Biomimetic Soft Robotics

Se Hwan Jeon

December 15, 2019

Introduction

Advances in the material sciences and new forms of actuation have allowed a novel subfield of robotics to be researched. This broadly labeled field of "soft" robotics concern mechanical constructs that are primarily composed of compliant materials. While conventional robots are built with stiff, hard materials to ensure fast, robust, strong, and repetitive movement for applications ranging from manufacturing lines to autonomous drones, the emerging field of soft robotics represents a significant paradigm shift in approaching the same challenges that have faced roboticists for decades.

A significant issue for many conventional robots built are the assumptions made when developing the control systems that govern its movement. Most are constructed under well-defined environmental conditions with predictable stresses, strains, and loads applied on the system. While these assumptions can be readily met in an industrial or laboratory setting where the environment is made of similarly hard, precise materials, the unpredictability of unstructured environments is often difficult to account for with "hard" robots. In applications such as invasive surgery, search-and-rescue, human-robot interaction, and disaster relief, the environment is far less predictable and can be difficult to navigate even for the most sophisticated control systems (Kim, Laschi, & Trimmer (2013)). In these cases, the unpredictable variations of the environment can be addressed not with deterministic control systems but rather by material properties and morphology of soft robotic bodies themselves. Research into the field opens up the possibility for robotic devices to expand their capabilities beyond artificial environments. Especially in regards to interaction with biological material, soft robotics presents unique advantages over conventional robots that should be explored further (Kim, Laschi, & Trimmer (2013)).

The largest inspiration for overcoming the unpredictability of the natural world comes from nature itself. The "soft" tissue present in many, if not all, organisms are well-adapted and resilient to many environmental fluctuations. They distribute stress, conform to surfaces, are malleable, self-repair, have naturally grooved ridges for grip, and so on. Researchers have begun constructing robotic systems (soft and otherwise) that emulate the behavior and response of animals to their environment, such as locomotion (running, swimming, climbing) and unique forms of manipulation (Trivedi, Rahn, Kier, & Walker (2008)). This "biomimicry" involves taking inspiration from the biological mechanisms present in the natural world and emulating them with mechanical components. Examples from previous work have included developing robotic fish, tentacles, geckos, and worms, each of which behave similarly to its natural counterpart (Kim, Laschi, & Trimmer (2013)).

As with many emerging technologies, the full effects of soft robotics are as of yet unknown on society, but the potential applications are numerous and could be greatly beneficial. From proof-of-concept studies, a number of soft robotic devices have already been developed that show great promise. Autonomous, aquatic exploratory robots, surgical imaging robots, and exoskeletons for rehabilitation and strength enhancement are few of the many areas where research into soft robotics could make a significant impact (Kim, Laschi, & Trimmer (2013)). From a broader perspective, future developments in soft robotics could potentially lead to huge improvements in the quality of life of everyone, with the development of personal medical robots, advanced and efficient disaster response units, and advanced treatment for the disabled. By studying the integration and interaction of the biological and mechanical fields, the significant impact of robotics on lives today could be further expanded and improved upon.

Soft Technologies

Actuation and Materials

The largest challenge of soft robotics is actuating flexible materials at the forces and scales needed for the specific application. The most common forms of soft robotic actuation today involve dielectric elastomeric actuation (DEAs), shape-memory alloys (SMAs), or pneumatic actuation.

Dielectric elastomeric actuation utilizes materials that actuate in response to electrostatic forces, as can be seen in Figure 1. A unique configuration, orientation, and shape for the mateiral can be defined when subject to a potential difference. While its performance with respect to stress, strain, and power per unit mass is desirable, it presents a number of limitations that diminish the advantages of using compliant materials in the first place. The infrastructure needed to control DEAs is significant and rigid, and requires high voltages to be actuated effectively. When considering applications that may directly be in contact with organisms, such as rehabilitation exoskeletons, these limitations can prevent using DEAs for some soft robotic applications (O'Halloran, O'Malley, & McHugh (2008)). An alternative method is the use of shape-memory alloys to achieve actuation in soft robotics. In principle, SMAs operate similarly to dielectric elastomers, but under the input of heat rather than a potential difference, as can be seen in Figure 2. This also presents a number of limitations however. Precise temperature control of the SMA can be challenging and is not instantaneous, preventing applications requiring quick or precise movement. Furthermore, the process of heating the material can be very inefficient (1%) and can damage the actuator itself when subjected to repeated cycles at high loads (Kim, Laschi, & Trimmer (2013)).

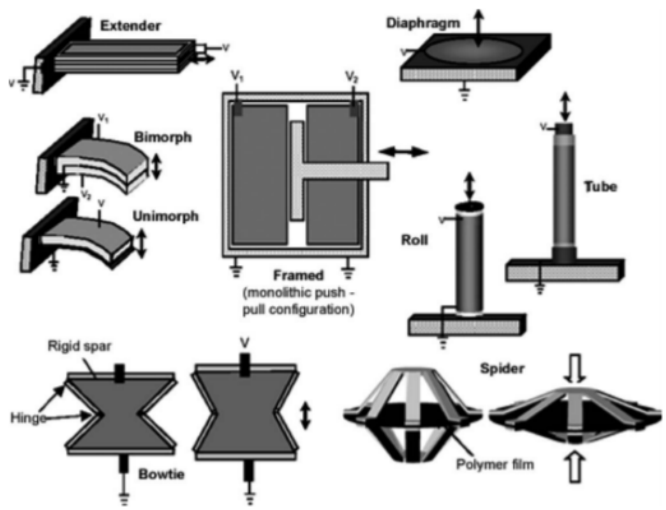

Figure 1: *Schematics of dielectric elastomeric actuation with various configurations. Taken from O'Halloran, O'Malley, & McHugh (2008)*

.

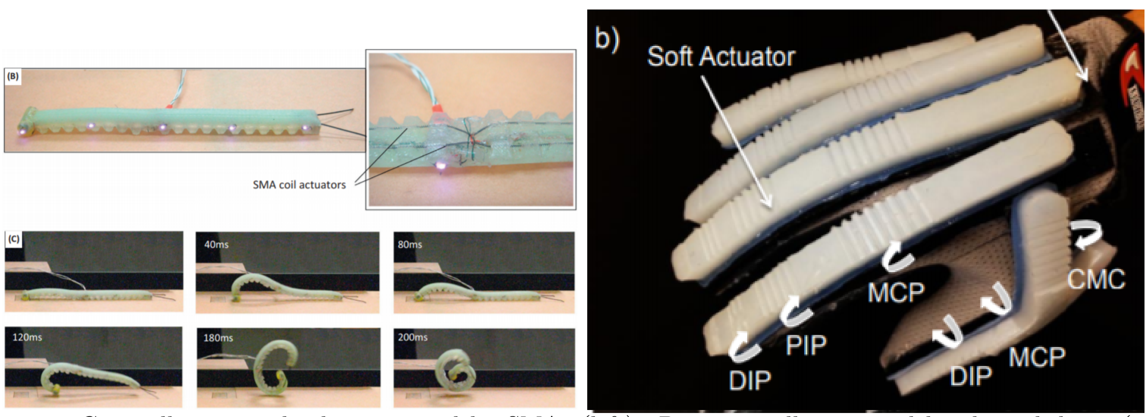

Figure 2: *Caterpillar-inspired robot actuated by SMAs (left). Pneumatically actuated hand exoskeleton (right). Taken from Kim, Laschi, & Trimmer (2013) and Yap, Lim, Nasrallah, Goh, & Yeow (2015)*

.

The most common method of soft robotic actuation involves using pressurized fluids to control actuation. Unlike the aforementioned methods, little infrastructure is needed and the pressure of the actuating device can be precisely controlled as needed. For examples, a soft robotic hand exoskeleton for the purposes of rehabilitation was developed actuated by a pressurized air source as can be seen in Figure 2 (Yap, Lim, Nasrallah, Goh, & Yeow (2015)). The glove successfully demonstrated actuation and forces sufficient for rehabilitation, but both the manufacturability and control over the device would have to be considered for future studies.

While conventional robotics employ discrete, articulated joints to move its components, soft robots use low-modulus materials such as silicone rubber or hydrogels. The primary difficulty of using such materials is in modeling its response to environmental stimuli. Determining the continuum mechanics for compliant materials remains a challenge, and as a result most modeling in soft robotics is limited to overall kinematic analysis (Kim, Laschi, & Trimmer (2013)).

Limitations

Soft robotics significantly expands upon the capabilities of conventional robotics, but it is also limited in a number of areas, most notably strength and precision. Because of the compliant materials it is constructed from, as well as the relatively limited forms of actuation, the pure mechanical strength of soft robotic devices can be far lesser than their hard counterparts. Because soft robotic devices are not generally designed to apply high loads, this is usually not a significant issue, but presents clear limits to the applications of soft robots. Furthermore, because of the imprecise nature of the response of compliant surfaces, it is difficult to precisely or quickly control soft robotic devices. Estimations need to be made regarding the response of its surfaces to stimuli, and only general kinematic analyses can be performed. Actions requiring fast, strong, and precise movement would be difficult to achieve with soft robots (Trivedi, Rahn, Kier, & Walker (2008)).

Methods

Because of the wide range of applications soft robots have been studied for, there is no consistent or necessarily standard method exists for its analysis or development. However, most soft robots generally rely on *some form of actuation* (such as the ones outlined previously), *some compliant material* to encase the actuator, and a unique design relevant to the application at hand. For example, to develop a soft robotic manipulator, a rational approach would be to cast and vulcanize rubber around a pneumatic actuator so that a "tentacle"' construct could be developed (Trivedi, Rahn, Kier, & Walker (2008)). By combining these constructs, one could ostensibly develop a soft robotic "hand" that could maneuver objects in liquid (Kim, Laschi, & Trimmer (2013)). To develop exoskeletal devices, another group actuated cables attached to a user's lower limbs to ease and enhance walking (Asbeck, Dyer, Larusson, & Walsh (2013)). Moments of up to 18% of a walking gait were applied, significantly easing movement for the user. While no standardized process for soft robotic development exists, these steps have been generally followed for the majority of soft robotic devices mentioned.

Biomimicry

Many of the mechanisms discussed, especially pneumatically-actuated systems, were directly or indirectly inspired by biology. Muscular organs, such as elephant trunks, tentacles, and tongues have served as models for soft robotic manipulators. Li et al., developed "artificial" muscles by manipulating origami structures in specific configurations, as can be seen in Figure 3 (Li, Vogt, Rus, & Wood (2017)). Locomotion unique to biological organisms have also been a significant area of interest to the soft robotic community. Most famous perhaps is the MIT Cheetah that achieved speeds of up to 14 mph. While not a soft robot, it is a direct example of bio-inspired robotics that characterizes many developed devices in the field. An optically-driven artificial ray was also

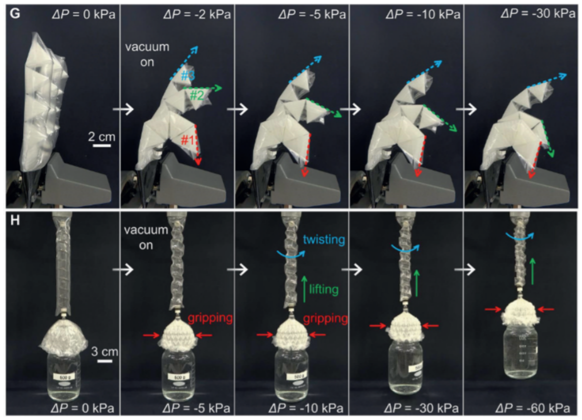

Figure 3: *Images of pneumatic actuation of origami "muscles". Taken from Li, Vogt, Rus, & Wood (2017)*

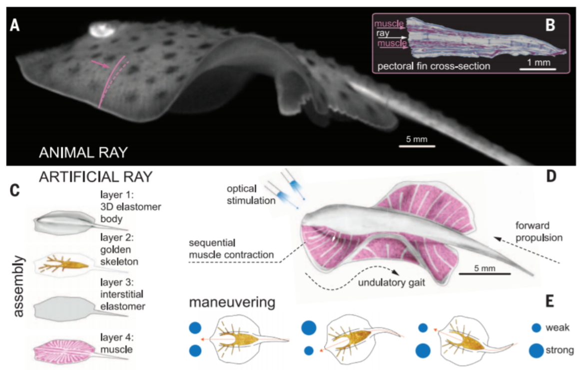

Figure 4: *Schematic of optically-driven artificial "ray" architecture. Taken from Park et al. (2016)*

developed that could navigate obstacles and be controlled in water, as can be seen in Figure 4 (Park et al. (2016)). Beyond the driving mechanisms of the soft robots described, research has also been done regarding the compliant materials themselves. Taking inspiration from the natural self-repairing qualities of skin and muscle tissue, Terryn et al. used thermoreversible polymers to develop soft robots that were capable of "self-healing" when cut or otherwise damaged, as can be seen in Figure 5 (Terryn, Brancart, Lefeber, Van Assche, & Vanderborght (2017)). Biomimicry in robotics has led to new breakthroughs in novel or more efficient methods of overcoming challenges, from manipulation of soft material in water to devices compatible and safe to the human body. Further understanding and research of how biological systems can overcome their environments will lead to better results for the artificial robotic systems being developed.

Future Directions

Results

As seen from the numerous examples presented throughout this paper, many soft robotic devices have been developed that are capable of manipulating objects, moving in unique and challenging environments, and aiding human locomotion and rehabilitation. While it is clear that soft robots

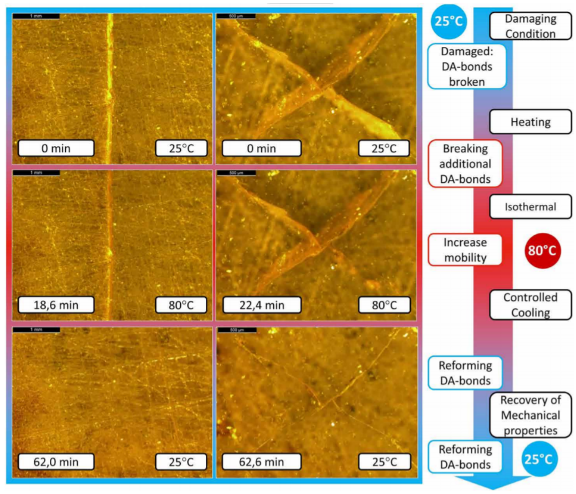

Figure 5: *Thermal "healing" of damage on soft robotic material. Taken from Terryn, Brancart, Lefeber, Van Assche, & Vanderborght (2017)*

.

can effectively address these issues, they are still limited in that the technology is still in its infancy. Currently, soft robotics only exists at the forefront of scientific development, being used for space exploration and trials in laboratories. With significant research in its manufacturability and scale of operations, soft robotics could positive benefit society as a whole (Trivedi, Rahn, Kier, & Walker (2008)).

Future Work

A notable emerging area of research is not just biomimicry, but actual bio-hybrid robotics. The field of soft robotics has seen a number of intersections with tissue engineering, with robots such as the aforementioned artificial ray being powered by laboratory grown cardiac tissue. Soft robots built from actual biological material could have both the benefits of being mechanically actuated and controllable while retaining all the advantages of being self-repairing, self-assembling, energy dense, biocompatible, and so on (Kim, Laschi, & Trimmer (2013)).

Soft robotics is currently limited primarily by the materials and actuation available. With advances in new materials that are more robust while remaining compliant, the limitations of soft robotics discussed earlier could potentially be overcome. Similarly, more refined and powerful forms of actuation should be researched so that soft robots could match the mechanical strength of their counterparts. As control and design of these soft robots becomes more sophisticated, so will the potential application of them to industry and society as a whole.

References

Asbeck AT, RJ Dyer, AF Larusson, & CJ Walsh (2013). "Biologically-inspired soft exosuit", 1–8. DOI: 10.1109/ICORR.2013.6650455.

Kim S, C Laschi, & B Trimmer (2013). "Soft robotics: a bioinspired evolution in robotics". *Trends in Biotechnology* 31 (5):287–294. DOI: 10.1016/j.tibtech.2013.03.002.

Li S, DM Vogt, D Rus, & RJ Wood (2017). "Fluid-driven origami-inspired artificial muscles". *Proceedings of the National Academy of Sciences* 114 (50):13132–13137. DOI: 10.1073/pnas.1713450114.

O'Halloran A, F O'Malley, & P McHugh (2008). "A review on dielectric elastomer actuators, technology, applications, and challenges". *Journal of Applied Physics* 104 (7):071101. DOI: 10.1063/1.2981642.

Park SJ et al. (2016). "Phototactic guidance of a tissue-engineered soft-robotic ray". *Science* 353 (6295):158–162. DOI: 10.1126/science.aaf4292.

Terryn S, J Brancart, D Lefeber, G Van Assche, & B Vanderborght (2017). "Self-healing soft pneumatic robots". *Science Robotics* 2 (9):eaan4268. DOI: 10.1126/scirobotics.aan4268.

Trivedi D, CD Rahn, WM Kier, & ID Walker (2008). "Soft robotics: Biological inspiration, state of the art, and future research". *Applied Bionics and Biomechanics* 5 (3):99–117. DOI: 10.1080/11762320802557865.

Yap HK, JH Lim, F Nasrallah, JCH Goh, & RCH Yeow (2015). "A soft exoskeleton for hand assistive and rehabilitation application using pneumatic actuators with variable stiffness". *2015 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, p. 4967–4972. DOI: 10.1109/ICRA.2015.7139889.