From Multimodal Actuation to Mechanical Intelligence: An Evolutionary Analysis of Liquid Crystal Polymer–Driven Soft Robots

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Abstract. Soft robots are gradually evolving from simple deformation actuation to intelligent systems with autonomous decision-making ability. In this transition process, liquid crystal elastomers (LCEs) play a key role due to their unique anisotropy and programmable properties. Based on the material properties, this paper analyzes why LCEs can solve the pain point of poor environmental adaptability of traditional rigid robots. Then, aiming at the problems of slow response, limited energy, and other soft robotic issues, the evolution process of various actuation strategies, such as electrothermal, photothermal and thermal gradient, is discussed. Then, this paper analyzes the current cutting-edge trend of "de electronization" of software robots, in other words, the use of space-time precise light control and bistable mechanism to make the robot body have the ability of logical judgment. Finally, aiming at the practical problems of short material life and lack of closed-loop perception, the corresponding prospects are put forward.

Keywords: Liquid Crystal Elastomers; Soft Robotics; Multimodal Actuation; Mechanical Intelligence; Embodied Logic

1 Introduction

In complex unstructured environments such as medical rehabilitation, post disaster rescue and deep space exploration, it is often difficult for traditional rigid robots to work flexibly in narrow spaces due to their fixed joints and high stiffness, and there are potential safety hazards when interacting with people. This has prompted the field of robotics to seek new technical paths to develop new robot systems that can adapt to the changing environment and interact with organisms flexibly. Soft robot technology came into being [1,2]. Its core idea is to use the continuous deformation ability of flexible materials to imitate the efficient movement and adaptation strategies of organisms in nature.

Selecting the right materials is the first step in building a soft robot. At present, smart materials have their own shortcomings. For example, dielectric elastomers have a rapid response, but they often need thousands of volts of high-voltage electricity, which poses great safety hazards and makes them difficult to miniaturize. Although the biocompatibility of hydrogels is good, they are prone to failure without water, and their strength is insufficient. Shape memory alloys have high strength, but their control frequency response is very low due to the characteristics of thermal actuation. Among these options, liquid crystal elastomers (LCEs) show unique

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advantages. It combines the orderly arrangement of liquid crystal molecules with the elasticity of polymers. Light, heat and electricity can drive it, and there is no need for complex external circuit connection. It is recognized as an ideal material for manufacturing "artificial muscle"[3,4].

This paper aims to analyze the internal logic of LCE soft robot technology development. This paper combs the evolution process from bionics and environmental adaptation, control to ontology logic. Firstly, in order to solve the limitation of single drive, how researchers realize multimodal actuation through multi-physics field coupling is discussed. Then, in order to get rid of the dependence on complex electronic control systems, how to evolve the field to mechanical intelligence and embodied logic is discussed. Finally,the challenges faced by the current technology are summarized and the future direction is prospected.

2 Multimodal Actuation Mechanisms Based on Multiphysics Coupling

In order to adapt to the changeable and complex unstructured environment, a soft robot must have the ability of multimodal motion. One of the advantages of LCE material is that it has response characteristics to thermal, optical, electrical and other physical fields. Using this feature, researchers have developed a series of multimodal actuation schemes combined with microstructure programming to effectively solve the practical problems such as slow response speed, limited motion range and difficult energy supply.

2.1 Electrothermal Actuation and Structural Design for Mitigating Response Lag

In order to move LCE materials, thermal induced phase transition is essential. However, its slow heat conduction leads to low heating and cooling efficiency, which seriously drags down the motion frequency. In order to solve this pain point, Xiao et al. designed a clever "Janus" double-layer structure [5,6]. Using the huge difference in the coefficient of thermal expansion between the two layers of materials, the film bending is induced by Joule heat instantaneously when the current is applied. Because the film is extremely thin and the heat capacity is small, the millisecond level rapid response is achieved. He et al. also followed this idea and made a tubular actuator by imitating the arrangement of muscle fibers, which contracted when energized, effectively solving the problem of low stress in soft materials [7].

2.2 Photonic Actuation for Overcoming Tethering Constraints

Although the electric drive improves the performance, the existence of the power line always limits the motion radius of the robot, making it difficult to be applied to closed or long-distance scenes. In order to realize the complete "untethered" movement, optical drive technology came into being. Light has the characteristics of long-range, precision and no electromagnetic interference, which is very suitable for underwater environment. Shahsavan et al. used structured LCE gels and the photothermal effect to produce wavy deformations [8], successfully simulating the wave propulsion mode of fish. This actuation method makes use of the spatial controllability of light, solves the problem of difficult insulation and wiring of electric drive in underwater environment, and significantly improves the hydrodynamic efficiency and concealment of the robot. At the same time, optical drive also provides a new possibility for minimally invasive medical devices, because it can achieve accurate control of micro robots without direct contact or electromagnetic interference.

2.3 Passive Autonomous Adaptation via Environmental Thermal Gradients

Although the above-mentioned method is effective, it is still inseparable from the battery or light source, which limits the range of motion of the micro robot. To solve the problem of endurance, Li et al. proposed a new idea: directly use the thermal gradient in the environment. In short, it is to break the symmetry of the actuator by using the temperature difference between the ground and the air [9]. By designing asymmetrical contact surfaces, the environmental heat flow is transformed into mechanical energy, enabling the robot to realize passive and autonomous crawling. This is essentially a self-excited oscillation, which is especially suitable for working in the energy limited scenario of waste heat pipeline inspection.

3 System-Level Evolution Toward Mechanical Intelligence and Embodied Logic

With the increasingly complex tasks undertaken by soft robots, the disadvantages of the traditional "sensor controller actuator" separation architecture are becoming more and more obvious. In extreme environments (such as strong radiation and high voltage), the integration of complex electronic circuits is not only difficult, but also prone to failure. Therefore, how to combine the computing and decision-making functions with the material itself, that is, the introduction of mechanical intelligence, has become the inevitable trend of the evolution of soft robot.

3.1 Spatiotemporal Precision to Overcome the Limits of Global Actuation

In the past, the light drive was mostly "full field illumination", and the robot could only move as a whole and could not do fine work. In order to make the control more flexible, Blackert et al. [10] proposed the "spatiotemporally controllable" technology.

They use projectors to project dynamic optical patterns, which can be used to drive specific parts of the robot body independently. This is actually transferring the complexity of the hardware structure to the software light field programming, so that the same robot can do different jobs by changing the lighting logic.

3.2 Constructing Physical-Layer Embodied Logic via Bistable Mechanisms

The so-called mechanical intelligence, to put it bluntly, is to throw away electronic chips. Today's robots rely too much on CPU. But in the micron scale, it is too difficult and expensive to insert a CPU. In the existing soft robot system, although the body uses flexible materials, its control core still relies on hard silicon-based chips. This "soft body hard brain" heterogeneous integration faces significant compatibility challenges in practical applications: on the one hand, there are huge differences in mechanical modulus between rigid circuit boards and flexible LCE materials, and the stress concentration at the interface easily causes structural failure. On the other hand, the stability of electronic components is often difficult to guarantee in extreme environments such as the micro/nano scale or strong radiation, high temperature and high pressure. Therefore, how to use the physical properties of materials to replace electronic computing and give the perception and decision-making functions to the body has become a key scientific problem in this field.

The key to achieve this goal is to find a mechanism that can simulate the "open" and "close" states of electronic logic gates at the physical level. Through some research findings, the snap through instability phenomenon caused by LCE materials combined with specific geometric design provides a natural solution for the construction of physical logic gates.

This mechanism physically simulates the "jump" instability behavior of the elastic shell: the structure first accumulates elastic potential energy under external excitation. Once the energy accumulation breaks through a specific potential barrier, the structure will undergo transient buckling and transition to another steady state. It is worth noting that since the system has only two stable equilibrium points at low energy levels and no intermediate transition state, this discontinuous mechanical feature is very similar to binary "0" and "1" in digital logic. Hyatt et al. used the thermal contraction effect of LCE to drive such bistable units, and successfully built a logical operation architecture without electronic participation at the physical entity level [11]. Experiments show that the basic Boolean operations such as and, or and not can be realized only by adjusting the topological layout and connection form of materials. This shows that the physical structure itself has the endogenous ability to perform arithmetic and logical judgment, and no longer relies on external code instructions in one direction.

Zhou et al. further transformed this static physical logic into a dynamic motion control strategy and designed a soft robot with autonomous gait switching function. This system has built-in bistable trigger mechanism based on LCE: under low energy input (such as weak light) [12], the robot maintains a "steady-state one" tiled configuration and crawls through the confined space. Once the environmental energy flux exceeds the critical threshold, the bistable unit in the material is activated instantaneously, releasing the stored strain energy, driving the body to suddenly turn into a "steady-state two" curl configuration, thus switching to an efficient rolling mode.

In this process, the traditional "sensor controller actuator" feedback loop is completely bypassed. The perception of environmental gradients, the discrimination of signal thresholds and the triggering of execution actions are all completed synchronously at the instant of material phase transition and structural instability. This mechanism, defined as "embodied logic", shows excellent response speed and environmental robustness due to its extremely short physical response path (see Figure 1 for the evolution route). At the same time, in order to expand the functional boundary of LCE robot, Wang et al., Li et al., and Liu et al. made breakthroughs in the fields of mechanical reinforcement and optical camouflage respectively: the former significantly improved the low load-bearing capacity of the actuator by using fiber composite technology [13], while the latter achieved adaptive environmental integration by adjusting the microstructure color [14,15]. These studies have jointly passed the proof of concept: the future soft robot is expected to evolve into an intelligent entity that does not rely on electronic bus and is completely driven by physical logic (Table 1).

Table 1. Comparison of different actuation mechanisms (Actuation Source–Core Mechanism–Key Characteristics)

Reference	Actuation Source	Core Mechanism	Key Characteristics
Xiao et al.	Electrical	Joule-heating-induced asymmetric expansion in a bilayer architecture	Janus structure: Enables millisecond-scale response for rapid bio-inspired walking and steering.
Shahsavan et al.	Optical	Photothermal deformation of structured LCE hydrogels	Underwater bio-inspiration: Mimics fish-like undulatory propulsion with high hydrodynamic efficiency.
He et al	Electrical	Electrothermal contraction via helically aligned liquid crystal directors	Tubular actuator: Provides high-load linear contraction and bending; applicable to soft manipulators.
Li et al.	Thermal	Non-uniform deformation induced by environmental thermal gradients	Autonomous crawling: Driven by ambient temperature differences without onboard power
Blackert et al.	Optical	Spatiotemporal modulation of optical fields	Precision control: Achieves localized and independent actuation through patterned light.
Zhou et al.	Multiphysics	Dynamic modulation of energy input across coupled physical fields	Autonomous gait switching: Enables self-regulated transitions among rolling, jumping, and crawling.

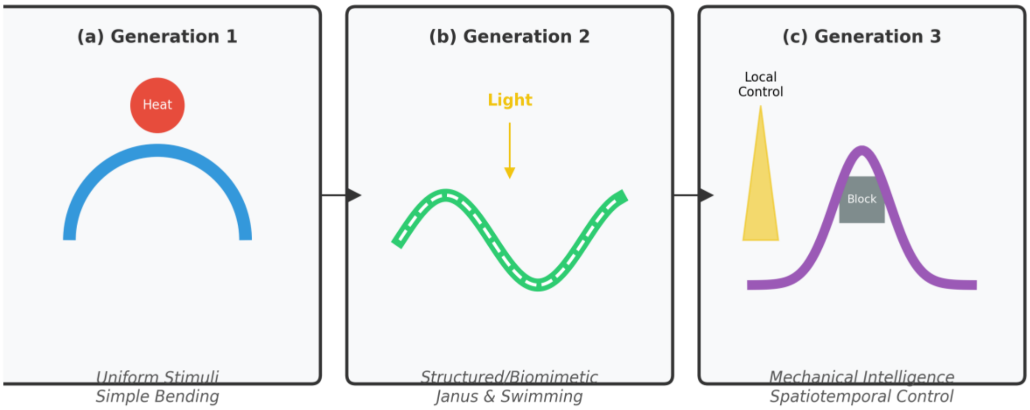

Fig. 1 Technological evolutionary roadmap of liquid crystal elastomer (LCE) soft robots.(a) Generation 1: Simple bending actuated by uniform external stimuli [11];(b) Generation 2: Multimodal biomimetic locomotion achieved via structured molecular programming [12];(c) Generation 3 (Current Frontier): Autonomous intelligent systems integrating spatiotemporal control and mechanical intelligence

4 Challenges and Outlook

LCE robots have indeed become increasingly intelligent, yet their large-scale application remains challenging. The biggest obstacle is the trade-off of material properties. In the existing LCE material system, it is often difficult to have both driving force and response speed, which is a typical performance trade-off phenomenon. Although high modulus materials can output large force, their thermal response speed is usually slow due to the high rigidity of the polymer chains. On the contrary, materials with rapid response tend to have a low modulus and are difficult to bear heavy load. In addition, LCE, as a polymer network, is prone to fatigue accumulation and even fracture after thousands of thermal cycles or light stimulation, which makes it unable to maintain long-term service life in industrial scenarios. The future research direction should focus on the development of new composite materials, so as to break the constraint between mechanical properties and response speed without sacrificing flexibility.

At present, most LCE systems still use open-loop control, lack real-time feedback on their own deformation states, and are difficult to deal with dynamic external disturbance. In the future, it is urgent to develop intelligent composite materials that can integrate liquid metal flexible sensors or fiber Bragg gratings to give robots the ability of "proprioception", so as to achieve accurate closed-loop control. The system integration and manufacturing process need to be further improved.

Although the existing 4D printing technology has realized molecular orientation programming, there are still difficulties in the integrated manufacturing of multi materials (such as rigid flexible coupling and conductive layer integration). The future manufacturing process should develop to multi-scale and multi-material hybrid printing to realize the full system integration of energy, drive, sensing and computing modules.

5 Conclusion

Using the methods of literature review and technology evolution analysis, this paper systematically reviews the evolution of liquid crystal elastomer soft robot from a simple mechanical intelligent system driven by a single physical field to a mechanical intelligent system with independent decision-making ability. It is found that LCE materials effectively overcome the constraints of intrinsic thermal hysteresis and wired connection through the structural programming of electrothermal coupling and photothermal effect, achieving millisecond response and untethered biomimetic movement. Recently, the passive autonomous crawling realized by using environmental thermal gradient has further solved the bottleneck of energy endurance for micro robots. More importantly, with the introduction of spatio-temporal precise light control technology and bistable mechanical mechanism, the field is undergoing a paradigm shift from "external algorithm control" to "ontology embodied logic". The robot realizes the gait autonomous switching without the participation of electronic chips through the physical nonlinearity of the material itself. Although there are still challenges such as limited fatigue life of materials and lack of closed-loop perception, this design concept of "material is computing" provides a new idea for solving the control problem of micro robot. If future research can further integrate liquid metal flexible sensing and multi-material integrated manufacturing technology, it will greatly promote the engineering landing of embodied intelligent soft robots in precision medicine, deep space exploration and unstructured environment operations.

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