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Soft Robotics in Engineering: Materials, Actuation Technologies, and Control Strategies

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Abstract: Soft robotics represents a transformative shift in robotic design, emphasizing compliance, adaptability, and safety through the use of deformable materials and bioinspired architectures. This review provides a comprehensive synthesis of recent advancements in soft robotic systems, focusing on three foundational pillars: functional materials, actuation technologies, and control strategies. We examine the development of elastomers, stimuli-responsive polymers, and nanocomposites that enable mechanical flexibility and multifunctionality. Key actuation approaches-including pneumatic, dielectric, thermal, magnetic, and hybrid systems-are analyzed with respect to their efficiency, scalability, and integration challenges. On the control side, we explore both model-based and AI-driven methods, highlighting the need for real-time adaptability and robust sensor feedback. Despite promising progress, major obstacles persist in system-level integration, precision control, and commercial scalability. To address these issues, we identify future research directions such as lightweight energy systems, multimodal feedback, and bioinspired material architectures. This review underscores the importance of interdisciplinary collaboration in advancing soft robotics from laboratory prototypes to practical, real-world applications.

Keywords: soft robotics; functional materials; intelligent control

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1. Introduction

Soft robotics has emerged over the past decade as a disruptive and rapidly evolving subfield in robotics, characterized by its use of deformable, compliant, and often bio-inspired materials and structures [1,2]. In contrast to traditional rigid-bodied robots that rely on precise joints and stiff links, soft robots draw inspiration from natural organisms such as octopuses, worms, and starfish, which exhibit smooth, adaptive, and distributed motion capabilities [3]. This paradigm shift has enabled the development of robotic systems that can bend, stretch, twist, and conform to complex environments in ways that rigid robots fundamentally cannot.

The advantages of soft robotics over conventional rigid robotics are manifold. First, their intrinsic mechanical compliance allows for safer interaction with humans, making them ideal for medical and wearable applications [4]. Second, their adaptability to unstructured and confined environments expands their potential use in search-and-rescue missions, agricultural automation, and marine exploration [5]. Third, their light weight and material simplicity reduce manufacturing cost and energy consumption, promoting scalable deployment [6]. These benefits, however, come at the expense of new technical challenges in terms of material durability, actuation efficiency, sensing, and control.

Despite the conceptual advantages, the transition of soft robotics from laboratory demonstration to real-world engineering applications remains a major obstacle. Many soft robotic prototypes are currently constrained by the lack of high-performance functional materials that can simultaneously provide flexibility, strength, and environmental robustness [7]. Moreover, commonly used actuation methods-such as pneumatic and shape memory-based systems-often suffer from slow response times, limited controllability, and integration difficulties [8]. In addition, the control of soft robotic systems presents unique challenges due to their high degrees of freedom, nonlinear dynamics, and the absence of rigid kinematic chains, making conventional robotics modeling techniques inadequate [9]. These issues are further compounded by the difficulty of integrating soft sensors, actuators, and power supplies into compact, reliable platforms [10].

In light of these challenges, this review provides a comprehensive and engineering-oriented synthesis of the current state of soft robotics. We begin by examining the materials that enable softness and deformability, including elastomers, hydrogels, and composite materials, highlighting how their properties impact robot performance and long-term stability. We then explore the landscape of actuation technologies, from well-established pneumatic systems to emerging classes of electroactive polymers, thermal actuators, and hybrid approaches. Next, we delve into recent advances in control strategies, covering both model-based and data-driven methods, with a focus on overcoming the unique modeling difficulties of soft-bodied systems. Finally, we reflect on the integration challenges that hinder the scalability and real-world deployment of soft robots, and outline key directions for future research.

By organizing the discussion around these three central pillars-materials, actuation, and control-this review aims to provide a unified framework for understanding the multidisciplinary progress in soft robotics, while identifying the critical technical gaps that must be bridged to transition these promising systems from research to engineering practice.

2. Functional Materials for Soft Robotics

2.1. Soft Structural Materials: Elastomers and Stimuli-Responsive Polymers

The foundational mechanical properties of soft robots are largely governed by the choice and design of structural materials, which dictate not only deformability and compliance but also long-term durability and functional integration. Among these, silicone-based elastomers such as polydimethylsiloxane (PDMS) and Ecoflex are widely adopted due to their outstanding elasticity, chemical stability, biocompatibility, and ease of molding or 3D printing. These materials can undergo substantial, reversible deformations without permanent plastic damage, making them ideal candidates for soft robotic components such as grippers, artificial muscles, flexible joints, and wearable assistive devices [11]. Their low modulus allows for intimate interaction with delicate objects or human tissue, which is essential in biomedical applications. However, a significant challenge persists in balancing mechanical robustness and extreme softness. While increased softness enhances flexibility and safety, it often comes at the cost of mechanical strength and fatigue resistance-resulting in issues like creep, material tearing, and reduced operational lifespan under cyclic or dynamic loading conditions [12].

Beyond these passive elastomers, considerable attention has been directed toward stimuli-responsive polymers (SRPs), a class of intelligent materials capable of active deformation when triggered by external stimuli such as temperature, humidity, light, pH, magnetic fields, or electric voltage. Unlike traditional elastomers that require external actuators to drive motion, SRPs enable directly embedded actuation through intrinsic material responses, thus simplifying system complexity and improving energy efficiency. For instance, shape memory polymers (SMPs) can retain a temporary shape and return to a predefined form when heated above a transition temperature. Similarly, thermoresponsive hydrogels can absorb or release water in response to temperature changes, causing volumetric swelling or contraction that mimics muscle-like motion [13].

Other variants, such as photoresponsive liquid crystalline elastomers, bend or twist upon light exposure, allowing for wireless control and spatial selectivity. However, despite their exciting functional potential, SRPs still face significant limitations in engineering contexts. These include slow actuation speed, limited strain range, temperature or humidity sensitivity, and difficulties in long-term cycling stability. Moreover, integrating SRPs with electronic control systems or hybrid materials without compromising performance or structural integrity remains a complex, unsolved problem in the field [13].

2.2. Functional Nanocomposites and Material Design Challenges

To enhance both functionality and durability, nanocomposite-based materials have been increasingly introduced into the design of soft robotic components. These advanced materials synergistically combine flexible polymer matrices-such as silicone elastomers or thermoplastic polyurethanes-with a wide variety of functional nanomaterials, including carbon nanotubes (CNTs), graphene, MXenes, silver nanowires, and liquid metal droplets. The resulting composites exhibit multifunctional properties that go beyond the passive behavior of traditional soft materials. Depending on the composition and fabrication method, they can support electrical conductivity, thermal responsiveness, self-healing capabilities, and strain-sensing functions-while retaining the essential softness and stretchability required for conformal integration with robotic bodies [14].

One of the most promising directions is the development of structural-sensory dual-purpose materials, where nanofillers enable the material to serve simultaneously as a mechanical framework and an embedded sensor. For instance, CNT- or graphene-filled silicone matrices can act as strain or pressure sensors by leveraging the piezoresistive effect, providing proprioceptive feedback in soft limbs or artificial skins. Such systems enable soft robots to perceive their own deformations and external stimuli without relying on discrete sensor elements, leading to thinner, lighter, and more flexible designs. In addition, the use of conductive nanofillers facilitates energy transport and distributed actuation, which is essential for emerging concepts such as soft electronic skins, integrated power delivery, and sensor networks embedded in deformable substrates.

However, the incorporation of these nanomaterials also brings significant engineering and materials science challenges. Maintaining homogeneous dispersion of nanofillers within the polymer matrix is critical to ensuring predictable and repeatable electrical and mechanical properties. Nanomaterials tend to aggregate, especially at higher concentrations, leading to local stiffening, reduced elasticity, and inconsistent sensing responses. Preventing delamination, phase separation, and interfacial weakening under cyclic loading remains a persistent issue, particularly when these materials are subjected to large, repetitive strains as seen in soft actuators and wearables [15].

Furthermore, there exists a tight and often nonlinear coupling between the material's intrinsic properties and the robot's actuation or sensing behavior. Variations in dielectric constant, Young's modulus, or thermal conductivityintroduced by nanofiller loading can directly alter actuation efficiency in dielectric elastomer actuators or thermal actuators. For example, a higher modulus improves structural stiffness but may reduce the achievable strain or increase actuation voltage thresholds. Similarly, enhancing conductivity may improve sensor resolution but at the cost of mechanical softness or stretchability. These design trade-offs must be carefully navigated during composite formulation and system-level integration.

From a practical perspective, several application-limiting factors still restrict the widespread deployment of nanocomposite-based soft materials. These include limited environmental stability-such as sensitivity to humidity, temperature, or UV exposure-long-term mechanical fatigue, and in some cases, biocompatibility concerns associated with free nanoparticles or unencapsulated conductive agents [15]. Additionally, scalable manufacturing techniques that allow for precise control of nanomaterial concentration and alignment during casting, extrusion, or 3D printing are still under development.

Therefore, advancing the field of nanocomposites in soft robotics requires not only molecular-level innovation in material chemistry and filler design, but also a systems-level perspective that considers how material properties interface with mechanical architecture, electrical performance, and control systems. Ultimately, successful implementation depends on co-designing materials, devices, and algorithms together, ensuring that the mechanical and functional advantages of nanocomposites translate into robust, high-performance soft robotic systems for real-world applications.

3. Actuation Technologies

3.1. Conventional and Stimuli-Responsive Actuators

Soft robotics leverages a variety of actuation technologies to produce programmable deformation, motion, and interaction with the environment. Among the most widely used are pneumatic and hydraulic actuators, which operate by controlling pressurized fluids to inflate or deflate internal chambers. These systems can generate large deformations and forces, making them ideal for soft grippers and locomotion units. However, their bulky external components, including pumps and valves, limit their portability and integration into compact, untethered robots.

Another prominent class includes dielectric elastomer actuators (DEAs), which rely on electro-mechanical coupling between soft dielectric films and compliant electrodes. When subjected to high voltage, the film compresses in thickness and expands laterally, generating rapid and reversible deformation [16]. DEAs offer fast response, high energy density, and low weight, but they typically require kilovolt-level inputs and suffer from electrical breakdown issues, particularly when the film thickness is reduced for performance enhancement.

Shape memory alloys (SMAs) and shape memory polymers (SMPs) represent thermally activated actuators that can recover predefined shapes when exposed to heat. While SMAs provide high force outputs, they tend to have slow response times and poor energy efficiency during repeated actuation cycles. SMPs offer greater design flexibility and lower cost, but they also exhibit limited actuation strain and temperature-dependent performance. Both SMA and SMP-based actuators are suitable for compact or bioinspired designs but are currently limited in high-frequency, real-time control applications.

To complement the discussion of unconventional actuation strategies, Figure 1 illustrates representative mechanisms underlying emerging and hybrid soft robotic actuators. The top row depicts magnetically driven actuators, which incorporate magnetic particles or structures within soft matrices and respond to external magnetic fields for contactless locomotion or deformation, and light-driven actuators, which utilize photoresponsive materials to produce bending or shape changes upon illumination. These systems are especially valuable in microscale or biomedical contexts where wireless control and minimal invasiveness are required.

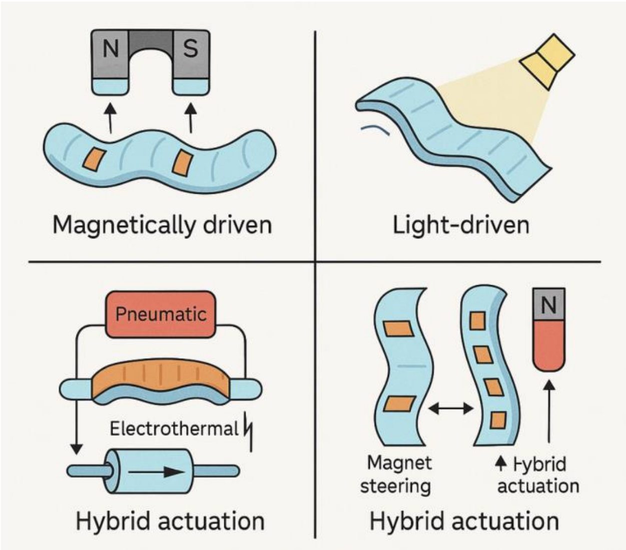

Figure 1. Emerging and hybrid actuation systems illustrating magnetic, light-driven, and hybrid actuator configurations commonly used in soft robotics.

The bottom row highlights hybrid actuation strategies, which integrate multiple physical principles to enhance adaptability and performance. One configuration combines pneumatic chambers with electrothermal elements, enabling actuation through both air pressure and Joule heating. Another shows the coupling of magnetic steering with internal soft actuation modules, allowing for multi-axis motion and task-specific tuning. Such hybrid systems offer increased versatility, but also raise challenges in material compatibility, control coordination, and fabrication complexity. Overall, these approaches reflect a trend toward more multifunctional and environment-adaptive soft robots.

3.2. Emerging and Hybrid Actuation Systems

To navigate the stringent constraints of Formula One (F1) vehicle development-namely, limited timeframes, strict testing regulations, and the dual requirement for aerodynamic and structural efficiency-teams have increasingly turned to digital twin technology as a transformative design tool. A digital twin is a real-time, data-synchronized virtual replica of the physical race car, constructed through high-fidelity modeling and continuously updated with telemetry and sensor data from the actual vehicle. This technology allows engineers to virtually simulate and assess the aerodynamic effects of component modifications or design updates before committing to costly physical builds. As a result, digital twins drastically accelerate the design iteration process, enabling teams to test a wide array of configurations in silico, thereby reducing both developmental risk and resource expenditure.

Recent research has turned to magnetically and optically driven actuators to enable wireless, untethered control in soft robotic systems. Magnetically responsive actuators integrate ferromagnetic or magnetorheological materials into soft matrices, enabling locomotion, reconfiguration, or targeted navigation under external magnetic fields [17]. Such systems are particularly attractive for biomedical and micro-scale applications due to their non-contact control and compatibility with closed environments. Light-responsive actuators, while less common, use photoresponsive materials to produce shape changes or contractions, offering a high level of spatial and temporal control.

In parallel, the development of hybrid actuation strategies-combining multiple driving mechanisms within a single system-has emerged as a promising route to address the limitations of individual actuators. For example, systems that integrate pneumatic actuation with electrothermal control or magnetic steering can adapt to variable task requirements and environmental conditions. These multifunctional platforms allow for redundancy, improved energy efficiency, and enhanced programmability.

Despite their promise, hybrid and emerging actuators face substantial challenges in integration, fabrication complexity, and control architecture design. Many materials exhibit incompatible mechanical or thermal properties, and combining actuators with different response times and power requirements complicates system-level optimization [18]. Moreover, the need for scalable manufacturing techniques and compact embedded control further limits their transition from lab-scale demonstrations to robust, field-deployable robots. Continued innovation in material formulation, modeling frameworks, and integrated circuit design will be crucial to realizing the full potential of multifunctional, environment-adaptive actuation systems [19].

4. Control Strategies for Soft Robotics

4.1. Model-Based and AI-Driven Control Approaches

Controlling soft robots presents unique challenges due to their high degrees of freedom, nonlinearity, and continuous deformation. Unlike rigid-body systems, which can often be modeled with discrete kinematic chains and link-joint dynamics, soft robotic structures require continuum-based modeling approaches such as finite element methods (FEM), piecewise constant curvature models, or Cosserat rod theory to capture their bending, twisting, and elongation behaviors [20]. These models offer physical interpretability and can enable precise motion planning and control when accurate material parameters are available.

However, such physics-based models are often computationally expensive and difficult to calibrate for real-time control. As a result, data-driven methods, particularly those based on deep reinforcement learning, imitation learning, and adaptive control architectures, have become increasingly popular for modeling and controlling soft robots [21]. These techniques can learn complex control policies from interaction data without requiring a full understanding of the underlying dynamics. Recurrent neural networks (RNNs), for instance, have been used to infer system states from temporal sensor data, enabling closed-loop control without explicit physical modeling [22].

Recent work has explored hybrid control frameworks that combine physical modeling and machine learning to leverage the strengths of both paradigms. In such systems, model-based predictions are used to constrain or guide the learning process, improving sample efficiency and stability while maintaining adaptability to uncertain or changing environments [21]. This integration is seen as a promising direction for achieving robust and generalizable control in soft robotics. To better illustrate the interplay between different control elements in soft robotics, Figure 2 presents a conceptual architecture that integrates model-based control, AI-driven strategies, sensor feedback, and human-in-the-loop mechanisms. At the foundation lies the physical system-the soft robot itself-comprising soft actuators and flexible materials whose behaviors are influenced by embedded sensors. Control signals are generated through two complementary modules: model-based control, relying on continuum dynamics and physical simulation (e.g., FEM, Cosserat rod theory), and AI-based control, which leverages data-driven methods such as reinforcement learning and recurrent neural networks. These two streams are merged in a hybrid control integration layer, which fuses physical and learned models to enhance system robustness and adaptability. Real-time feedback is facilitated through embedded sensors, while a human-in-the-loop interface allows for interactive or assistive control, ensuring that the robot can respond intuitively to both environmental changes and user inputs. This framework highlights the multidirectional flow of information and underscores the need for cohesive system-level design in next-generation soft robotic platforms.

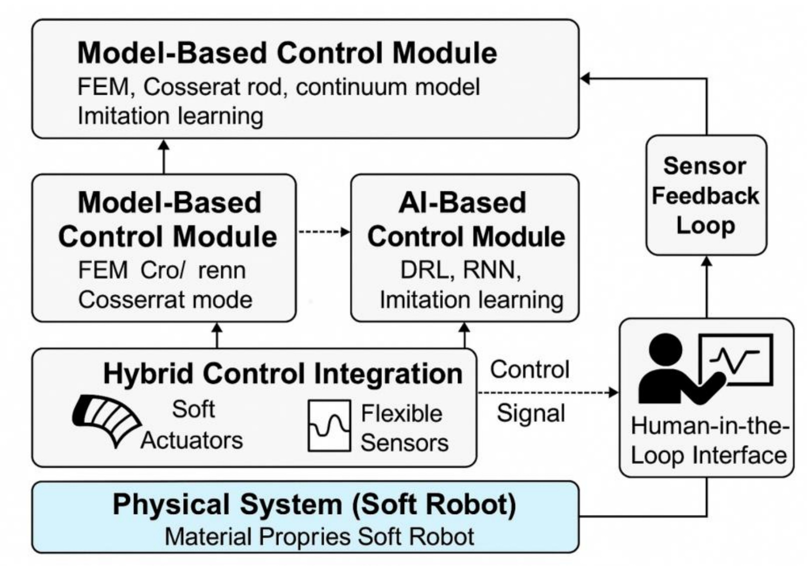

Figure 2. Control architecture for soft robotic systems integrating modeling, AI learning, sensing, and human interaction.

4.2. Sensor Integration, Feedback, and Human Interaction

Sensor integration plays a pivotal role in enabling real-time, closed-loop, and adaptive control of soft robotic systems. Unlike rigid robots, whose states can often be inferred from predefined kinematic models, soft robots exhibit complex, continuous deformations that demand distributed, embedded sensing to accurately monitor their shape, movement, and interaction with the environment. In recent years, there have been significant advancements in flexible, stretchable, and skin-conformal sensors, particularly those based on resistive, capacitive, piezoresistive, piezoelectric, and optical mechanisms [22]. These sensors can be seamlessly integrated into or onto soft robotic bodies, allowing for continuous perception of strain, pressure, shear force, bending, and curvature, even on irregular or time-varying surfaces. Materials such as carbon nanotubes, silver nanowires, graphene composites, and liquid metals have been widely used to fabricate soft sensors with high stretchability, mechanical compliance, and minimal signal drift under deformation.

By embedding these sensors directly into the robot's structure-whether in actuator walls, joint areas, or contact surfaces-researchers have enabled proprioceptive feedback, allowing soft robots to estimate their internal state (e.g., joint angle, elongation, stiffness) in the absence of external measurements. This feedback is crucial for adaptive behavior, as it allows the robot to autonomously respond to external disturbances, terrain changes, object properties, or unforeseen user interactions [23]. Furthermore, coupling embedded sensing with lightweight, low-power embedded microcontrollers or neuromorphic processors facilitates onboard decision-making, moving soft robots toward greater autonomy and real-world deployability.

Such sensor-rich systems form the foundation for closed-loop control architectures, where feedback signals are continuously processed to adjust actuator commands in real time. Unlike open-loop systems, which suffer from drift and lack adaptability, closed-loop designs improve precision, stability, and robustness across variable and dynamic environments. In addition, the emergence of multi-modal sensing-which fuses tactile, positional (e.g., IMU or stretch sensors), thermal, and even visual data-enables richer perception capabilities, supporting more nuanced tasks such as object recognition, force estimation, or intention inference [23]. These sensing modalities, when processed using modern machine learning algorithms or probabilistic filters, can dramatically improve the reliability of soft robots in unstructured settings.

Beyond autonomy, there is increasing interest in human-in-the-loop (HITL) control and teleoperation, especially for assistive, wearable, and rehabilitative applications. Devices such as soft robotic gloves, exosleeves, and haptic interfaces integrate pneumatic or tendon-driven actuation with soft sensors and user-friendly control interfaces, enabling users to initiate, guide, or modulate robotic motion through intuitive inputs like finger flexion, surface EMG, or motion tracking [24]. These systems emphasize bidirectional interaction, where the robot not only assists motion but also provides haptic or visual feedback to the user, enabling co-adaptive behaviors. To ensure effective human-robot collaboration, low-latency data processing, fail-safe mechanisms, and intent-aware algorithms must be designed, particularly when the system is deployed in safety-critical domains such as stroke rehabilitation, prosthetics, or industrial assistance [25].

However, several challenges remain in advancing these capabilities toward widespread adoption. Designing sensor-actuator-controller pipelines that are lightweight, fast, and robust is non-trivial, especially when dealing with noisy signals, material hysteresis, and signal crosstalk. Moreover, calibrating sensor arrays under dynamic loading, ensuring long-term reliability under repeated strain, and establishing universal interfaces for sensor integration continue to be bottlenecks. Finally, building control frameworks that can interpret variable user intent, adapt to changing physiological or cognitive states, and maintain safety across diverse users is an open and active area of research, requiring collaboration between robotics, human factors, neuroscience, and clinical sciences.

5. Current Challenges and Future Directions

Despite significant advances in materials, actuation mechanisms, and control strategies, the field of soft robotics continues to face several critical challenges that hinder its widespread deployment and commercial scalability. One of the most pressing issues is the lack of integrated design frameworks that tightly couple material properties, structural configurations, and control architectures. In many current systems, materials are selected independently of control considerations, or actuators are integrated without full compatibility with sensing or feedback loops. This fragmented design approach leads to inefficiencies, unpredictable behaviors, and limits the performance envelope of soft robotic systems.

Moreover, achieving high-fidelity modeling and precision control remains a fundamental bottleneck. The inherent nonlinearity, hysteresis, and viscoelasticity of soft materials make them difficult to model accurately using conventional rigid-body dynamics. While data-driven models offer a promising alternative, they often require large datasets, lack generalizability, and can be unstable in edge-case scenarios. As such, developing real-time, robust control strategies that can accommodate material uncertainties and environmental variability remains an open research frontier.

From an engineering perspective, the scale-up and commercialization of soft robotics are constrained by practical limitations, including the bulkiness of external power supplies, limited durability of soft materials under prolonged use, and the absence of standardized manufacturing processes. Many high-performance soft robotic prototypes remain confined to laboratory settings due to reliance on external pumps, fragile elastomers, or non-reproducible fabrication techniques.

Looking ahead, several future research directions are poised to address these limitations. First, the development of compact and lightweight energy systems, such as on-board soft batteries, microfluidic power units, or untethered pneumatic modules, is essential for mobile and wearable soft robots. Second, multi-modal sensing and closed-loop feedback control, integrating tactile, proprioceptive, and environmental information, will be critical for enabling adaptive, context-aware behaviors. Finally, the use of bioinspired architectures and multifunctional materials-such as muscle-like fiber composites or self-healing hydrogels-holds promise for creating soft robots that are not only more capable but also more resilient, efficient, and autonomous.

By addressing these multidisciplinary challenges through co-design across material science, robotics, and artificial intelligence, the next generation of soft robotic systems may evolve from experimental devices to deployable tools with real-world impact across medicine, industry, and human augmentation.

6. Conclusion

Soft robotics has evolved into a dynamic and multidisciplinary field, driven by advances in functional materials, innovative actuation mechanisms, and intelligent control strategies. In terms of materials, researchers have developed a wide range of elastomers, stimuli-responsive polymers, and nanocomposites that provide the mechanical compliance, deformability, and multifunctionality required for soft robotic systems. However, challenges remain in balancing flexibility with durability, integrating sensing functions, and ensuring environmental stability.

On the actuation front, progress has been made from traditional pneumatic systems to dielectric elastomers, thermal-responsive polymers, magnetic and optical actuators, and hybrid schemes. Yet, most existing actuators still struggle with trade-offs between force output, speed, efficiency, and system integration. Achieving reliable, untethered actuation in portable or wearable formats remains a key engineering hurdle.

In terms of control, both model-based and data-driven methods have contributed to greater autonomy and adaptability in soft robots. While physics-based modeling enables interpretable control, it often lacks real-time efficiency; data-driven methods offer flexibility but demand extensive training and can lack robustness. Integrating these approaches, alongside flexible sensors and closed-loop feedback, is essential to unlock context-aware, high-performance behavior in real-world environments.

Ultimately, realizing the full potential of soft robotics requires tight integration across materials science, mechanical engineering, electronics, and artificial intelligence. Such cross-disciplinary synergy is vital for transforming lab-scale prototypes into deployable, robust, and intelligent systems capable of addressing challenges in medicine, manufacturing, exploration, and human assistance. Continued collaboration and co-design across these domains will shape the future of soft robotics-from compliant machines to truly adaptive agents.

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