Soft Robotics—The Next Industrial Revolution?

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The robot dance has, since its inception in 1967, been a caricature of how robots move. Its imitation of the series of precise, linear motions with abrupt starts and stops is instantly recognizable. Despite a certain wavering in its popularity, it remains part of modern culture. What is so remarkable about the robot dance is that it mimics the movements and constraints of conventional rigid robots, a type of robot that is ubiquitous in automated manufacturing and object handling, and it could so easily have been invented now. It also strikingly shows that industrial robotics have relied on conventional hard technologies for

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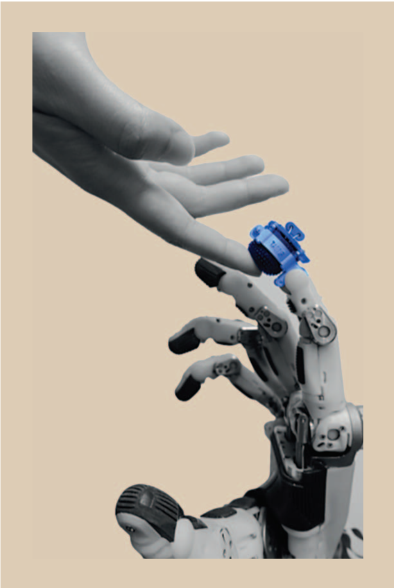

Figure 1. Soft robotics enable soft and natural human-robotics interactions.

more than 40 years and still does. However, this is about to change. The last few years has seen a rapid growth in soft robotics, technologies that are fundamentally different from their rigid counterparts. Soft robotics is set to have a major impact on all aspects of our society and industries, ranging from manufacturing and consumer devices to medical applications and wearable technology.

Soft Robotic Technologies

Soft robotics is an umbrella term that covers all types of active and reactive compliant systems. These include soft actuators, or artificial muscles (e.g., pneumatic nets, electroactive polymers), soft stretchable sensors (e.g., dielectric elastomer strain sensors), soft energy harvesting (e.g., dielectric elastomer generators), and even soft electronics. The recent rapid increase in research and development of soft robotics is mainly fueled by advances in three core areas: smart materials, mathematical modeling of compliant systems, and fabrication technologies. *Smart materials* is a term used for materials that generate a measureable output in one physical domain (e.g., optical or mechanical) when stimulated by a signal or energy in an orthogonal domain (e.g., electrical or pH value). For example, soft-smart electroactive materials can generate force when they are electrically stimulated and have the potential as artificial muscles to replace conventional electromagnetic motors. Such smart and compliant materials exhibit nonlinear dynamic behaviors, and recent developments in mathematical and finite element modeling have provided us with the tools to take these nonlinearities into account. It has even been shown that these nonlinear behaviors can be exploited as computational resources to alleviate the control problem of compliant structures. Finally, the revolution in 3-D printing and rapid prototyping has greatly contributed to the development of soft robotics, with major 3-D printer manufacturers selling off-the-shelf printers capable of depositing both hard and soft materials that can be directly used as soft robotic structures, sensors, and actuators.

A growing number of researchers and industries are looking to soft robotics as a new and exciting set of technologies because of its notable advantages. The most obvious one is the inherent safety provided by compliant body parts. Whenever there is a need for physical interaction between machine and human, soft robotic body parts serve as an additional safety layer in case the behavior of human participants does not match predictions. Soft robotics therefore has the potential to deliver completely new and safe human–machine interaction systems for workers and the elderly and for entertainment (Figure 1).

Often, soft robots are directly inspired by biology, such as the remarkable movement and camouflage abilities of the octopus. However, instead of simply copying the shape of an organism, soft robotics is also able to mimic the physical properties of the body, resulting in much more natural and fluid movements. This is highly relevant for the acceptance of robot companions in our working and private spaces. Moreover, it allows us to predict their movements with higher confidence and thereby improve precision and control.

Another advantage of soft robots is their potential with respect to energy efficiency. Similar to biological systems, compliant materials are able to convert forces into shape changes and thereby store energy to be released later (e.g., during locomotion). Considering the remarkable energy efficiency of animal movements, this bioinspired soft robotics approach is very promising. Furthermore, using smart materials such as dielectric elastomers, soft robotics provides a clever way of energy harvesting directly implementable in the body of the robot. Other smart materials enable even more exciting capabilities. For example, by selecting biocompatible soft-smart materials, we can safely use soft robotics inside the body and in delicate environments. Moreover, by exploiting biodegradable materials, we can deploy thousands and even millions of soft robots, safe in the knowledge that they will degrade to nothing in the environment and cause no damage.

One might think that a soft robot would be more prone to damage than rigid robots, but, in many cases, the reverse is true. A soft robot deforms under pressure, spreads the destructive load, and squeezes out of constrictive gaps. You can even run over a soft robot with a car, try to set fire to it, freeze it, or take it to the bottom of the ocean, and it will still operate. In a dynamic, industrial environment with chemicals and heavy machinery, soft robots are more likely to be reliable compared to their rigid counterparts.

In contrast to rigid robotics, soft robotics embrace the compromises that must be made between precision, compliance, and adaptability. Just as biological organisms detect changes in their environment through their soft bodies and then change their stiffness and stimulate their muscles to achieve their goal, soft robots can do the same. In fact, control and computation can even be devolved to the body itself, completely bypassing the brain or control system. This concept is often referred to as *morphological computation*. For example, octopuses exploit this devolved computation in their tentacles to aid in autonomous behaviors such as reaching and grasping. We can exploit this morphological computation in soft robotics, yielding self-adaptive mechanisms such as smart grippers, adaptive energy efficient locomotion, automatic object sorting surfaces, morphing aerofoils, and self-tuning pumps and fluidic propulsion mechanisms.

Given all these remarkable abilities, it is perhaps surprising that soft robotics can be built so inexpensively, even for less than a dollar, leading to the possibility of disposable robotics (which could also be biodegradable!). This opens the door to mass production, lower prices, and a broadening of the impact of robotics in general.

Turning these advantages of soft robotic technologies into real products requires advancement in soft and stretchable electronics. These include compliant interconnects and wires formed into weave structures or formed from nanomaterials, including silver nanowires, carbon nanotubes, and graphene inks. Compliant semiconductors are also needed to perform embedded control and computation. Instead of relying on silicone integrated circuits, plastic, and even elastic, semiconductors (termed *stretchtronics*) can be embedded within and across the soft robotic device.

Soft Robotics Applications

Due to their versatility and range of advantages, soft robots have the potential to provide solutions for industrial applications that rigid robots are not able to solve with satisfaction. For example, in agriculture, most fruits and vegetables are manually picked since a metallic gripper would damage the product. Self-adapting soft robotic grippers are therefore an ideal solution.

Another driving factor for applications of soft robots is their previously mentioned inherent safety. Soft robot bodies will play a crucial role in human–robot interaction in factories (e.g., robotic coworkers, wearable assistance) and private spaces (e.g., household robots) as well as public spaces (e.g., guides in museums). In addition, softness and safety play a key role in the field of medicine and health care. The soft–soft interfacing of soft robotics and biological tissue is much safer, less invasive, and more effective than the soft–hard interfacing of traditional rigid medical devices. Robotic health care is a sector that can readily benefit from soft materials and mechanisms, including support robots in patient care (lifting and carrying patients), minimally invasive surgery, wearable devices for mobility restoration (e.g., rehabilitation after a stroke), and implantable devices to treat conditions following illness, trauma, surgery, or age-related degradation (e.g., compliant ventricular assist devices). The shift in demographics toward an elderly population in the United States, Japan, and Europe requires more effective treatments for age-related decline. Soft robotics is highly suited to this role in both physical and mental support, for example, as adaptive daily living tools and as cognitive and sensory exercisers. Consider an elderly person with mobility problems. The state-of-the-art robotic solution is the rigid exoskeleton, such as the Cyberdyne Systems' HAL suit, effective for only a constrained set of environments and users. A soft robotic exosuit would be more versatile and comfortable, being compliant when needed, for example, when the wearer was able to move on their own, but would transition to active muscle assistance when needed. We can extend the notion of wearable soft robotic devices to almost any clothing; a blind person could use a comfortable and nonobtrusive soft robotic jacket that warns him or her of dangerous situations, or a surgeon could use superthin soft robotic gloves that give extra tactile sensory input and recording capabilities as he or she performs an operation.

Entertainment and edutainment are fields in which soft robotics is perhaps set for its most meteoric rise in the short term. Over the last year, virtual reality has come to the fore as a consumer-level technology. These devices are extremely sophisticated in the visual and audio senses, but physical representations of the virtual environment are sorely lacking—the user is physically isolated from the virtual scene. Soft robots offer safe, low cost, versatile, and effective technologies for a radical enhancement of virtual reality devices by delivering realistic tactile and physical interaction sensation, including pushing, stroking, and object interaction.

Another, perhaps surprising, field of application is architecture. Our built environment is a fusion of soft structures (comfortable chairs and soft furnishing) and hard surfaces (walls and ceilings). The concept of morphological computation suggests that soft robotics structures will allow highly adaptive living spaces that are able, enriched by smart sensing materials, to react to environmental changes. Why should a wall be rigid when it could morph smoothly into a different shape? Even soft-smart furniture is conceivable in this context.

The future of soft robotics looks bright, and we have only briefly touched on its potential to generate exciting new technologies and new applications that were science fiction but a few years ago. Soft robotics allows us to think beyond classical robotic approaches by using other components than metal, rigid plastics, and electric motors. Robotics is changing and becoming softer and safer. We will have to change the way we think about robots; out with the dated rigid robot dance and in with the new smooth and natural soft robot dance!