SOFT ROBOTS

Harnessing the circular economy to develop sustainable soft robots

Yu Jun Tan

Fully recyclable and degradable materials have been used for the development of soft devices for omnidirectional sensing and actuation.

Nature is an ideal role model for creating a circular economy, with mutual and benign causality between living and nonliving things. In particular, all the living things thriving in nature abide by two main feedback systems; each organism adapts and responds to the dynamic environments through homeostasis, i.e., using self-regulating and internal feedback systems; and all living and non-living elements in nature eventually become the fuel for other organisms so as to form a balanced and resilient ecosystem. Unfortunately, humans are breaking this cycle by excessively exploiting natural resources. We currently consume, discard, and accumulate synthetic materials in an ever-growing way. Adopting nature-inspired materials in robots could bring about ecofriendly yet smart technologies not only for consumer use but also for applications in biomedicine and health care, putting a halt to the surging issue of technology and electronic waste. Such approaches will aid in the design and adoption of technologies that emulate natural feedback loops, with artificial homeostatic regulation such as self-adaptable (*1*) and self-healing (*2*) and with materials that are easily recyclable and/or biodegradable (*3*).

Writing in *Science Robotics*, Heiden *et al.* (*4*) report on a soft actuator that is capable of real-time sensing and omnidirectional actuation while having the potential to be recycled and biodegraded (Fig. 1). The soft actuator was constructed using a biogel developed earlier by the same group (*5*), formulated from biodegradable materials such as gelatin, glycerol, glucose, and citric acid, to replace the commonly used synthetic materials. When compared to other "green" materials, this biogel exhibited superior mechanical integrity, reusability, and biodegradability. Moreover, it is tunable in terms of its elastic modulus (0.3 to 3 MPa) and stretchability (>300%) by varying the concentrations of glycerol and glucose in the network of gelatin hydrogel. Citric acid serves as a natural preservative in the biogel, preventing the growth of bacteria and mold, which facilitates a long shelf life. The biogel can swell and dissolve in water, with the potential for full biodegradation.

The biogel is thermoreversible and can be three-dimensional (3D)–printed using a direct ink writing method, where the ink was softened at an elevated temperature at the printhead and then extruded onto a chilled printing platform that subsequently solidifies the ink. Additive manufacturing enables high design freedom and, at the same time, significantly reduces the materials wastage in the product development stage when compared to the conventional mold casting method. The authors demonstrated a 3D-printed, pneumatically driven actuator, enabling omnidirectional actuation. Moreover, the biogel can be remelted and reprinted as many as four more times, giving rise to the facile recycling of the material.

Heiden and coworkers also printed stretchable waveguide sensors using the biogel to showcase a soft robot with dynamic real-time control equipped with automated search-and-wipe routines. The waveguide sensors were developed by connecting the printed biogel structures to light-emitting diodes (LEDs) for light transmission and photodiodes for light detection, where the detected light intensity varied due to bending and compression of the biogel. They subsequently placed the waveguides over an actuator, and they showed the potential to detect deformation of the actuator in all directions due to changes in light intensity from bending or touch inputs. They demonstrated the ability of these soft robots containing the waveguides to perform a search-and-wipe motion to remove obstacles in the proximity of the actuator, realizing a multifunctional soft robot with sensing and actuating capabilities. In another demonstration of the potential of these waveguides, Heiden and colleagues developed touch sensors that can detect contact with objects or other waveguides, and these were used as video game controller pads connected to six buttons. A network of three waveguides was connected to the six buttons. Pressing these buttons led to compression of the waveguides, which subsequently altered the light intensity. Varying composition in light intensity due to deformation and stretching of the waveguide corresponded to specific buttons on the controller. The printed waveguides were capable of complete degradation, demonstrating their potential in the future development of sustainable devices.

The biodegradable and recyclable soft robot developed by Heiden and colleagues shows promise for many applications; however, we still need to develop new materials adopting the same principles of sustainability while also having the potential for high

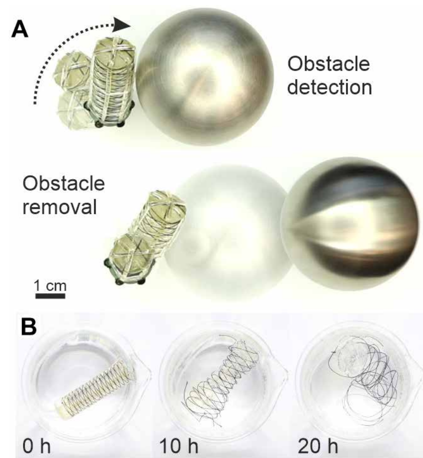

Fig. 1. Multifunctional and sustainable soft actuator. (**A**) By integrating waveguide sensors, the soft actuator can detect and remove obstacles in all directions. (**B**) The 3D-printed soft actuator can swell and disintegrate in water.

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performance in other applications. For example, materials having greater thermal and water stability could open the door for other applications. Besides, to design a fully sustainable nature-inspired robot equipped with cybernetic loops, we will require "green" materials with a wide variety of properties, ranging from electrically (or ionically) conducting or semiconducting to insulating materials. Looking forward, despite all the challenges, there is great potential for robotic research to take inspiration from nature to bring positive environmental and scientific impact worldwide.

REFERENCES

1. B. Mazzolai, C. Laschi, A vision for future bioinspired and biohybrid robots. *Sci. Robot.* **5**, eaba6893 (2020).
2. Y. J. Tan, G. J. Susanto, H. P. Anwar Ali, B. C. K. Tee, Progress and roadmap for intelligent self-healing materials in autonomous robotics. *Adv. Mater.* **33**, 2002800 (2020).
3. F. Hartmann, M. Baumgartner, M. Kaltenbrunner, Becoming sustainable, the new frontier in soft robotics. *Adv. Mater.* **33**, 2004413 (2021).
4. A. Heiden, D. Preninger, L. Lehner, M. Baumgartner, M. Drack, E. Woritzka, D. Schiller, R. Gerstmayr, F. Hartmann, M. Kaltenbrunner, 3D-printing of resilient biogels for omnidirectional and exteroceptive soft actuators. *Sci. Robot.* **7**, eabk2119 (2022).
5. M. Baumgartner, F. Hartmann, M. Drack, D. Preninger, D. Wirthl, R. Gerstmayr, L. Lehner, G. Mao, R. Pruckner, S. Demchyshyn, L. Reiter, M. Strobel, T. Stockinger, D. Schiller, S. Kimeswenger, F. Greibich, G. Buchberger, E. Bradt, S. Hild, S. Bauer, M. Kaltenbrunner, Resilient yet entirely degradable gelatin-based biogels for soft robots and electronics. *Nat. Mater.* **19**, 1102–1109 (2020).

10.1126/scirobotics.abn8147

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Sci. Robot. **7** (63), eabn8147. DOI: 10.1126/scirobotics.abn8147

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