Matter of Opinion

Intelligent soft robots that couple soft sensing, actuation, computation, and power sources

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Soft robots, whose core components are made of soft materials or compliant structures, have greater flexibility, enhanced adaptability, and safer interactions with humans and external environments compared to conventional rigid counterparts. Intelligent fully soft robots that couple soft sensing, actuation, computation, and power sources into monolithic machines can be exploited to bring the next generation of soft robots, which can bring unprecedented capabilities in unstructured and unknown environments.

Most traditional robots (such as industrial arms[1]) are made of rigid materials (such as metals and plastics) and structures and are excellent at performing precision tasks and sustaining large loads; thus they have been extensively used for aerospace, industrial manufacturing, construction, agriculture, and logistics, among others. Soft robots (such as soft grippers[2]), whose core components (such as actuators and sensors) are made of soft materials or compliant/pliable structures, can be used to bring greater flexibility (due to an infinite number of degrees of freedom), enhanced adaptability (due to the capability of continuous, large deformations), and safter interactions (due to inherent impact resistance and collision energy absorption) with humans and external environments and have thus been used for delicate grasping, biomedical devices, and conducting tasks in unstructured and unknown environments where conventional rigid robots are difficult to deal with.[3,4]

Due to the aforesaid unique advantages, the soft robotics community has been enjoying an increasing number of academic studies (on topics such as soft pneumatic arms and grippers, soft rollers, octopus inspired soft robots, soft underwater robots, etc.) and industrial products (such as pneumatic artificial muscles, soft grippers, soft arms, soft wearable devices, etc.). As shown in Figure 1, the number of publications until 2024, obtained from the Web of Science Core Collection (1900–present) using "Topic: Soft Robot," had been increasing sharply, especially after the beginning of the 21st century. The first international conference and the first international journal on soft robotics were also initiated in 2014 and 2018, respectively. In addition, the first soft robotics company, commercializing pneumatic soft grippers and their automated material handling systems, was established in 2016. Among all the key developments and milestones,[3,4] the first soft robot for deep-sea explorations in the Mariana Trench, developed by Li et al.,[5] and the first fully soft robot that can achieve untethered, autonomous motions, developed by Wehner et al.,[6] are two important academic breakthroughs.

Fully soft robots are made of entirely soft materials and structures and are able to produce large, complex deformations. Most current soft robots are partially made of soft materials and structures and usually rely on rigid control modules and external rigid power systems. They cannot match the level of "soft" as the octopus-inspired fully soft robot that integrated soft actuation and soft computation into a monolithic machine[6] and therefore are difficult to realize the full potential of aforesaid advantages. Intelligent fully soft robots, analogous to living creatures such as octopuses, cuttlefishes, and worms, that couple soft sensing, actuation, computation, and power sources into monolithic machines (see Figure 2), may provide a viable solution and truly enable them to have surprising adaptabilities such as escaping autonomously from a size that is significantly smaller than their body dimensions and producing higher precision operations than most soft robots, which usually use simple open-loop controls.

Soft sensing enables soft robots to have proprioceptive (such as the awareness of their own deformations) and exteroceptive (such as environmental temperatures and humidities) capabilities. Soft sensors can be classified into light (such as fiber-optic and visio-tactile sensors), electric (such as resistive, capacitive, inductive, piezoelectric, piezoresistive, and thermoelectric sensors), magnetic (such as hall-effect and magneto-resistive sensors), and chemical (such as humidity and gas sensors) ones and have their own advantages and disadvantages. Multimodal sensing, analogous to living creatures who couple multiple sensing capabilities together, has been increasingly needed for intelligent fully soft robots. Currently, most soft multimodal sensors usually stack different sensing mechanisms together. One typical example of a multimodal sensor using a single mechanism that can distinguish the deformation locations, magnitudes, and modes such as stretch, bend, or press is a stretchable fiber-optic sensor developed by Bai et al.[7] How to decouple and retrieve useful signals under super-large, complex deformations and from dynamic environments where

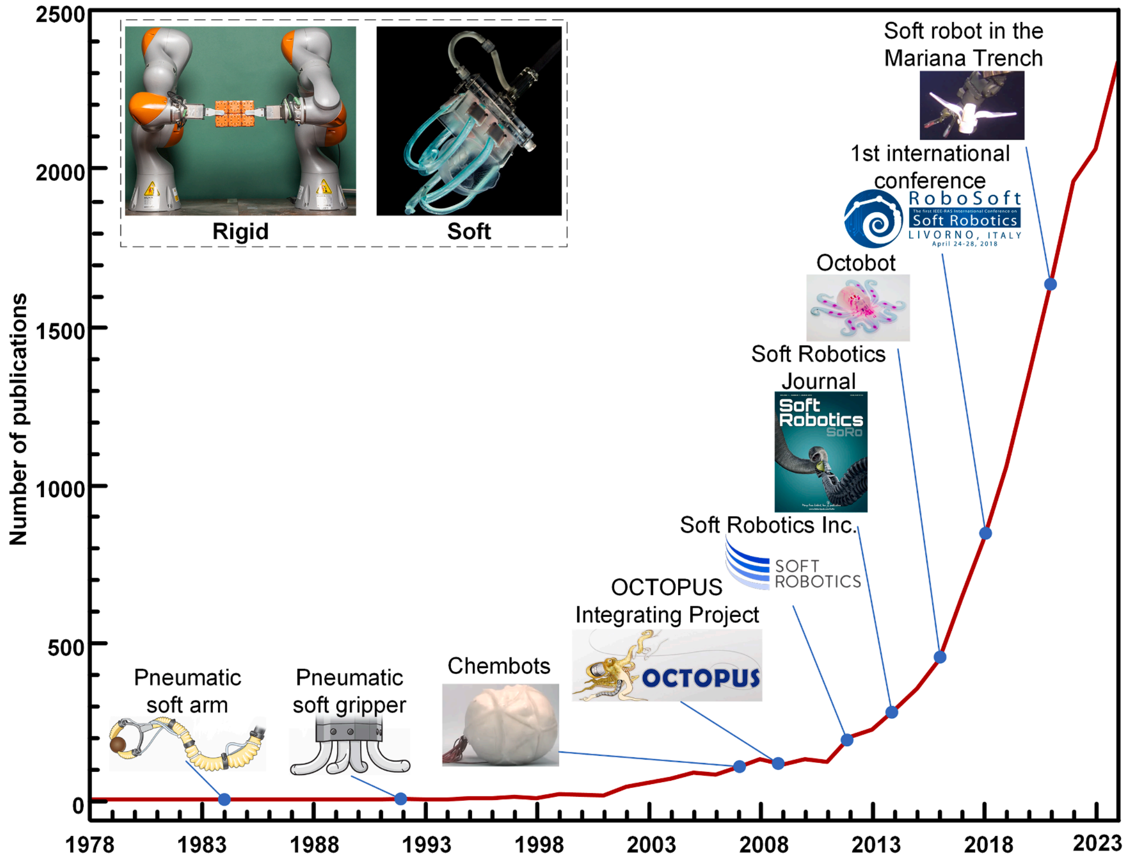

Figure 1. Key developments and milestones in the soft robot community

The top left inset shows the comparison between conventional rigid robots and soft robots.

The data of the number of publications until 2024 was obtained from the Web of Science Core Collection (1900–present) using "Topic: Soft Robot."

temperature, humidity, and other factors are changing is always a challenge.

Soft actuation equips soft robots with abilities of stretching, bending, and twisting deformations and versatile moving without the need of traditional motors. Soft actuators can be classified into physical driven ones (such as electric motor and pressure-driven actuators), smart material driven ones (such as electric, magnetic, and light-responsive actuators), and others (such as chemical-reaction and bio-hybrid actuators), where soft pressure-driven actuators include hydraulic and pneumatic (including positive and negative pressure) ones. For example, Li et al.[5] used a typical soft electric responsive actuator (i.e., dielectric elastomer actuator); Sinatra et al.[2] used a soft pressure-driven actuator; and Wehner et al.[6] used a chemical-reaction-based pressure-driven soft actuator for deformations. Multimodal soft actuators, analogous to living creatures who couple multiple deformation modes together, have been increasingly needed for intelligent fully soft robots. It is challenging to have a single soft actuator (with single stimulus or input) that can output as many deformation modes as possible. It is also desirable to have soft actuators that can output controlled large forces while having large deformations.

Soft computation brings entirely soft controllers for soft robots. Currently, most soft robots are often controlled by rigid electronic microcontrollers. Soft computation is an emerging area at its early development stage, and only a few examples have been published. For instance, Wehner et al.[6] used a microfluidic logic that can be used to regulate fluid flows for soft computation. Garrad et al.[8] developed a vascular-system-inspired conductive fluid receptor that can be used to map a fluidic input signal to an electrical output signal and perform both analog and digital computation. The soft robotics community encourages new soft controller realization methods (such as new physical/mechanical intelligence mechanisms without the need of complex logics) toward the next generation of soft computation.

Soft power sources are required for fully soft robots that undergo large, complex deformations, while providing effective power to soft sensing, actuation, and computation. Currently most soft robots are tethered to external rigid power supplies, thus limiting their operational ranges and navigational abilities. Most untethered soft robots usually employ rigid batteries that, for sure, will limit their versatile deformations. Stretchable lithium-ion batteries,[9] supercapacitors, microbial fuel cells, and energy harvesters may provide viable solutions to soft power sources, although they usually have limited energy storage capacities and their performance would degrade noticeably over time. Kim et al.[10] recently developed a compliant redox flow battery that can be used to provide sufficient power and capacity to soft actuators for,

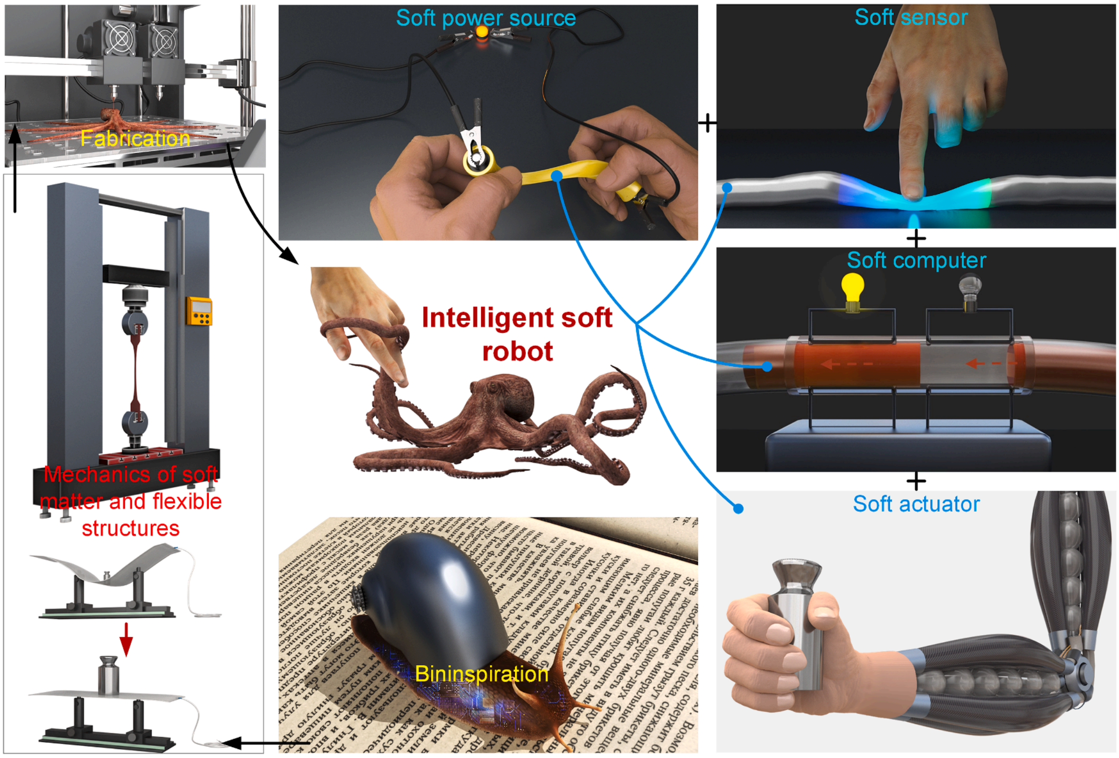

Figure 2. Key components toward intelligent fully soft robot
Intelligent fully soft robots, usually inspired by living creatures, integrate soft sensors, soft actuators, soft controllers, and soft power sources into monolithic machines.

theoretically, over 35 h. The soft robotics community is still anticipating soft power sources with longer cycle times and higher energy densities while having the ability to deform as much as needed.

Nature always offers perfect examples for inspiring the design and development of intelligent fully soft robot designs. Soft robot design, therefore, often starts with bioinspiration and biomimetics. Soft materials and structures bring highly non-linear, multi-physics coupling, and time-varying characteristics, thus making the precise modeling and control a rather difficult problem to tackle. New and confident experimental methods and setups to understand the mechanics of soft matter and flexible structures are highly desirable. Soft lithography, molding, machining, and 3D printing are popular soft robot manufacturing methods, and hybrid (i.e., a combination of different manufacturing methods) fabrication is always needed for fully soft robots. Mechanism-data hybrid-driven methods may provide viable solutions to model and control soft robots in a better way. This soft material-structure-powering-sensing-controlling-actuating integrated design pipeline (see Figure 2) will facilitate the design and development of the next generation of fully soft robots, which can bring unprecedented capabilities in unstructured and unknown environments.

AUTHOR CONTRIBUTIONS

J.G. wrote the draft. Y.L. and J.L. commented and fully revised the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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