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Perspective for soft robotics: the field's past and future

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Abstract

Since its beginnings in the 1960s, soft robotics has been a steadily growing field that has enjoyed recent growth with the advent of rapid prototyping and the provision of new flexible materials. These two innovations have enabled the development of fully flexible and untethered soft robotic systems. The integration of novel sensors enabled by new manufacturing processes and materials shows promise for enabling the production of soft systems with ‘embodied intelligence’. Here, four experts present their perspectives for the future of the field of soft robotics based on these past innovations. Their focus is on finding answers to the questions of: how to manufacture soft robots, and on how soft robots can sense, move, and think. We highlight industrial production techniques, which are unused to date for manufacturing soft robots. They discuss how novel tactile sensors for soft robots could be created to enable better interaction of the soft robot with the environment. In conclusion this article highlights how embodied intelligence in soft robots could be used to make soft robots think and to make systems that can compute, autonomously, from sensory inputs.

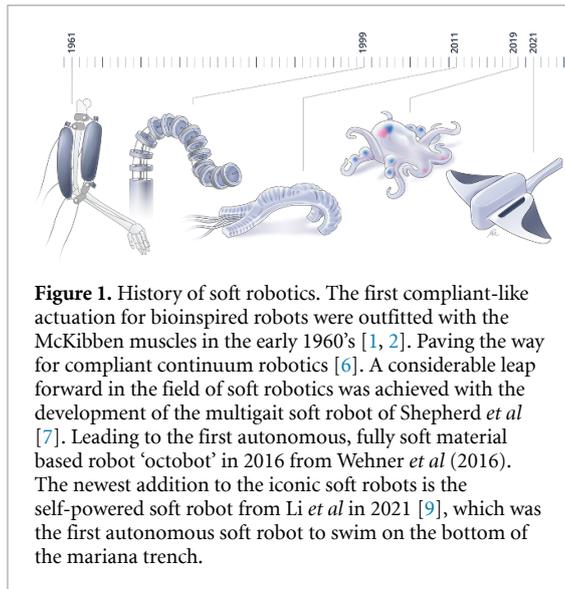
1. Introduction

The field of soft robotics had its beginnings with the first appearance of compliant actuators, e.g. McKibben muscles [1, 2]. In the second half of the 20th century the field has grown exponentially, with major developments and growth in the last decade. The pneumatic McKibben muscles that started the field [3], inspired inflatable and flexible micro-actuators [4, 5] which considerably downsized the scale for compliant actuation. These developments led to the development of flexible continuum robots [6], and then further to flexible robots based on silicone—like the iconic multigait soft robot of Shepherd *et al* [7]. Through systems such as the iconic fully soft autonomous robot ‘octobot’ [8] or Li’s self-powered system—the first autonomous soft robot to swim on the bottom of the mariana trench [9]—the level of complexity and system-integrations has been raised

from compliant, to fully flexible autonomous soft machines (figure 1).

Spanning over 70 years, research in soft-robotics has allowed a transition from hard robots with soft actuation to entirely soft systems [3] towards making systems like the ‘octobot’ or Li’s self powered soft robots. It has been necessary to utilize smart and partially soft materials as actuators, such as dielectric elastomers [9–11] or other electroactive polymers (IPMC, [12]). Further developments have included materials which can react or adapt to changing environmental conditions, in the form of a shape change in response to a rise in temperature (shape memory alloys (SMAs) [13] and polymers [14–16]), in response to certain wavelengths of light (liquid crystal elastomers [17]), and or a change in humidity such as hydrogel [18].

Actuation and control go and in hand in robots, especially in human-machine interaction situation



sensor and controllers must ensure that the actuators stop before dangerous situations arise. Soft robotics represents a new way to build devices that are explicitly designed for interaction tasks. The technologies resulting from this field of study provide an increase in the palette of materials and options available to designers of robotic systems and medical devices. 'Soft' adds value to robotics and we propose that hybrid systems will provide the most utility. As actuators become limbs in soft robots [7, 8, 19] and flexible sensors, can now be directly integrated into actuators walls.

The incorporation of liquid metals and conductive materials (e.g. EGaln, consisting of a mixture of gallium, indium, and tin or carbon paste) into these flexible materials brought forth an even more advanced actuator types capable of 'soft sensing' [20]. Even more recent developments have used living materials—including animal muscle and tissue cells, as well as bacteria—to drive soft systems, these developments have led to the creation of a new class soft robotics: bio-hybrids [21].

This rich history and technological developments have enabled a new age of sensing and environmentally-adaptive robots [3] and this backdrop opens up our discussion on each of our perspectives for the future of the field of soft robotics. Here, we focus on past developments within the field of soft robotics to answer the following questions concerning soft robots for the future:

- How to build them?
- How to make them sense?
- How to make them move? and
- How to make them think?

To answer these four questions, we will take a look at novel principles and techniques for the field of

soft robotics. We will show how current, yet unused industrial manufacturing techniques could accelerate the production of soft robots. We will show how bio-inspired sensing systems offer a perspective for developing fully flexible sensing soft machines, and how integrating the concept of 'embodied intelligence' into soft robots will lead to fully autonomous soft systems that are able to adapting and respond. This perspective is intended for researchers entering the field of soft robotics to provide an overview of the future direction of soft robotics, not in depth, but in breadth.

2. Perspective fields

In this section, three experts in soft robotics highlight the current state of the art of their respective fields, showcase the beacon systems, and provide their opinion on the challenges, opportunities and perspectives for the future based on their presentations at the living machines conference 2021 workshop perspectives for soft robotics.

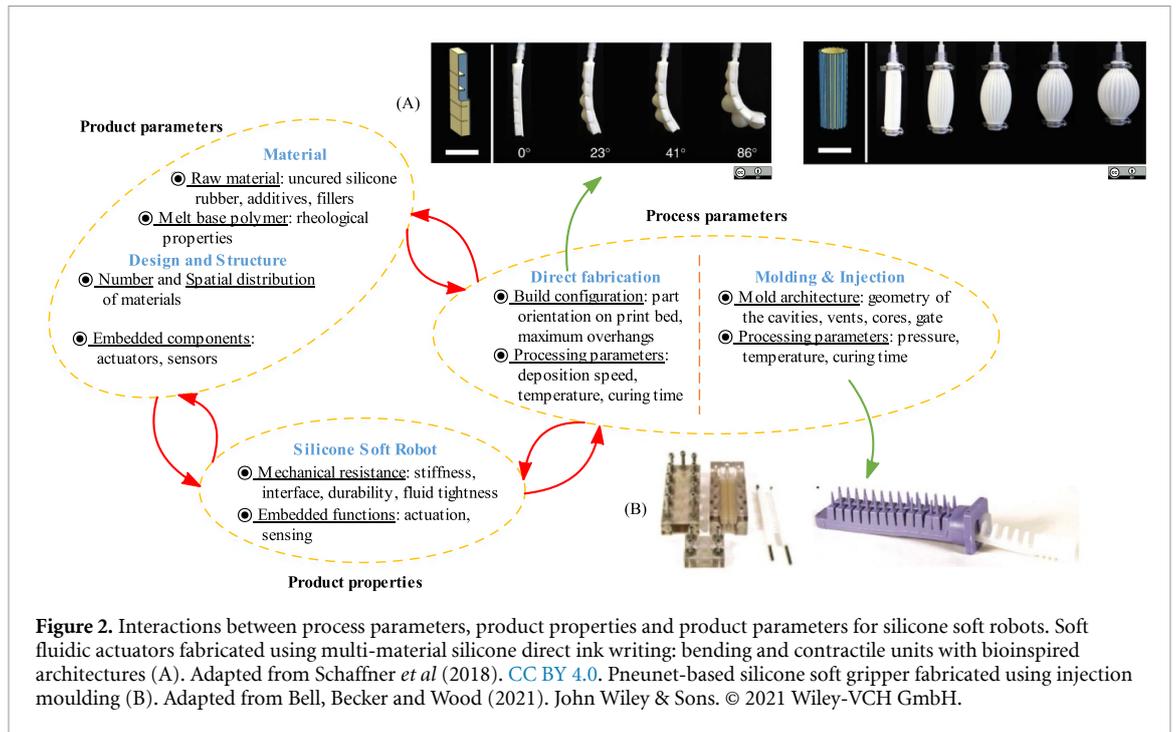
2.1. Manufacturing of soft robots

Soft robots are so different in types and forms that the question of their manufacturing can only be studied after setting specific boundaries. In this section, the scope of manufacturing is delineated to the large range of soft robots built using elastomer materials. Elastomers have numerous interesting features for soft robot construction such as high levels of extensibility, tensile strength, energy absorption and resistance to fatigue. They can also be combined with other materials via reinforcement fillers or using over molding to change locally the mechanical properties of the resulting parts.

2.1.1. Elastomer types and material/process/design interactions

Elastomers for soft robots can be classified into thermosets (TSE) and thermoplastics (TPE) [22]. In TSEs, an irreversible chemical reaction occurs by the action of heat, pressure, catalysts or light leading to a relatively infusible, nonreversible state. This class forms the vast majority of elastomers used in industrial applications. In contrast, TPEs do not need to be cured during fabrication and can be shaped by heating and return to solid state after cooling. Upon heating again, the material can be simply reprocessed. Iconic examples of TSE include natural rubbers and silicone elastomers whereas TPE polyurethanes or TPE copolyesters are typical TPEs that can be found as flexible filaments for 3D printing.

Interactions between materials, processes and shapes are of central importance for achieving intended properties of any product or system [23] and this particularly true when designing and fabricating soft robots. Product properties are descriptive of



the final features that the product acquires at the end of its fabrication process. These properties mainly depend on the nature of ‘ingredients’ that have been chosen and on their arrangement obtained using a specific design or architecture. These ingredients and the design structure correspond to the product parameters on which the designer can act. But fabrication processes or ‘recipes’ have also their specific conditions and requirements that can be gathered into a set of process parameters which have a strong influence on both product parameters and finally on the resulting product. Thus, manufacturing processes for elastomers need to be selected carefully to comply with the part geometry and depend on multiple factors including material related properties (TSE or TPE polymers, viscosity, curing parameters), production batch size (unitary or larger series). Figure 2 shows some typical parameters and properties in interaction influencing silicone soft robots manufacturing exemplified using two distinct fabrication processes, namely, direct fabrication and injection moulding.

2.1.2. Direct fabrication approaches

Even if the first rapid prototyping techniques have emerged more than 40 years ago, it is only during the last decade that some 3D printing technologies such as FDM (fused deposition modeling) and SLA (stereolithography) have become widely available and inexpensive helped by the expiry of several patents. FDM is certainly the most affordable and simple 3D printing technology that uses TPE polymers and TPEs. The usage of FDM to produce soft components has been demonstrated but fabrication of parts with functional air-tight cavities remains challenging

because support material needs to be removed and layer by layer construction leads to adverse anisotropic properties with delamination risks [26].

To gain more robust characteristics, SLA-based printers using TSEs can generally provide superior results at the price of a more complex process since the material needs to be cured during printing. Recent advances in printing technologies based on light-curable silicone inks or resins have opened new opportunities for the direct production of soft parts with complex geometries, good mechanical properties and at high production speeds [27]. Carbon [28] or 3D printing companies as Spectroplast [29] are examples of commercially available options to obtain silicone parts but more advanced systems of interest for soft robots such as fluidic elastomer actuators still need research efforts to achieve acceptable and durable material properties [24].

Beside the fact that most of the technologies are proprietary, these approaches still have several shortcomings:

- direct fabrication fulfills at best a single main design goal, e.g. the achievement of a right geometry with the desired material properties;
- soft robots requires the integration of additional functions such as actuation or sensing;
- hollow geometries are still challenging to achieve although promising techniques have been trialed [30];
- high dependence exists regarding the resin formulations and their rheological properties;
- fine control is required over the chemical reaction of photopolymerization;

- expensive for soft robots development;
- few manufacturing technologies are integrative, i.e. allow the integration of other processes for multi-functionalities or reduction of interfaces.

2.1.3. Mixed fabrication approaches

Another way to process TSEs for soft robots consists in using casting techniques in adequate combination with existing 3D printing approaches [31]. One key benefit is the abundance of available engineering-grade silicone resins, which can be processed at room temperature. This guarantees the best results for the final part properties but requires intermediates steps such as the fabrication of molds and inserts. For small series productions, these elements can be obtained using additive manufacturing with low-cost 3D printers [32].

Other benefits include the possibility to create functional airtight voids and hollow shapes using inserts as well as embedding over molded components with optimal bonding conditions [33]. Such components could be elements with different stiffness levels that change the way the soft matrix will deform upon loading, or parts in active materials for both actuation and sensing.

2.1.4. Perspectives in silicone soft robots manufacturing

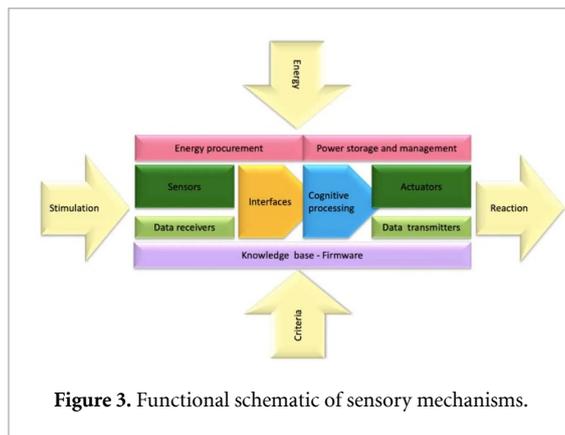
As mentioned above only few commercial silicone 3D printers are available and so far none are capable of multimaterial printing one workpiece. Skylar-Scott *et al* show with their voxelated multinozzle approach that multimaterial 3D printing silicones for soft robots is possible [34] which is a first step towards more complex and highly durable 3D printed soft robots. Currently, most direct fabrication processes implying TSEs and silicones are not amenable to simulation, contrary to molding methods in which process simulation can help the designer to get defect-free parts. A remaining challenge to take is to advance on more extended process simulation of such dedicated printers so that the final part properties can be better predicted using computer-aided engineering with less trials-and-errors.

One aspect to keep in mind for future manufacturing of soft robots is the implementation of existing industrial guidelines used in the polymer industry for the design of polymer-based workpieces. These could be used for the manufacture of soft robots and the corresponding tooling to enable repeatable performance of the soft systems produced. Initial approaches for such integration are given by VDI (Association of German Engineers) guidelines 6220 part 2 [35] and 6224 part 3 [36]. Another aspect is the specific development of novel tools to facilitate the casting process, such as low-pressure injection devices for the production of soft robots [25]. As well as the development of new high speed silicone 3D printers, as the current 3D printing processes are very time consuming.

2.2. Sensing in soft robots

Sensing in robots has depended in the past on electronic sensors for touch and smell, chemical sensors for taste, cameras for sight and microphones for hearing. To grasp an object a robot would require object recognition algorithms, proximity sensing and contact sensing. All these systems would need a computer to process sensor information and generate an appropriate response like gripping. Most of the human senses are already represented in bioinspired robots which have for example artificial taste sensors for artificial tongues enabling taste [37–39], bionic ears giving hearing [40], artificial retinas for sight [41–43] and biomimetic chemical sensors as artificial olfactory receptors to enable smell modality [44–46]. However, these sensors systems are not yet fully integrated into soft robotics although large progress has been made through the advancements of soft robotic manufacturing highlighted previously in this perspective review article. For example, 3D printing of conductive ionogels allowing for the first time the direct integration and embedding of flexible sensors into the elastomer or silicone based matrix body for the creation of a pneumatic soft robotic gripper allowing a robot to perceive an object by touch [8, 47]. In the following subsections advanced tactile sensing systems are presented that are or could be integrated into soft robots in the future.

Sensing in nature can be divided into the five senses: hearing, sight, smell, taste, touch [48]. All these sensory perceptions use different sensory organs (in some cases, more than one type of sensors for a given sensing modality) and are based on a single principle: a physical stimulus (light, smell, sound, taste, surface texture) is transformed into information by a sensor or series of sensors (retina in the eye, olfactory epithelium in the nose, taste buds in the tongue, eardrum in the ear, mechanoreceptors as well as heat and cold receptors in the skin) [48]. In non-reflex arc mode, information is conveyed via an electrical signal (action potential), and transmitted through nerves to the brain where it is processed to trigger a reaction. Most sensory neurons synapse however in the spinal cord for faster reflex actions without the delay by the interconnection of signals to the brain. Both sensory pathways can be represented however by a functional schematic shown in figure 3 that is relevant not only to most sensory systems in the animal kingdom, but can also be applied to many man-made systems [49]. Energy is needed for the electronic/cognitive processing unit, firmware, and data receivers of the sensory system as well as its interfaces governing the various domains of energy (electrical-mechanical etc.). Such energy needs also to be stored, managed and procured to the sensory system. Criteria regulate what information is relevant for cognitive processing to not waste energy on irrelevant information, as well as the threshold



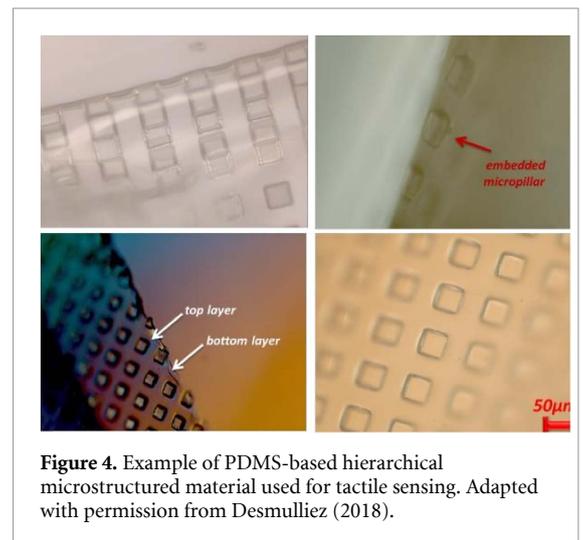
for decision-making process in terms of reaction. Sensory systems in nature are inherently miniaturized with a cognitive processing not necessarily centralized. Such systems can also be predictive and/ or have a ‘memory’ effect. If directly translating such a functional schematic to soft robotics, one could conceive a decentralized system with sensor on the outer shell of the soft robot and processing unit embedded inside, on the surface or even outside of the body in form of on-board processing unit or a standalone computer.

Sensory mechanisms include collection of signal, transduction, processing and action. An external stimulus will be transduced from a physical (e.g. touch) via the sensor into a computable signal (electrical e.g. action potential). The transducer stimulus is conveyed to the cognitive processing unit (brain or computer) and, based on a set of criteria; an appropriate reaction is generated through actuators (motors or muscles) or data transmission devices. The energy comes from the environment or the machine or organism directly. Natural sensory mechanisms tend to be multi-functional allowing thereby the reduction of interfaces.

2.2.1. Bioinspired tactile sensors

Tactile sensor systems found in vertebrates are based on mechanoreceptor cells which include Merkel discs, Meissner cells or tactile corpuscles, Pacinian corpuscles and hair follicle which are e.g. beneath the skin, around the basal part of hairs (especially whiskers) [50, 51]. These sensor systems detect touch, pressure and vibration and react with an electrical discharge to the central nervous system. Counterparts can be found in invertebrates (e.g. insects) [52] as well as in plants, such as the Venus flytrap trigger hairs [53].

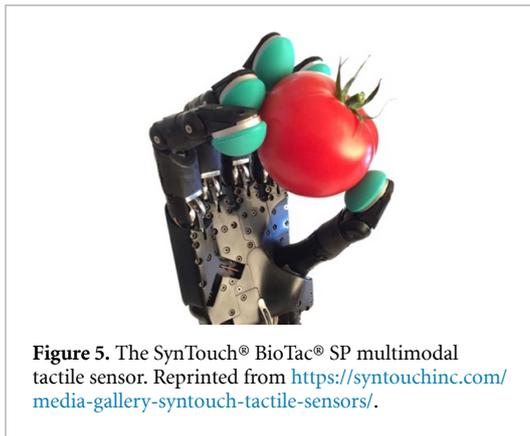
Amoli *et al* classify bioinspired tactile sensors into three categories [54]: Nature-inspired structural designs, nature-inspired functional designs and advanced sensory systems. Nature inspired structural designs encompass systems based on



whisker structures [55–57], interlocked structures [56, 58–62], Hierarchical structures [63–65]) as shown in figure 4 [66] and porous structures [67–69].

Such systems translate the basic structural design into a technical application such as electronic whiskers for example. Natural whiskers are specialized hairs, stiffer and longer than normal body hairs that are connected to a variety of subcutaneous sensory nerve cells [55]. Natural systems are highly sophisticated as the animal can detect location, size and texture of an object [54]. Their technical counterparts focus on integrating the multifunctionality of the whiskers in a thin flexible polymer substrate or strip paired with a flexible thin film of conductive materials doped with e.g. silver nanoparticles [70, 71]. Bending, compressing or stretching these thin multilayers will result in a deflection of the silver nanoparticles and a change in conductivity, which can be measured. One of the most sophisticated and representative bioinspired mechanical tactile sensor system is the multimodal tactile sensor BioTac[®] shown in figure 5 and commercialized by the company SynTouch LLC. BioTac[®] utilizes various different sensors [72]. This enables the SynTouch system to sense contact forces, as the elastic skin of the fingertips is distorted the impedance change of the conductive liquid underneath is registered by electrodes integrated into the rigid frame of the system. In addition, the system includes pressure sensors for vibrational measurements as well as thermistors for temperature sensing. All this makes the system usable not only as a high tech prosthesis but also for industrial material characterizations [72].

As the above described systems highlight, the current focus of research in soft robotic sensing is on nature inspired structural designs of tactile sensors as well as on advanced sensory system to create neurobotic systems [54], in our opinion more research work still needs to be carried out on nature-inspired



functional designs of tactile sensors. This is one of the key future directions of research that need proper consideration.

For these designs, the focus is on the translation of the basic natural principle into a technical application as seen in artificial ion channels [73], viscoporoelastic ion channels or ionic mechanoreceptors [74]. Such systems use for example polycarbonate track-etched (PCTE) nanoporous membranes to simulate the ion channels in between two electrolyte reservoirs supported on poly(vinylidene fluoride-trifluoroethylene) (PVDF) films as artificial mechanosensitive receptors [73]. Through a deformation of or strain on the outer membrane, a transport of ions through the nanoporous material is triggered, mimicking the release of ions and change in membrane potential of the biological mechanoreceptors [54, 73–75]. Such highly sophisticated nanoscale systems enable the production of highly sensitive artificial skins. However, large-scale production of such systems remains problematic.

Advanced sensory systems are another direction of research that should deserve more studies. Such systems try to mimic the functionality of natural sensor or nerve cells in function or incorporate into artificial systems like a digital mechanoreceptor [76–79], an artificial afferent nerve [80–82] or a neuromorphic tactile processing system [83, 84]. These systems could be directly integrated into biorobots to utilize the combination of living cells and soft robots. Use cases for such systems are tactile skins for soft robots as well as industrial robots [85], electronic whiskers [70], touch and object recognition sensors for robotic finger tips in robotic gripper as well as prosthetics and orthoses [85], and haptic feedback systems. Although such systems demonstrate how far biomimetic tactile sensors have advanced over the last decade in comparison to their commercially available counterparts [54], only few biomimetic tactile sensors effectively operate over a wide pressure range [72]. Further research progress in miniaturization, integration, self-test and self-repair is still

needed. The creation of such systems is still taking place laboratories or at small manufactory scale; large-scale industry grade production is still missing. First attempts are being attempted for example in the beginning of 2023 a big manufacturer for the chemical industry is launching flexible electro-active polymer laminates for actuators and capacitive sensors on a global scale [86]. Such system could be easily integrated into soft robots as compression and expansion sensors for tactile and movement sensing.

2.2.2. Autonomous biorobotic sensors

Leaving aside technical specifications such as accuracy, precision, specificity, requirements for ideal robotic sensors for autonomous systems can be drawn from lessons learned from presented tactile systems and examples taken from nature. These include:

- Self-powering, self-interrogation
- Robust and reliable
- Built-in self-test capability [87]
- Built-in self-repair capability
- Multi-modal sensing to reduce number of interfaces
- Fast-time response (application dependent)

Autonomous soft robots must have reliable as well as redundant internal systems to cope with harsh environments or changing conditions. For an autonomous system with a limited power supply or the reliance on renewable energy source such as solar power, the above-mentioned criteria are of utmost importance. Sensory systems should consume, as little energy as possible, should be robust, enable multimodal sensing and be capable of self-repair to keep system complexity and maintenance requirements on a bare minimum. Operational areas could be extreme environments such as the human body, outer space or the mariana trench [9].

One such a system would be a haptic feedback sensor system, which would be a wirelessly self-powered, self-interrogated sensor tunable to different applications [66]. The system could be made from an array of flexible capacitive pressure sensors sensing normal and shear forces, and compatible with mass-produced semiconductor manufacturing processes. Thus, these systems would be able to sense different pressures over a large-range from 1 Pa to 100 kPa. Most interesting pressures in respect to an application would be 1 kPa to 10 kPa for pulse pressure and 10 Pa to 100 kPa for gentle touch. The power system could be incorporated inside the robot to create an autonomous sensor. Such systems can be used for sensing in and monitoring of soft robotic systems but also as autonomous sensor systems for medical application such as gut pressure measurements.

Soft robots, which can keep their homeostasis through harvesting energy from the environment, outfitted with such sensors, would be able to sense and interact with the environment. Fully integrated autonomous soft robotic systems would inherit self-awareness by design; such embodied intelligence will be discussed in the next section.

2.3. Embodied intelligence in soft systems

The integration of ‘embodied intelligence [88]’ into soft robotic systems will lead to a new level of adaptability and autonomy. By incorporating physical characteristics and environmental interaction into modeling, control, and decision-making processes, the robotic system can respond and adapt to its surroundings in a more natural and energy-efficient way. Systems of this type mimic the natural world far more closely than with conventional robotics (figure 6). For example, a soft robotic hand with embodied intelligence would be able to grasp and manipulate objects based upon a model of the interaction between the robot’s physical properties and the forces exerted by the object, rather than relying solely on pre-programmed instructions. This approach will lead to more robust and reliable systems because the robotic system can continue to function even if it encounters unexpected situations or if it malfunctions.

The incorporation of embodied or physical-intelligence into soft robotic systems will also open up new possibilities for their use [89]. For example, in fields such as medicine and search and rescue, a soft robotic system with embodied intelligence would be able to navigate and interact with its environment in a more human-like way, making it more suitable for tasks such as assisting surgeons or searching for survivors in disaster-stricken areas. In addition, the ability of soft robotic systems with embodied intelligence to adapt and respond to their environment can also enable them to be used in areas where traditional rigid robotic systems would struggle, such as in environments with complex and changing geometries [90].

Answering the last open question of our four we will focus on controlling the actuation of soft robotic systems.

2.3.1. How to make soft systems move: design and control

A particular challenge in controlling the motion of soft systems is that the process of modeling and control is very different to the tools commonly employed in conventional kinematic-robotics [91]. These differences arise from the use of non-linear sub-system elements such as the use of viscoelastic elastomers and pneumatic actuation, as well as from the interaction of the soft-system with the environment. These

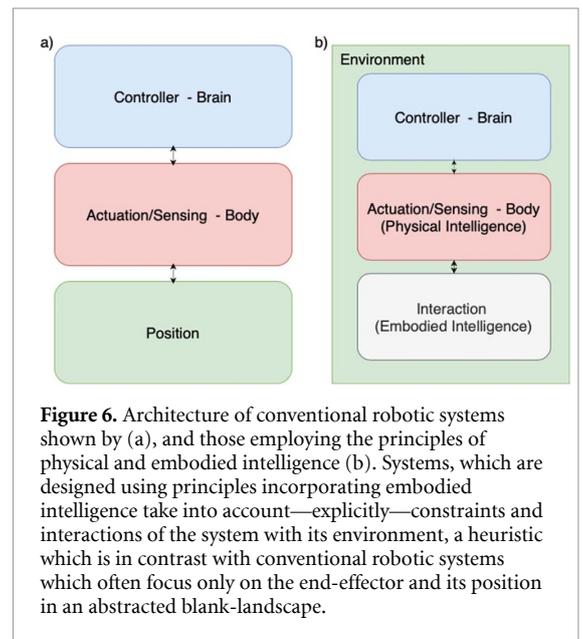


Figure 6. Architecture of conventional robotic systems shown by (a), and those employing the principles of physical and embodied intelligence (b). Systems, which are designed using principles incorporating embodied intelligence take into account—explicitly—constraints and interactions of the system with its environment, a heuristic which is in contrast with conventional robotic systems which often focus only on the end-effector and its position in an abstracted blank-landscape.

interaction dynamics need to be taken into account explicitly in the control of the motion of soft robotic machines.

One of the open challenges in the space of soft systems research is how to make the technology ‘engineerable’, by which we mean that engineers who are not scientific specialists in the field need to have sufficient information and specifications about the technology, as well as a framework in which to test their designs. Currently, with the creative outpouring of new experimental systems this information is often not readily available.

For engineers working with soft robots, it is essential that we work towards utilizing computer simulations in the design of our controllers. These simulations will allow system designers to test and optimize their controllers in a virtual environment, prior to implementation on the physical robot. This approach is not only cost-effective, but it also enables rapid iteration and experimentation. Furthermore, through the use of simulations, we will be able to gain valuable insight into the behavior of our robots and controllers, which may not be easily observable in the physical world. This insight is particularly important when working with soft robots, as their unique physical properties and behavior can prove to be challenging to predict and understand. Additionally, simulations can be utilized to test our controllers in a wide range of operating conditions and scenarios, which may not be feasible or safe to replicate in the physical world. In short, the use of computer simulations is a crucial step in the design process of controllers for soft robots.

The approach that some groups are taking is to focus on soft-systems as machines that comprise a hierarchy of stable sub-systems: including

sensors, control, actuation, and power. This systems-of-systems approach—which has its roots in the parable of Hora and Tempus [92]—aims to enable designers to decompose complex soft machines, and to provide insights which would enable designers to evaluate prognostics (e.g. how long can we operate the machine given the available stored energy), and to design for robust-operation of complex soft machines which are made from simpler sub-systems.

Designers of soft systems require the ability to predict energy requirements and time-to-failure; and also to enable control architectures that optimize motion of the system for task-efficiency.

2.3.2. *Contrasting the design and control of hard and soft robotic systems: soft is hard*

6-axis robotic arms can be thought of as stable sub-assemblies of rotational joints connected by rigid links. Controlling their kinematics is not complex—their motion is quite simply described by the serial combination of each link's mobility using, for instance, homogeneous/transformation matrices. The arm end-effector is then controlled from the top-down using prescribed motion by inverse kinematic control, Jacobians, etc. These systems are widely-used because they are highly engineered, and they perform a useful task: Manipulation.

Soft manipulation arms have more in common with an octopus tentacle than with a 6-axis robot, but the task being performed remains the same: manipulation. A similar reductionist analysis can be performed using 2/3D scaling and shearing transformation matrices, but the complexity of control is orders of magnitude higher due to the continuum nature of the architecture and the non-linearities in the system. Regardless, this reductionist approach gives insight that designers of soft systems tend to build stable-sub assemblies and then stack these to give rise to the complex motions that we see in many soft robotic systems. These 'intelligent' materials arise through a well defined engineering design paradigm of stacking sub-assemblies, but the stack gives rise to complex motions due to the interactions between these well defined sub-systems. Predicting and controlling the motion of these systems remains an open area of intense research.

2.3.3. *Development of useful tools requires the simulation and prediction of motion and energy-requirements*

We, and others, have been working on one approach to describing and controlling complex soft machines via the application of port-based modeling to soft sub-systems [73, 93, 94]. This energy-level abstraction provides a task-orientated development approach. A task-based approach to soft systems development speaks to a systems-engineering approach rather than an approach based upon

scientific enquiry. Design rather than observation. Working from specifications, of a system that is required, demands a fundamentally different approach than building complex systems with the aim of observing their complex behavior.

An energy-based approach enables very high-level abstraction of a physical system, where the energy interactions, both within the system and between the system and the environment, can be investigated and the mechanical efficiency is then easily evaluated. This high-level modeling enables a few key areas of engineering these systems:

- (a) Rational Choice of Components—choosing the most appropriate actuator for the job.
- (b) Prognostics—how long we can run the system given our available energy.
- (c) Optimization for efficiency—relax constraints on the kinematics/dynamics and allow the system to evolve energy-minimizing behaviors.
- (d) Moving towards Systems Engineering with soft actuation technologies.

This approach highlights one of the challenges in controlling the motion of soft systems, we cannot simply repurpose the tools and techniques used in conventional robotics, to do so would miss the opportunities presented by these new systems.

2.3.4. *Embodiment: A body gives the controller something to think about*

The motion of a robotic system is intimately linked with control. The kinematic and dynamic control of conventional robotic systems can be readily emulated, and so disembodied simulations in-silico are one of the routine tools used in the development of robotic systems.

In soft systems control is more complex, indeed—as an active area of research—control of soft systems is significantly less mature than actuation. Embodied soft systems demand a scientific approach based upon a loop of design, build, test, and observe. There are three major elements in this experimental system: the controller, the body, and the environment [90, 95]. A significant challenge is on-boarding the control onto the body, rather than having a separation between an off-board controller with a tether to the actuation system. Importantly, the role of the environment cannot be understated. The interactions between the body and the environment prescribe both the motion of the body, and the action that the body can make on the environment. This line of thinking carries the notion of 'task'. To prescribe, rather than to observe, motion of complex soft systems is an open area of research. We, and others, are working on an approach to on-board control by building 'Fluidic Logic' which is manufactured in the same materials as the actuation elements contained within the body of the robot [96,

97]. Fluidic Logic enables control of actuators using simple automation loops such as state machines, but to enable truly ‘living machines’ then one final sub-systems needs to be introduced: sensing.

2.3.5. Embodied systems can react to environmental stimuli, without electronics

Robots have been around in one form or another, whether embodied or merely existing in thought, for thousands of years. Talos was described by the ancient greeks as a huge bronze automaton that was filled with cogs, gears, and hydraulic fluid: the ichor. Talos was an embodied system, designed with a very specific task in-mind, the protection of the island of Crete. Humans, again as described by the ancient greeks, are a plaything made by Prometheus who tricked Athena into breathing life into clay prototypes. Neither of these systems, Talos and Humans, contain electronics. Both were ‘created’, and both can react to environmental stimuli.

The modern fascination with electronics, and electromechanical systems, arises from the enormous amount of engineering that has gone into these technologies. It is, however, entirely possible—using ancient thinking—to consider how one would make robotic machines from non-electronic but well-engineered stable sub-assemblies. See for example the recent work from Mahon *et al* [96] on a soft robot which incorporates fluidic logic, and even more recently from Decker *et al* [98] where they demonstrate a fully programmable soft robot with sensing, and which uses no electronics. Intelligent materials can also be designed to be responsive using mechanisms such as ionic swelling of hydrogels, ionic polymer-metal composites (IPMCs) as well as protein-based systems [12, 17, 99–106].

The embodiment of these systems highlights the requirement to explore, as an emergent area of research, the duality between Artificial Intelligence and Physical Intelligence: hybrids.

3. Conclusion and outlook

Soft robotics as a research field is still quite young at 60 years old. With the advent of rapid prototyping and the increasingly accelerated development of new manufacturing processes for soft robots, new opportunities are arising for the application and use of soft robots. Through entrepreneurial companies like ‘Fluidic Logic Ltd.’ or ‘Soft Robotics Inc.’ the application areas of soft robots are currently changing from laboratory benches and test tracks ever more to commercial areas and environments with extreme conditions.

As early successes in commercialization show novel applicational fields could be:

- agriculture picking,
- logistics picking,
- soft sensors and sensing skins for robots,

- medical and environmental monitoring,
- haptics in wearables,
- under water exploration.

Here four experts have described the changing world of soft robots and highlighted perspectives for the future, they have pointed out what is currently possible, and signposted solutions to current shortcomings. The main consensus is that soft robotics as a field of science is now moving from its infancy into adolescence. With the help of new production processes, high tech sensor technology and the use of novel materials and engineering approaches, autonomous systems with embodied intelligence can be developed.

New approaches are needed for closer coupling between soft robot systems and users in the case of wearables or human-machine interaction. As well as soft lab-on-chip devices or implantable soft robot applications and materials in the medical field, with capabilities better suited for long-term implantation or biodegradability.

Soft robotics should also be integrated into science technology engineering mathematics fields (STEM) and engineering education as initiated by initiatives like the soft robotic toolkit [89], which introduces the topic of soft robots, their production, use and investigation in an easy-to-understand way. Another path for progression is the development of dedicated analysis and design tools that would increase quantitative understanding, to foster soft robots emergence and public acceptance.

A final challenge will be the creation of a fully autonomous, self-healing and possibly self-replicating systems, which are able to draw energy and materials from the environment to maintain their homeostasis. A first step towards such system is the challenge to create systems that integrate non electronic information computation in soft robotic systems to create a reactive soft machine. Such system would need to be self-powered for example converting solar energy into chemical energy for storage and on demand usage.

In 20 years we predict that robots will be all around us in our every day lives—much like mobile phones are today—that is, in such a non-intrusive and ubiquitous way that we will not notice them anymore. One of the key technologies and area of research that will enable this paradigm shift is soft robotics.

Data availability statement

No new data were created or analysed in this study.

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