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Actuation Technologies for Soft Robots: Performance Trade-Offs in Single Actuation and Advances in Hybrid Actuation

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Abstract. In recent years, soft robots have attracted widespread attention due to their unique compliance, adaptability, and safety, and soft robot technology holds broad application prospects. Actuation technology is the core factor determining the performance of soft robots. While various actuation solutions have their own advantages and disadvantages, a single drive solution struggles to simultaneously meet all performance requirements—such as large output force, fast response, compliance, and untethered operation. At present, there is a lack of a systematic review and summary of single and hybrid systems. This review focuses on summarizing single-actuation and hybrid-actuaqtion technologies for soft robots. By classifying and analyzing the mechanisms and performance limitations of single-actuation approaches such as fluidic, electroactive polymer(EAP), and magnetic systems, it introduces and demonstrates that hybrid actuation can alleviate the trade-off contradictions in the performance of single actuation. Hybrid actuation is expected to become an important direction for the future development of soft robotics. This review also identifies current technical bottlenecks in soft robot actuation, including system complexity, multiphysics coupling, energy efficiency, and reliability.

Keywords: Soft Robots, Actuation Technologies, Hybrid Actuation, Multiphysics Actuation, Soft Actuators

1. Introduction

Benefiting from their continuous structures, compliance, and excellent environmental adaptability, soft robots have demonstrated significant application potential in confined-space navigation, multimodal locomotion, object manipulation, and other fields [1]. Actuation represents a core technology in soft robotics and carries enormous significance. The main actuation methods for soft robots are fluidic actuation, smart-material-based actuation, and magnetic actuation. These single-mode actuation technologies have established relatively mature research frameworks [2].

However, individual actuation methods generally suffer from inherent limitations, with their performance in terms of untethered operation, biocompatibility, response speed, output force, and performance degradation often being mutually constrained [3]. Consequently, it remains challenging for a single actuation method to simultaneously satisfy the comprehensive requirements of high precision, lightweight design, and autonomous operation. In recent years, novel hybrid actuation systems integrating multiple actuation mechanisms have emerged, further advancing the field and

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providing potential solutions to key challenges related to actuation speed, force density, and operational flexibility [4]. However, existing research has primarily focused on the optimization of individual actuation methods. For example, pneumatic actuation has been optimized through actuator design and control strategies to improve actuation performance [5]. For electroactive polymer actuators, material and structural designs have been explored to improve their deformation and response characteristics [6, 7]. In magnetic actuation, the design of untethered soft robots actuated by external magnetic fields has been investigated to achieve controllable and multifunctional locomotion [8]. However, systematic reviews and cross-comparisons of different types of hybrid actuation systems remain relatively limited.

In this study, an inductive and analytical approach is adopted to systematically review the technical characteristics of single actuation technologies for soft robots, including fluidic, electroactive polymer, and magnetic actuation. Based on this analysis, the research progress of six types of hybrid actuation approaches, including pneumatic–tendon, pneumatic–magnetic, pneumatic–hydraulic, pneumatic–SMA, magnetic–optical, and magnetic–photothermal actuation, is further reviewed. The key challenges and technical bottlenecks associated with current actuation technologies are also summarized. By systematically reviewing and synthesizing existing research findings, this study clarifies the advantages and application potential of hybrid actuation technologies, providing a theoretical reference for actuation-method selection, structural optimization, and subsequent innovative design of soft robots.

2. Single actuation methods

2.1. Fluidic actuation

With the rapid development of soft robotics in recent years, fluidic actuation has become a relatively mature actuation technology. It drives the motion of soft robots by converting fluid pressure into mechanical energy. The basic principle is to regulate the pressure within the internal fluidic chambers of a soft robot, causing the internal channels to expand and thereby achieving controlled deformation of the robot structure [2]. Fluidic actuation can be divided into two types: pneumatic and hydraulic actuation.

Pneumatic actuation employs gas as the driving medium and produces force via air pressure to drive soft robots [2]. Its fundamental principle lies in that pressurized gas is delivered into embedded channels and elastic chambers, which generates stress at the gas–solid interface and induces deformation of the soft robotic structure [2, 9]. Youssef Moustafa et al. [5] proposed a soft robotic finger fabricated from silicone material and actuated pneumatically to mimic the motion of a natural finger. They performed finite element analysis (FEA) using the static structural module of CATIA V5. When the air pump operated at 100% power, the equivalent force reached 15.5 N, the grasping load capacity was 0.5 kg, and the maximum bending angle was 30°. The study combined finite element modeling, numerical simulation, and physical fabrication to achieve comprehensive optimization of the soft finger structure and actuation performance, providing a reference for the design of low-cost and reliable pneumatic soft actuators. Overall, pneumatic actuation features high compliance, large deformation, relatively fast response, favorable safety and a high force-to-weight ratio [2, 9]. However, due to the compressibility of air, its output and control performance are susceptible to pressure variations and system nonlinearities. In addition, pneumatic systems typically require external air sources and connecting tubing, which limits their miniaturization and autonomous operation to some extent [9].

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Both pneumatic and hydraulic actuation are forms of fluidic actuation, but they use different working media. Pneumatic actuation uses compressible gases as the working medium, whereas hydraulic actuation uses approximately incompressible liquids. Consequently, the two actuation methods exhibit significant differences in output capability, response characteristics, and system complexity.

Hydraulic actuation is typically achieved by injecting fluid into specially designed chambers. Owing to the incompressibility of liquids, these chambers can be used to generate the desired motion [10]. Compared with pneumatic actuation, hydraulically driven soft robots are better suited to underwater environments because of the characteristics of the working medium and can provide higher output force. However, their applications remain relatively limited due to the size and weight constraints of hydraulic systems. In the medical field, Ling-Wu Meng et al. [11] developed a biomimetic soft robot consisting of three actuators based on the locomotion mechanism of earthworms for the treatment of chronic total occlusion (CTO) lesions in coronary or peripheral arteries. The actuators are deformed by pumping fluid into and extracting fluid from the sealed soft chambers to regulate the internal hydraulic pressure. The study employed a bidirectional fluid–structure interaction (FSI) method to establish a kinematic model of the soft robot. The simulation results demonstrated that the deformation of the actuators could be precisely controlled by adjusting the hydraulic pressure within the axial actuator chambers, thereby enabling the controlled motion of the soft robot. However, compared with pneumatic actuation, hydraulic systems typically require more complex pumps, valves, and fluid delivery components, while also facing challenges related to system weight, size, and potential fluid leakage [10].

2.2. Electroactive polymers (EAPs)

EAPs are a class of polymers capable of changing their dimensions and shapes in response to an applied electric field. By converting electrical energy into mechanical energy, EAPs can actuate the motion of soft robots. They exhibit high strain capability, excellent flexibility, low weight, and high resistance to fracture [6], making them ideal materials for soft robotic actuation. EAPs can be broadly classified into two main categories according to their actuation mechanisms: ionic EAPs and electronic EAPs [12]. Ionic EAPs deform as a result of ion migration within the polymer structure, with volume change serving as the underlying mechanism of actuation. Because they can generate significant bending displacement, ionic EAP technology has gradually approached technological maturity. Ionic Polymer–Metal Composites (IPMCs) are characterized primarily by low operating voltage and large bending strain induced by the migration of cations within the polymer matrix [2]. IPMCs have broad application prospects in biomimetic robotic muscle actuation, optomechanical systems, and biomedical engineering [13].

Unlike ionic EAPs, electronic EAPs do not require an electrolyte medium, and their electromechanical coupling process does not involve ion migration [14]. In contrast to ionic EAPs that work at low voltage, most electronic EAPs generally require relatively high-voltage excitation yet deliver faster response speeds. To date, electronic EAPs have undergone extensive development. Here, dielectric elastomer actuators (DEAs), one of the most common types of electronic EAPs, are introduced as an example. The operating principle of DEAs is based on the Coulombic attraction between two charged flexible electrodes with a potential difference, which are located on opposite sides of a compliant film [10]. DEAs have been applied in the field of soft robotics, and their biomimetic properties have demonstrated significant application value in various fields [7]. Chenghong Zhang [7] reported a Carangidae-mimetic robotic fish driven by DEA technology in 2025. Preliminary calculations revealed that the thrust output varied from 12 to 15 mN at 3 Hz and

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4.5 kV. Under the optimal working condition (3 Hz excitation frequency and 60° connector angle), the robotic fish reached a top swimming speed of 8.6 mm/s. The results proved that periodic electric excitation enables DEAs to produce biomimetic thrust, presenting a novel actuation solution for lightweight and highly compliant soft robots in underwater applications. However, the system still faces challenges such as relatively high actuation voltage and limited output capability. In addition, its propulsion speed remains lower than that of real fish, indicating that DEA-based actuation requires further improvements in actuation efficiency and overall performance for practical applications.

2.3. Magnetic actuation

Since magnetic actuators can achieve untethered actuation through magnetic fields, the application of magnetic principles to generate forces and torques for soft robotic systems has been proposed and demonstrated as a promising technology [15]. In general, magnetic actuation can be primarily classified into two forms. The first generates axial contraction and extension by rotating the magnetic poles within the actuator, while the second induces deformation of the outer surface layer of an actuator containing magnetic particles by varying the external magnetic field, thereby producing displacement [16].

Inspired by the locomotion mechanisms of insects, Ruomeng Xu et al. [8] designed a soft octopod robot fabricated by mixing magnetic particles with a silicone polymer and subsequently magnetizing the material using a specific magnetic field. The robot was actuated by an external magnetic field. Experimental results showed that the soft robot could achieve high-speed locomotion at 0.536–1.604 mm/s on different surfaces, including paper, wood, and PMMA. These results demonstrated that the soft robot could achieve performance comparable to that of other soft robots even under a relatively low driving magnetic field strength, thereby reducing energy consumption.

Overall, magnetic actuation features merits including contactless operation, remote controllability and rapid response. By modulating external magnetic fields, this technique can drive soft robots to move, making it highly suitable for miniaturized robotic platforms and applications in complex environments [11, 8]. However, magnetic actuation typically relies on external magnetic-field generation systems, and its actuation performance is influenced by factors such as magnetic field strength, spatial distribution, and the properties of magnetic materials. In addition, magnetic-field control for complex locomotion modes and system integration further increases control complexity [11]. Therefore, single magnetic actuation still has certain limitations in terms of output capability, locomotion modes, and system autonomy.

2.4. Cross-comparison of single actuation methods

In addition to the typical soft robotic actuation methods discussed in this paper, several other emerging actuation approaches with considerable application potential are also under development, such as shape memory alloy (SMA)-based actuation and optical actuation. This review summarizes the commonly used actuation methods for soft robots, their specific subcategories, and their corresponding advantages and disadvantages, as presented in Table 1.

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Table 1. Comparison of single actuation methods for soft robots

Actuation method	Subcategory	Main advantages	Main limitations
Fluid actuation	Pneumatic actuation	Large deformation; high compliance; fast response	Requires external air source; tubing and bulky setup
	Hydraulic actuation	High output force; high force density; stable transmission	Leakage risk; relatively heavy and complex
EAP actuation	Electronic EAP	Lightweight; large strain; fast response	High driving voltage; limited output force
	Ionic EAP	Low driving voltage; high flexibility; large deformation	Low output force; environmental sensitivity
SMA actuation	-	High energy density; compact; high recovery force	Slow response; difficult cooling and control
Magnetic actuation	-	Wireless; fast response; remote control	Requires external magnetic field
Optical actuation	-	Contactless; remote stimulation; programmable deformation	Requires light source; limited penetration

Single actuation methods involve inherent trade-offs, with different performance characteristics often constraining one another. With continuous technological advancements, single actuation methods can no longer fully meet the evolving requirements of soft robotics.

3. Hybrid actuation methods

Currently, research on hybrid actuation has gradually evolved from simple combinations of multiple actuation methods toward multiphysics coordination, locomotion-mode switching, and structural reconfiguration. Accordingly, based on the combinations of different actuation mechanisms, this review categorizes hybrid actuation technologies into six types: pneumatic–tendon actuation, pneumatic–magnetic actuation, pneumatic–hydraulic actuation, pneumatic–SMA actuation, magnetic–optical actuation, and magnetic–photothermal actuation.

3.1. Pneumatic–tendon hybrid actuation

Pneumatic–tendon hybrid actuation combines pneumatic actuation with tendon actuation. Pneumatic actuation enables flexible chambers to undergo large-range contraction, extension, bending, and twisting deformations, while tendons apply directional pulling forces to soft structures through tension transmission, thereby enabling further posture adjustment and precise positioning. These two actuation methods typically form a complementary relationship characterized by "large-range deformation–fine control." Kang et al. [17] created an embedded tendon-pneumatic continuum robot, where pneumatic muscles generate large deformation and tendons offer fine positioning, boosting end-effector accuracy without sacrificing pneumatic actuation's large-displacement feature. Stilli et al. [18] proposed an antagonistic flexible manipulator realizing bending, extension and stiffness adjustment through combined pneumatic–tendon actuation. Roshanfar et al. [19] carried out hyperelastic modeling and experiments to study the coupled influence of air pressure and tendon

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tension on robot kinematics and stiffness. Their results demonstrate that simultaneous tuning of pressure and tension expands motion range and control performance. This hybrid strategy has found applications in medical continuum robots. Dynamic models based on Cosserat rod theory were constructed to support soft robotic deployment in precision procedures such as cardiac ablation [20].

3.2. Pneumatic–magnetic hybrid actuation

Research on both pneumatic and magnetic actuation is relatively mature. Pneumatic–magnetic hybrid actuation combines pneumatic deformation with magnetic-field-induced actuation, enabling soft robots to combine the large-deformation capability of pneumatic actuation with the non-contact manipulation capability of magnetic actuation. Pneumatic pressure serves as the primary driving force for deformation, while magnetic fields can be used to alter local morphology, adjust the direction of locomotion, or introduce additional degrees of freedom. Liao et al. proposed a soft robot based on pneumatic–magnetic hybrid actuation for locomotion in complex, unstructured environments [21]. The robot achieves multi-degree-of-freedom deformation through the synergistic action of pneumatic pressure and magnetic fields, enabling it to adapt to environments with varying slopes and surface roughness. Compared with single pneumatic actuation, magnetic fields provide additional remote-control degrees of freedom without requiring mechanical tendons, making this approach suitable for applications in space-constrained environments or environments where mechanical contact is difficult to achieve. The main feature of this type of hybrid actuation is the complementarity between pneumatic actuation and non-contact magnetic actuation. However, the addition of magnetic particles may alter the mechanical properties of the flexible material, while external magnetic-field generation systems are typically bulky. Therefore, miniaturizing the magnetic-field generation system and achieving precise coordinated control between pneumatic pressure and magnetic fields remain important areas of research.

3.3. Pneumatic–hydraulic hybrid actuation

Pneumatic–hydraulic hybrid actuation utilizes both air and liquid as working fluid media for actuation. Compared with pneumatic actuation, hydraulic actuation offers higher force transmission capability and load-bearing capacity, whereas pneumatic actuation is characterized by lower weight, faster response, and the ability to generate large deformations. Therefore, the two actuation methods can complement each other in terms of output force, locomotion speed, and structural deformation. Chen et al. proposed a pneumatic–hydraulic hybrid actuator for swimming and crawling in underwater soft robots [22]. The system can generate complex three-dimensional bending of flexible structures by controlling different fluid pressures, while switching between different actuation media enables swimming, crawling, and posture adjustment. The results demonstrated that this hybrid system can effectively adapt to complex underwater environments. Pneumatic–hydraulic hybrid actuation is particularly suitable for soft robots that require both deformation capability and load-bearing capacity, especially underwater robots. However, this approach requires additional components such as air and liquid supplies, valves, and tubing, which increase the system size and control complexity. In addition, liquid leakage can compromise system reliability.

3.4. Pneumatic–sma hybrid actuation

Shape memory alloys (SMAs) can generate reversible shape recovery and contraction in response to temperature changes and are characterized by compact structures, low weight, and high output force.

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Pneumatic actuation, in contrast, offers high compliance and a large deformation range. Therefore, combining these two actuation methods enables pneumatic pressure to generate overall deformation while SMAs provide localized driving forces or auxiliary adjustment.

Brașoveanu and Burlacu [23] studied an SMA-pneumatic hybrid actuation setup. Using mathematical modeling and numerical simulation, they analyzed the coupling behavior of the two actuation mechanisms and verified that this hybrid design merges the merits of SMA and pneumatic actuators to overcome drawbacks of single-mode actuation. Zhang et al. [24] further integrated SMAs with pneumatic muscles into an origami-based continuum manipulator, achieving multiple locomotion modes through the coordinated action of the two actuation mechanisms. Each module can realize axial extension as well as bending in four directions: left, right, forward, and backward, yielding five active deformation modes. Under different pneumatic pressure conditions, each module can achieve 31 distinct deformation states, and the four-module manipulator can theoretically generate $31^4 = 923{,}521$ configurations [24]. These results demonstrate that combining SMA and pneumatic actuation can substantially expand the deformation modes and configuration space of soft manipulators while maintaining structural compliance. The advantages of pneumatic–SMA hybrid actuation include a high level of structural integration and the ability to achieve both large flexible deformation and relatively high localized output force. However, SMAs are typically actuated through electrothermal heating, and their heating and cooling processes involve thermal inertia, thereby limiting their response speed. Additionally, heat accumulation may compromise the safety of soft robots and degrade material properties.

3.5. Magnetic–optical hybrid actuation

Magnetic–optical hybrid actuation utilizes magnetic fields and optical stimuli to enable remote control of soft robots. Magnetic fields offer non-contact operation, fast response, and a high number of control degrees of freedom, while optical stimuli can alter the morphology of soft structures through photoresponsive or photothermal materials. Therefore, these two actuation methods can perform different functions, such as locomotion control and structural deformation.

Han et al. [25] proposed a reprogrammable soft robot based on the synergistic interaction of magnetic and optical fields. This system integrates magnetic materials with photoresponsive structures, using magnetic fields to control robot locomotion while optical stimuli are employed to alter the morphology and energy distribution of local structures. Cui et al. [26] similarly proposed a magnetic–optical hybrid soft actuator. In this study, Fe_3O_4 magnetic nanoparticles and graphene oxide (GO) layers were integrated into a flexible PDMS structure. Optical irradiation induces a photothermal effect in the GO, resulting in structural deformation, while the magnetic field generates actuation forces through the magnetic nanoparticles. Through the synergistic action of the two stimuli, the actuator can achieve richer locomotion behaviors than those enabled by a single actuation method. The major advantage of magnetic–optical hybrid actuation is its wireless and non-contact control capability, making it particularly suitable for miniature soft robots and remote manipulation in confined environments. However, the actuation performance is affected by factors such as the optical irradiation range, photothermal conversion efficiency of the materials, and spatial distribution of the magnetic field. In addition, when optical stimulation primarily induces mechanical deformation through a photothermal effect, the actuation mechanism already involves thermal responsiveness. Therefore, it is necessary to distinguish this approach from magnetic–photothermal hybrid actuation.

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3.6. Magnetic–photothermal hybrid actuation

Magnetic–photothermal hybrid actuation further integrates magnetic-field actuation, photothermal conversion, and thermoresponsive materials. Compared with magnetic–optical actuation, this type of system places greater emphasis on the multiphysics synergy among "optical–thermal conversion–deformation" and "magnetic field–locomotion control." Wang et al. [27] introduced a thermally responsive magnetic soft robotic system fabricated by embedding magnetic microparticles into liquid crystal elastomer (LCE) matrices. The system leverages near-infrared (NIR) irradiation to produce localized photothermal effects, which trigger targeted morphological transitions of the LCE material, while an externally applied magnetic field governs the robot's movement orientation and supports high-speed rolling locomotion. The robot could switch between a closed spherical configuration and an open configuration, achieving a maximum locomotion speed of approximately 30 body lengths per second and maintaining locomotion capabilities in dry, humid, and underwater environments.

This type of hybrid actuation exhibits a more complex multiphysics coupling relationship among optical, thermal, and magnetic fields. Therefore, compared with purely magnetic–optical hybrid actuation, magnetic–photothermal systems offer stronger capabilities for morphological reconfiguration and functional expansion. Overall, magnetic–photothermal hybrid actuation provides advantages including wireless operation, remote control, multimodal functionality, and reconfigurability, making it suitable for miniature robots, underwater robots, and intelligent soft robotic systems operating in complex environments. However, its performance is affected by factors such as photothermal conversion efficiency, material thermal conductivity, and environmental heat dissipation conditions. Strong coupling may also exist between the magnetic and temperature fields.

3.7. Cross-comparison of hybrid actuation methods

The six aforementioned hybrid actuation methods exhibit distinct characteristics in terms of actuation performance, control strategies, and application scenarios. A detailed comparison is presented in Table 2.

Table 2. Comparison of hybrid actuation strategies for soft robots

Hybrid actuation	Actuation mechanisms	Main advantages	Main limitations	Typical characteristics
Pneumatic–Tendon	Pneumatic + tendon-driven	High output force; improved positioning and controllability	Complex structure; potential friction and mechanical loss	Combines compliance with precise force transmission
Pneumatic–Magnetic	Pneumatic + magnetic	Large deformation; wireless or remote control; enhanced locomotion	Requires magnetic field; relatively complex control	Combines deformation capability with remote actuation
Pneumatic–Hydraulic	Pneumatic + hydraulic	High output force; improved stiffness and load capacity	Heavy and complex; possible leakage	Suitable for high-load and underwater applications

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Table 2. (continued)

Pneumatic–SMA	Pneumatic + SMA	High force density; compact; improved shape control	Slow thermal response; heat management required	Combines fast pneumatic motion with SMA-based contraction
Magnetic–Light	Magnetic + optical	Remote and contactless control; programmable deformation	Requires external magnetic/light sources; environmental dependence	Enables multimodal and reconfigurable motion
Magnetic–Light–Thermal	Magnetic + light/photothermal	Multiple deformation modes; adaptive and reconfigurable	Complex material design and control; thermal response limitations	Integrates magnetic actuation with light-induced thermal reprogramming

4. Current challenges of soft robot actuation systems

Although hybrid actuation can address some of the limitations of single actuation methods, its further development and application still face challenges in areas such as system integration, control, energy utilization, and reliability.

1. System integration and miniaturization. Different actuation methods typically require different energy sources and actuation devices, such as air pumps, magnetic-field generation systems, and photothermal stimulation devices. Increasing the number of actuation methods increases system complexity and limits the miniaturization and untethered operation of soft robots. Therefore, future efforts should focus on developing integrated designs for actuation, energy supply, and control modules to reduce dependence on external equipment [28].

2. Multiphysics coupling and control. Hybrid actuation involves multiple physical fields, including pneumatic pressure, magnetic fields, light, and heat. Their interactions increase system nonlinearity and control difficulty. Li et al. [29] designed a cable–pneumatic hybrid-driven variable-stiffness soft manipulator to tackle severe nonlinearities from the coupling of cable mechanical actuation and pneumatic actuation. To resolve the challenge of accurate deformation prediction for soft materials, they built a system dynamic model and adopted sensor-feedback closed-loop control to realize high-precision motion control of the manipulator. Therefore, developing accurate dynamic models and implementing closed-loop control through sensor feedback are important directions for improving the locomotion accuracy of hybrid-actuated soft robots.

3. Response speed and energy efficiency. Different actuation mechanisms exhibit distinct response characteristics. Pneumatic and magnetic actuation typically offer relatively fast response, whereas SMAs and certain thermoresponsive materials are constrained by heating and cooling processes, resulting in relatively slower response speeds. Furthermore, multi-actuation systems often require multiple forms of energy input to be supplied simultaneously, necessitating further improvements in energy utilization efficiency.

4. Reliability and practical application. In the future, it will be necessary to further improve the reliability of actuation materials and structures and to advance hybrid actuation systems toward miniaturization, wireless operation, and practical applications.

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5. Conclusion

Compared with single actuation, hybrid actuation leverages the complementary advantages of different actuation mechanisms to achieve improved overall performance in terms of output capability, range of motion, control strategies, and environmental adaptability. Different hybrid actuation methods exhibit distinct application characteristics. Pneumatic-related hybrid actuation primarily emphasizes output capability and locomotion control, while magnetic-related hybrid actuation offers advantages in wireless manipulation and remote actuation. Meanwhile, multiphysics actuation approaches, such as magnetic–photothermal hybrid actuation, further expand the morphological reconfiguration and multimodal locomotion capabilities of soft robots. However, hybrid actuation also introduces challenges, including increased system complexity, multiphysics coupling, energy efficiency, and reliability. In the future, soft robot actuation technologies are expected to further develop toward multiphysics coordination, integrated actuation and sensing, intelligent closed-loop control, and miniaturization, thereby promoting the evolution of soft robots from simple motion execution toward more autonomous and intelligent systems.

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