Untethered Autonomous Soft Robotics

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ABSTRACT

Liquid crystal elastomer (LCE)–based soft robots with reversible actuation could be beneficial for both Department of Defense and civilian applications, including in exploration of confined spaces, payload delivery, remote sensing and data collection, and small biomedical devices. In the work described in this article, we developed a first-principle model for designing high-work-capacity LCEs. Further, we built bilayer structures for actuation applications. We then built a Bluetooth-controlled soft robotic system and quantified its performance. The article also discusses the outlook for LCE-based soft robotics for Department of Defense applications.

Thermo-responsive liquid crystal elastomers (LCEs) have high potential for use in soft robotic applications as programmable, smart, phase-changing materials. These LCEs consist of two phases: a mesogenic liquid crystal phase and an elastomeric network. LCE alignment can be programmed by mechanical straining,[1] electric fields,[2] and magnetic fields,[3] among others. Once alignment has been programmed, a final network crosslinking reaction is introduced to lock in the programmed strain leading to polymer chains in an oblate conformation. Upon the input of thermal energy, the aligned LCE network will change from an ordered liquid crystalline state to the unordered isotropic state.[4] The result of this phase change is a macroscopic shape change in which the aligned chains contract along the orientation direction and expand perpendicular to the orientation direction.

Since Yakacki et al.[5] developed a "simplified LCE synthesis" method using the thiol-Michael chemistry, there have been many reports on using LCEs as novel phase-changing materials for actuator applications.[6] However, none of these LCE-based robotic systems have been truly untethered autonomous systems. In addition, these systems suffer from slow response kinetics. All these issues greatly limit the use of LCEs for untethered robotics applications.

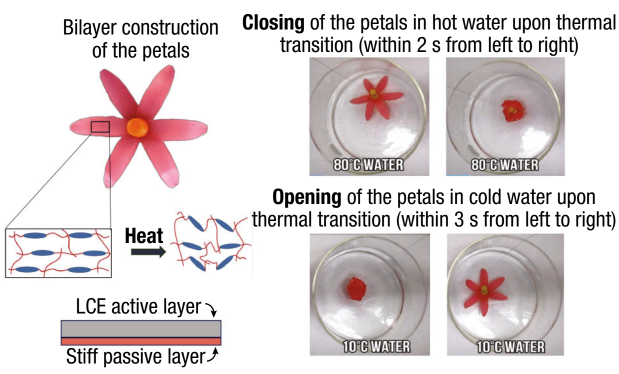

Figure 1. Bilayer structures made of LCE and silicone tape for demonstration of bending actuation in a flower shape. Conductive heat transfer to/from liquid enables rapid switching between open and closed state.

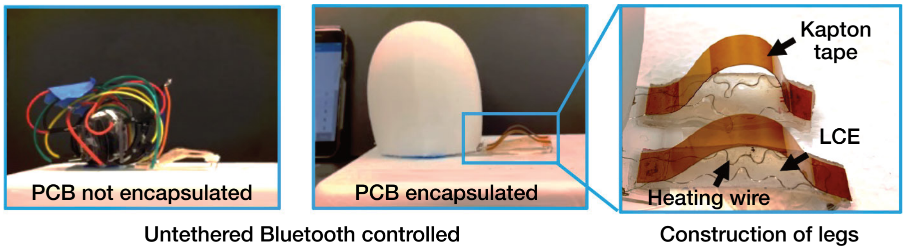

Figure 2. Bluetooth-controlled untethered soft robotic systems. Left, Snail robot with the printed circuit board (PCB) not encapsulated. Middle, The same system with the PCB fully encapsulated. Right, a close-up of leg construction. The controlling unit is encapsulated inside the white shell made by 3-D printing.

This work aims at developing an untethered autonomous robot that uses LCE as an actuator for unique Department of Defense applications by leveraging APL's expertise in thiol-Michael chemistry and system design and optimization. Our overall effort comprised two steps: (1) LCE optimization and (2) LCE-enabled untethered soft robotic system development.

LCE OPTIMIZATION

We took a fundamental polymer physics approach, with a focus on investigating ways of improving the work capacity of LCEs. Based on ideal rubber theory and the first law of thermodynamics, we developed a first-principle model showing that the work capacity (W) of an LCE increases with increasing network stretchability (λ) but decreases with increasing specific heat (C_p) (Eq. 1).[7] Using this relationship, we synthesized a series of LCEs with different compositions and determined that the experimentally measured work capacity correlated well with the model-predicted values. In addition, we developed LCEs with a maximum work capacity of 150 kJ/m^3—an impressive value compared with the value of 50 kJ/m^3 in published literature.[8]

$$\Delta W \propto \frac{1}{2} N \kappa T^2 \lambda_{max}{}^2 - C_p \Delta T \qquad (1)$$

LCE-ENABLED UNTETHERED SOFT ROBOTIC SYSTEM DEVELOPMENT

To leverage the phase-changing behavior of LCEs, we fabricated bilayer structures (Figure 1) to achieve simple bending upon thermal activation. These systems demonstrated quick shape change induced by thermal conduction.

Next, we designed and built an untethered soft robotic snail with LCE/Kapton bilayer films as actuators. The actuation was triggered via Bluetooth-controlled Joule heating of two stainless steel wires adhered to the surface of the LCE legs (Figure 2).[9] Upon activation, the robotic snail was able to move a load of 55 g using two 4 cm × 1 cm LCE/Kapton bilayers.

Last, to overcome the intrinsically slow response of LCE, we developed a snapping robot based on a metastable, constrained bilayer design[10] (Figure 3). Upon activation, a fast actuation (<2 s) was successfully achieved, resulting in jumping.

FUTURE OUTLOOK

The use of advanced, robust, soft materials in robot components or systems promises a significant leap in functionality approaching human-like capabilities. The field is popular, with fundamental research of bio-inspired form factors (e.g., eel, octopus, jellyfish, spider, inchworm, and flowers) and novel actuation by various mechanisms (thermal, hydration, pressure, magnetic). However, the field is still in its infancy, with some progress being made but significant opportunities remaining. Often these systems lack appropriate onboard power, processing, and sensing such that they rely on tethers. Additionally, significant challenges remain with control theory, inverse kinematics of infinite-degree-of-freedom constructs, appropriate accuracy/repeatability, and durability in complex environments.

Figure 3. A snapping robot using a bilayer LCE/Kapton structure adhered to a polymeric rectangular frame. Activation led to a fast actuation (<2 s) resulting in jumping.

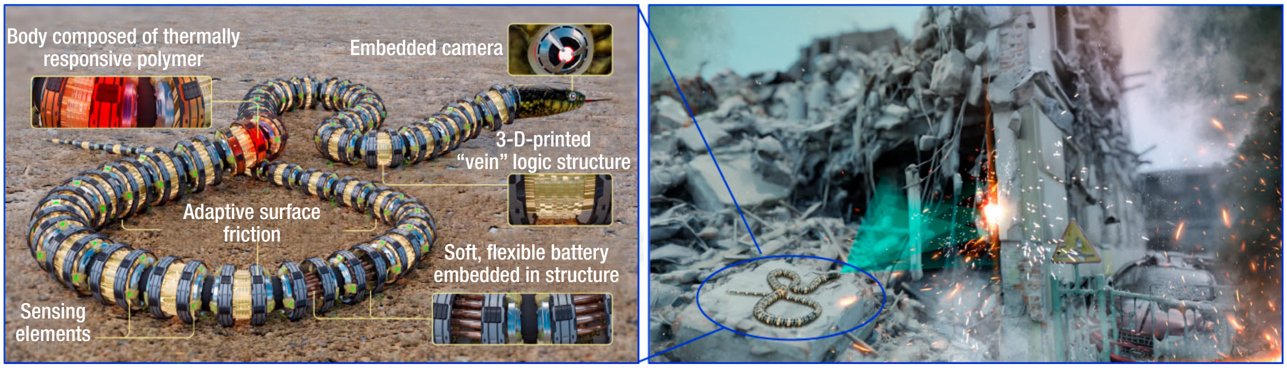

Figure 4. The robosnake. The vision for a soft, untethered robosnake integrates a variety of technologies and can be used for both Department of Defense and civilian applications.

By leveraging APL's expertise and capabilities in novel materials and manufacturing, sensing, novel power sources, controls, and artificial intelligence and robotics, complex untethered soft robotic systems such as the robosnake (Figure 4) can be realized. By advancing and integrating the component-level capabilities, we can take the first step toward enabling the vision of soft, silent, untethered robot fleets. Additionally, this technology can lead to exquisite manipulation such as soft touch for classic robot systems, most certainly bringing new capabilities to the warfighter.

REFERENCES

[1]F. Bergmann, H. Finkelmann, V. Percec, and M. Zhao, "Liquid-crystalline main-chain elastomers," *Macromol. Rapid Commun.*, vol. 18, no. 5, pp. 353–360, 1997, https://doi.org/10.1002/marc.1997.030180501.

[2]E. M. Terentjev, M. Warner, and P. Bladon, "Orientation of nematic elastomers and gels by electric fields," *J. Phys. II France*, vol. 4, no. 4, pp. 667–676, 1994, https://doi.org/10.1051/jp2:1994154.

[3]A. Buguin, M. H. Li, P. Silberzan, B. Ladoux, and P. Keller, "Micro-actuators: When artificial muscles made of nematic liquid crystal elastomers meet soft lithography," *J. Am. Chem. Soc.*, vol. 128, no. 4, pp. 1088–1089, 2006, https://doi.org/10.1021/ja0575070.

[4]M. O. Saed, R. H. Volpe, N. A. Traugutt, R. Visvanathan, N. A. Clark, and C. M. Yakacki, "High strain actuation liquid crystal elastomers via modulation of mesophase structure" *Soft Matter*, vol. 13, pp. 7537–7547, 2017, https://doi.org/10.1039/C7SM01380A.

[5]C. N. Yakacki, M. Saed, D. P. Nair, T. Gong, S. M. Reed, and C. N. Bowman, "Tailorable and programmable liquid-crystalline elastomers using a two-stage thiol–acrylate reaction," *RSC Adv.*, vol. 25, no. 5, pp. 18997–19001, 2015, https://doi.org/10.1039/C5RA01039J.

[6]D. Liu and D. J. Broer, "Liquid crystal polymer networks: Preparation, properties, and applications of films with patterned molecular alignment," *Langmuir*, vol. 30, no. 45, pp. 13499–13509, 2014, https://doi.org/10.1021/la500454d.

[7]J. Boothby, T. VanVolkenburg, N. Le, K. Ohiri, M. Hagedon, and Z. Xia, "Effects of network structure on the mechanical and thermal responses of liquid crystal elastomers," *Multifunct. Mat.*, vol., 3, no. 1, pp. 015002, pp. 1–9, 2020, https://doi.org/10.1088/2399-7532/ab6d1e.

[8]S. Rich, R. J. Wood, and C. Majidi, "Untethered soft robotics," *Nat. Electron.*, vol. 1, pp. 102–112, 2018, https://doi.org/10.1038/s41928-018-0024-1.

[9]J. M. Boothby, J. C. Gagnon, E. McDowell, T. Van Volkenburg, L. Currano, and Z. Xia, "An untethered soft robot based on liquid crystal elastomers" *Soft Robot.*, online ahead of print Jan. 8, 2021, http://doi.org/10.1089/soro.2020.0135.

[10]J. Beharic, T. M. Lucas, and C. K. Harnett, "Analysis of a compressed bistable buckled beam on a flexible support," *J. Appl. Mech.*, vol. 81, no. 8, 081011, pp. 1–5, 2014, https://doi.org/10.1115/1.4027463.

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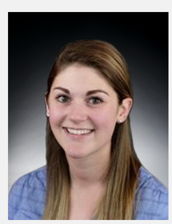

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