underwater robot (PoseiDRONE, see [2, 3]) (Fig. 2c). A model of the robot dynamics was developed and fed into an evolutionary engine that, by tweaking a number of morphological parameters (24 in total), discovered thousands of alternative robot designs by maximizing a metric of behavioral novelty. This novelty metric was computed in a behavioral space defined by some locomotion-specific features. A clustering procedure was then implemented in the space spanned by the morphological parameters that evolution could modify, in order to identify groups of similar morphologies. At this point, an algorithm searched inside each cluster for similar morphologies that maximally differ in their behavior (i.e. that are far apart in the behavioral space): these are good candidates for morphosis. The procedure was able to discover several configurations in which the robot was able to dramatically and qualitatively change its behavior by slightly adjusting a single morphological parameter, in presence of a constant open loop control. For example, by slightly rearranging their bodies, discovered robots could switch from walking to swimming, from crawling to hopping (compare Fig. 2c), and others. Moreover, once morphosis was triggered, the transition between one morphology (and its associated behavior) to another did not have to be actively and precisely controlled, and relied in fact on the robustness and self-stabilizing properties of the attractor landscapes shaped by morphosis.

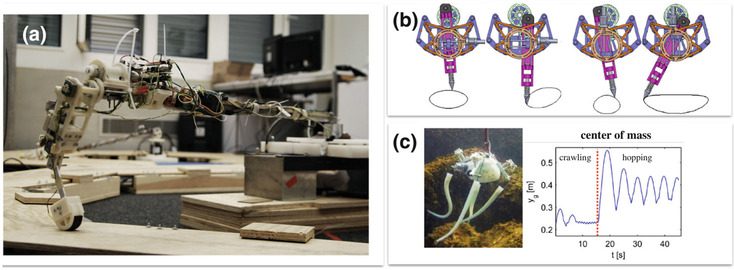

Fig. 2 Three examples of morphosis in robotics. Increase **a** versatility in locomotion, **b** number of gaits, and **c** behavioral repertoire (plot of CoM, switch at $t = 15$ s from crawling to hopping)

3 Outlooks and Conclusions

The concept of adaptive morphology/morphosis has been discussed from the view point of dynamical system theory. The presented robotic examples suggest a number of advantages. Morphosis can increase the range of operative conditions in which a robot is able to work. It also enables the implementation of different (robust) behaviours that resort on the power of morphology instead of on complex controllers, implying a new way to design versatile robots. Morphosis also implicitly establishes a hierarchical control structure, further reducing the control complexity. It also allows for imprecise high-level control signals, which can help robot to operate in noisy, real-world scenarios. Looking more into the future, morphosis will play a crucial role in artificially growing [8] and self-healing systems. Control systems will benefit from adaptive and reconfigurable bodies, that will take care of most of the low level control thus freeing resources for higher level and, ultimately, cognitive tasks. In order to exploit these ideas, processes to optimize morphologies will be needed [8, 12], allowing them to adapt during their lifetime and react to environmental stimuli [8]. Ultimately, these concepts will enable more robust, adaptive and intelligent robots, helping robotic technology to become truly pervasive.

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