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Polymer-Based Smart Materials for Adaptive and Sustainable Robotic Systems: A Review

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Abstract:

The development and integration of polymer-based smart materials, which have the inherent capacity to recognize and respond to a variety of external stimuli (such as thermal, electrical, and mechanical), are driving the growth and change of the robotics field. This combination is essential for the shift in robotic design towards bio-inspired and flexible designs. This review describes the various smart polymer-based materials used in robotics, along with advances in the field and representative applications. A brief overview of recent developments is provided, with particular attention to 3D printing and the development of hybrid stimuli-responsive composites. The increasing integration of polymer-based smart materials will enable the next generation of robots to achieve unprecedented levels of agility, autonomy, and flexible operation in challenging applications, highlighting their transformative role in robotics evolution.

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1. Introduction

Machine perception and interaction with surrounding environments have greatly benefited from recent advances within the field of smart materials, which are revolutionizing tactile functionalities while delivering unprecedented precision and adaptability.

Addressing the requirements of unstructured environments remains a major challenge in robotics. In recent years, tactile sensing technologies have evolved from rigid structures and single-technology systems toward flexible and bio-inspired architectures based on smart materials[1]. Conductive elastomers [2-4], piezoelectric polymers such as poly(vinylidene fluoride) (PVDF) and P(VDF-TrFE), triboelectric nanogenerators, and optical or fiber-based sensing platforms are enabling stretchable, multifunctional sensors capable of detecting pressure, strain, temperature, and vibration[5]. These technologies increasingly allow multimodal sensing architectures capable of replicating key aspects of biological mechanoreception.

Recent advances also highlight the growing role of artificial intelligence in robotic perception, which has brought machine learning algorithms to process heavy loads of tactile data generated by distributed sensor arrays, enabling real-time interpretation of pressure patterns, slip detection and object recognition[2]. Furthermore, through AI-driven data processing and adaptive control strategies, robotic systems can dynamically adjust grasp forces, which improves manipulation accuracy and enhance interaction with uncertain environments. Smart materials for sensing integration technologies are therefore emerging as a key pathway, which reaches even the robot whole body, using technologies such as electrical impedance tomography [6] or optical waveguides [7], towards the next generation of adaptive robotic systems.

Despite these advances, several challenges remain, particularly regarding scalability, durability under cyclic loading, hysteresis effects, and environmental sensitivity to moisture and temperature variations. Therefore, emerging strategies to address these limitations include biological mimicking of neurological pathways for low power consumption by using event-driven tactile processing [8]. Additionally, self-healing methods with polymers that inherently repair microcracks in an autonomous way do contribute to increased lifespan [9, 10]. Finally, the integration of living cells through synthetic biomaterials enables an organic-like response for biohybrid systems [11].

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The interaction between human and robots must also be a concern, thus some concepts have been developed such as threshold-based frameworks to adjust robot behavior to human comfort levels, regarding interactions by pausing when overstimulated [12]. Further, the use of reinforced learning allows the systems to refine dialogue and gestures based on the user's feedback.

From all the above mentioned concepts, it is expected that the unification of AI with next-generation tactile system may enable a transcendence from the conventional robotic systems known today, reaching real sense of touch in an human-like way, which brings a revolution on healthcare, industry manufacturing, and human-machine cooperation [5, 13, 14].

As robotic systems move towards autonomous and interactive operation, the integration of smart materials provided with intelligent sensing and data processing frameworks becomes progressively more critical. While several recent review articles have focused on specific material classes or fabrication routes—such as printed shape-memory systems [15, 16], bioinspired actuators or molecular design [17, 18], biocompatible or biodegradable soft robotic components [19, 20], most studies focus primarily on individual material classes or fabrication techniques. This work provides a comprehensive perspective connecting polymer-based smart materials with robotic design, sensing architecture, energy efficiency and emerging artificial intelligence-assisted control strategies, which remain yet limited. Therefore, this review addresses this gap by providing a system level analysis of polymer-based smart materials highlighting their role as key enablers of technologies for adaptive, sustainable and intelligent robotic systems.

The seamless integration of actuation, sensing, and structural integrity into a single component, which significantly improves system adaptability, allows for safer human-robot interaction, enables miniaturization, and offers the possibility of self-repair functionality, among other benefits provided by the integration of smart materials.

The reminder of the paper is structured as follows: Section 2 introduces the main classes of smart polymer materials—such as shape memory polymers, electroactive polymers, and magnetorheological/electrorheological materials—emphasizing their mechanisms, properties, and fabrication methods; Section 3 discusses the integration of these advanced materials into robotic systems, highlighting enhanced adaptability, improved sensing and actuation, sustainability, energy-efficient design approaches and emerging artificial intelligence data processing strategies for intelligent robotic interaction; Section 4 presents representative applications across medical robotics, prosthetics, industrial,

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agricultural, and space sectors, demonstrating the technological potential and versatility of polymer-based smart materials; finally, Section 5 summarizes the main findings, outlines the current challenges, and provides insights into future research directions and opportunities in the field of smart materials for robotics.

2. Smart Polymer Materials for Robotic Applications

Haptic feedback is the main method used in robotics applications to restore various characteristics of touch sensation, such as pressure, vibration, and heat, among others [21, 22]. Haptic feedback detection depends on the sensors and actuators used, which are based on different materials, such as shape memory polymers (SMPs) [23], piezoelectric materials [24], electroactive polymers (EAPs) [25], and magnetorheological /electrorheological materials (MR/ER materials) [26], among others. The main material classes, key properties and most typical robotic applications are summarized in Figure 1 and Table 1.

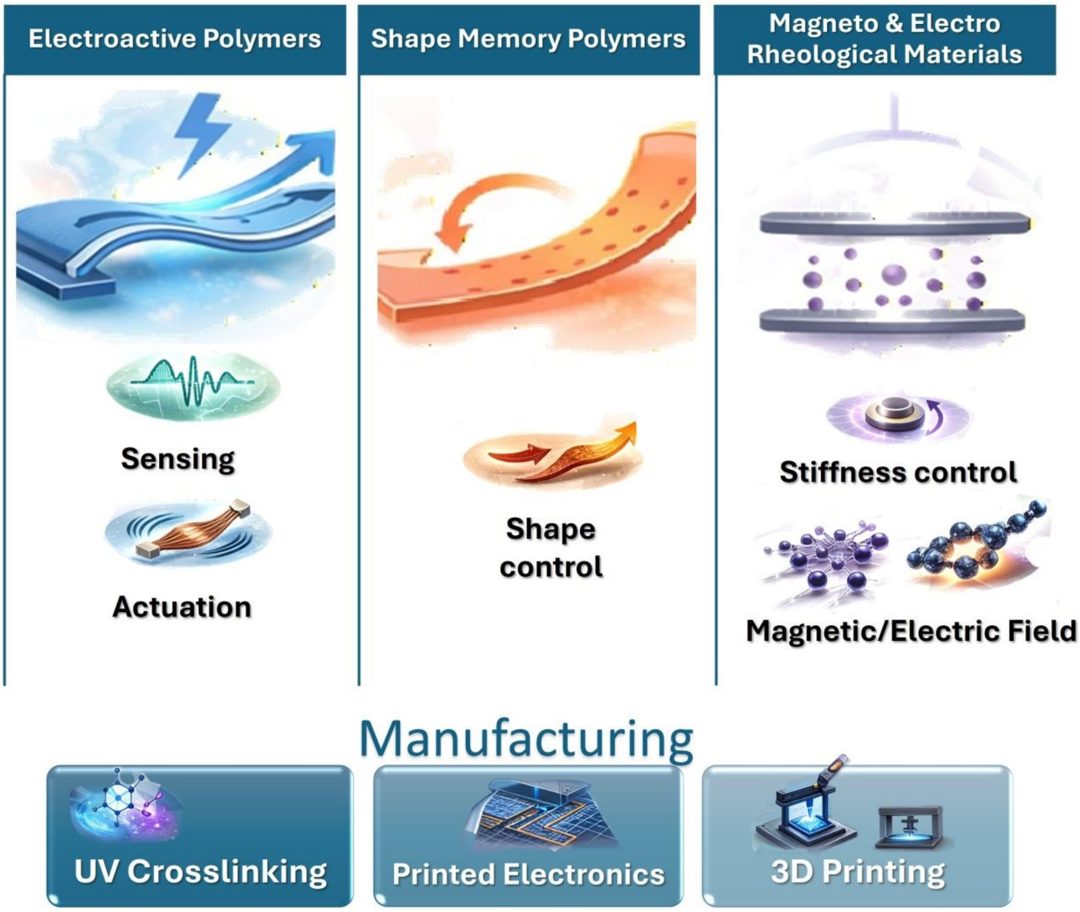

Figure 1 – Most relevant smart polymer materials types and manufacturing techniques applied to robotics applications.

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Besides the different types based on polymers, ceramic [27] and single crystal [28] materials are also widely used in robotics, providing high performance responses but lacking of flexibility and conformability, and more challenging processing, integration and sustainability.

Manufacturing techniques are critical to properly integrate materials into sensing and structural components, having also a relevant influence in overall performance. The primary smart materials used in robotic applications are described in the following.

2.1. Shape Memory Polymers

Shape-memory polymers are materials capable of recovering a predefined shape in response to external stimuli, most commonly temperature, but also magnetic, electric field or pH, among others, and are widely used as actuators in soft robotics[29]. Typical SMPs, including poly(ethylene-co-octene), polyurethane, poly(ε-caprolactone), and styrene butadiene carboxylic rubber enable programmable deformation and have been applied in a wide range of robotic platforms such as soft grippers, locomotion systems and bioinspired devices [30-32].

These materials are differentiated by deformation responsiveness, their high energy density and biocompatibility properties [31]. The main current limitations are a low absolute force and high cycle time [33]. For these materials, the control method [34] is essential to ensure greater precision in terms of positioning and force generation, with feedback from the actuators being important.

Furthermore, thanks to advances in electronics, these materials can be custom-processed using different techniques such as melt processing [35], 3D printing [36], UV-radiation crosslinking [37] in order to increase processing capacity while simultaneously decreasing energy consumption to meet increasingly stringent criteria.

2.2. Electroactive Polymers

Electroactive polymers (EAPs) are smart materials that exhibit mechanical deformation under electrical stimulation or generate electrical signals in response to mechanical or thermal input [38, 39]. These materials undergo changes in particular physicochemical properties when subjected to an electric field and/or develop an electrical signal in response to specific inputs. Based on their actuation mechanism, they are typically

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classified into electronic EAPs, driven by electric fields or Coulomb forces, and ionic EAPs, which rely on ion migration and diffusion processes [40].

Dielectric, electrostatic, electrostrictive, ferroelectric, piezoelectric, and liquid crystal elastomers (LCE) are varieties of electronic EAPs that often require high activation fields (>150 V/μm), which are near the material's breakdown level [40].

Gels, conductive polymers, polymer-metal ionic composites, and carbon nanotubes are examples of ionic EAP materials that need low drive voltages, about 1–5 V [40].

The most widely used material within the electronic EAP class is polyvinylidene fluoride (PVDF), which contributes to various robotic systems due to its piezoelectric and pyroelectric coefficients, flexibility, biocompatibility, and ease of production [41]. Furthermore, conductive polymers with fast actuation speeds and high deformation capabilities, such as polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) (PEDOT), are employed [41].

These materials can be fabricated using various techniques, including 2D and 3D additive manufacturing approaches [42]. In particular, 3D printing has gained significant attention in robotics due to its ability to produce lightweight, complex, multifunctional components with reduced assembly requirements and improved reliability [43], therefore becoming increasingly popular [8].

2.3. Magnetorheological and Electrorheological Materials

When an electric or magnetic field is applied, these materials—which typically are composed of particles in a fluid or dispersed in a polymeric matrix—undergo a rheological change due to the application of the field [44].

These materials can be used in both rigid and flexible grippers, where the gripper's stiffness can be altered within the continuum spectrum between non-rigid and rigid, simply by changing the field intensity [45]. For these applications, geometric optimization, operating principles, and control schemes are important requirements that must be considered [46].

With regard to materials, the rheological behavior of the polymer affects the reaction rates, in which the dispersion and sedimentation of particles are also important [47].

For magnetorheological and electrorheological applications, the materials used are, respectively, manganese-cobalt ferrite ($Mn_xCo_{1-x}Fe_2O_4$), ferrite nanoparticles, iron-based alloys such as FeCo, Ni-Fe, FePt and colloidal SiO_2, zeolites, TiO_2 and clays [48].

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These fillers are dispersed in different polymer matrices such as polydimethylsiloxane (PDMS), natural rubber (NR), silicone rubber (SR), styrene–ethylene–butylene–styrene (SEBS), among others [49].

Chemical composition, size and shape, and stabilizing agents are other significant factors that influence behavior [48]. Its constitutive model is based on the combination of general laws for mass, linear and angular momentum, the second law of thermodynamics, among others [50].

Those materials have been used, for example in teleoperated robotic system dampers, with good torque precision and a quick response time [51].

Table 1 – Smart material types with key attributes.

Material Class	Operating Mechanism	Key Properties	Typical Robotic Application
Shape Memory Polymers (SMPs)	Thermally (or other stimuli) induced shape recovery via phase transition	High deformability, programmability, biocompatibility, high energy density	Soft actuators, deployable structures, biomedical robots, bioinspired systems
Electroactive Polymers (EAPs)	Electrical stimulation (electronic EAPs) or ion migration (ionic EAPs) induces deformation. Mechanical stimulation leads to electrical sensing response	Lightweight, multifunctionality (actuation + sensing). Low strain, large force, fast response (electronic); large strain, low force, slow response (ionic)	Artificial muscles, flexible sensors, wearable robotics, adaptive actuation systems
Magnetorheological / Electrorheological Materials (MR/ER)	Field-induced change in viscosity or stiffness due to particle alignment in a matrix	Tunable stiffness, fast response, reversible behavior, controllable damping	Variable-stiffness grippers, adaptive joints, damping systems, teleoperated robotics

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3. Advanced smart materials in the scope of robotics applications

Smart materials have emerged as fundamental materials for the development of sensors and actuators in the field of soft robotics due to their exceptional flexibility, adaptability and multifunctional sensing capabilities, the advantages of which for this application are illustrated in Figure 2.

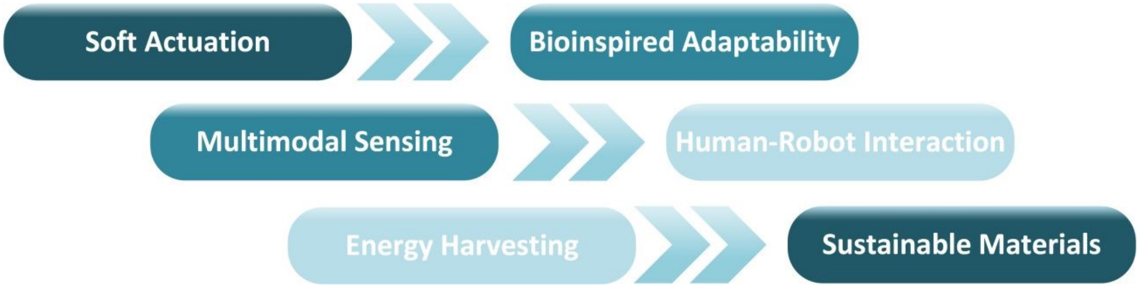

Figure 2 – Advantages of smart materials for robotics applications.

Their sensing and actuating performance stems either from intrinsic material properties or from the possibility of developing blends and composites. These often involve integrating functionalized particles or applying external electric or magnetic fields to tailor specific responses. The inherent softness and mechanical resilience of polymers enable soft robotic systems to undergo large deformations, achieving complex motion patterns and enabling a wide range of applications.

In the past, research and development focused on automation and mechanisms prioritized expanding human capabilities, specifically in executing tasks that were too hazardous or otherwise inaccessible. However, mimicking human skills and dexterous abilities has become the main priority, marking a paradigm shift. The convergence of artificial intelligence, machine learning, and advanced soft sensing and actuation technologies opens the opportunity window to the realization of human-like task-execution machines. Thereby, when considering human force sensitivity and range itself, there are studies stating that a healthy human applies finger forces ranging from 1.4 ± 0.6 N to 34.8 ± 1.6 N during daily activities [52]. Subsequentially, the isometric maximum pull force, in the case of females, while using the index fingertip was measured to reach as much as 59.5 ± 21.4 N and with the four fingers in a straight bar reached 268.7 ± 77.2 N [53]. In the case of males, it has been estimated to be 62 % higher [54], resulting in less than 100 N per index finger and less than 450 N in the case of the four fingers contribution.

Regarding the sensitivity of human finger to force, it has been confirmed that it is remarkably high, reaching thresholds in the millinewtons order, where young adults were

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able to detect as low as 2.4 mN, where some individuals even reached 80 μN [55]. When discussing the optimal friction force for surface exploration, humans use a contact force of about 0.4 N, while it is probed with forces ranging from 0.3 N to 2 N [56]. This range is directly related to the fact that humans can consistently perceive steps of pressing and tangential forces as low as 0.15 N to 0.7 N [57].

Among the most promising applications are delicate manipulation of fragile or irregular objects, a challenge that soft robotics is uniquely positioned to address. The enabling of artificial human skills may be the solution to mitigating the scarcity of workers in critical fields, such as agriculture, construction, medical, among others. Finally, the performance of flexible sensors is typically characterized through parameters such as sensitivity, response and recovery time, hysteresis, durability and signal stability. Flexible soft sensors may struggle with some of those features, especially durability. Further, high sensitivity enables detection of small forces, while low hysteresis ensures measurement reliability during cyclic loading. Dynamic robotic applications in which response and recovery times are particularly important typically require real-time feedback for suitable operation.

3.1. Enhanced Adaptability and Flexibility

Throughout the advent of flexible materials, which resulted in flex-sensing and printed electronics, robotic adaptability and flexibility have been experiencing constant breakthroughs and opening new prospects. These advances are culminating in improved robot interaction within dynamic environments, human collaboration and increased enhancements when handling complex tasks. Some of these advancements include multi-modal sensing and AI integration for sensing pattern interpretation and behavior predictions simulating human senses [14].

Thus, when considering tact as the aiming sense of soft polymers, the respective tactile intelligence may be enabled by the combination of vision-tactile symbiotic advantages. The approach takes advantage of an actuator using red, green and blue light (RGB) on deformable gel while using opposite high resolution cameras for color variation measurement following the concept presented in Figure 3 and explored in [58, 59]. Those advancements have culminated in the development of the gel-based palms known as MIT GelPalm [60]. The obtained measured RGB color codes enable the 3D reconstruction of contact information providing precise manipulation of irregular objects [61, 62]. Although this method brings high level of surface detection detail, it still requires heavy video

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processing with suitable hardware, which may hinder its application for broader applications and may be a technology more suitable for specific tasks, where surface detail measurements are a requirement such as manufacturing control or robotic assembly.

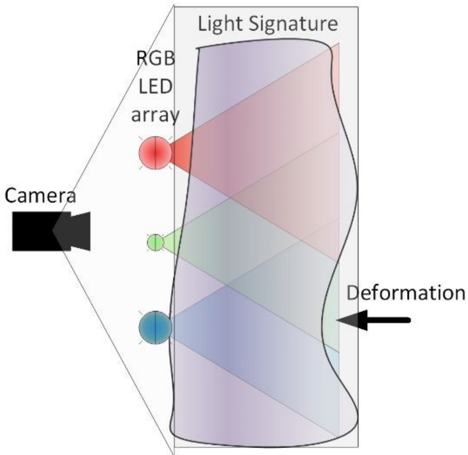

Figure 3 – Concept for obtaining detailed 3D models with a soft touch approach, which may include one or more high resolution camera angles for improved detection of mechanical details and textures.

Alternatively, other materials operate as self-powered sensors such as piezoelectric foams and triboelectric nanogenerators, which also provide real-time force feedback while offer the possibility to be used as energy harvesters [63, 64].

Further, dual mode sensors have been presented with conductive porous structures designed for piezoresistive response, but also featuring capacitive variation by using simultaneously dielectric microstructures (e.g. pyramid arrays), this approach being able to achieve linear ranges between 0 to 600 kPa [65].

Regarding data treatment, the multi-sensing possibilities of multimodal sensors can be performed by neural networks, machine learning and deep learning, which may classify textures and adjust grip force while detecting anomalies in objects, aiming to improve quality control on assembly lines. Artificial Intelligence is set to dramatically improve sensor performance throughout deep data processing, which can extremely enhance the decision-making machine skills [14].

The integration of hybrid piezoresistive-capacitive systems delivers improved adaptability in modern soft robotics, where dual-sensing becomes a symbiotic of touch

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and hovering detection. In [66] the authors achieved a sensor able to detect proximity and measure a wide range of forces effectively, being able to combine both capacitive and piezoresistive mechanisms proving high performance for tasks with human-robot cooperation. They were able to achieve object detection from 0 to 100 mm and to measure contact forces from 0 to 450 N, with a maximum sensitivity of 0.65 mm^{-1} and 17.73 N^{-1}, respectively. The system relied on five layers, including interdigitated copper foil electrodes and a carbon black filled polymer matrix inserted into a construct of PDMS components, as represented in Figure 4.

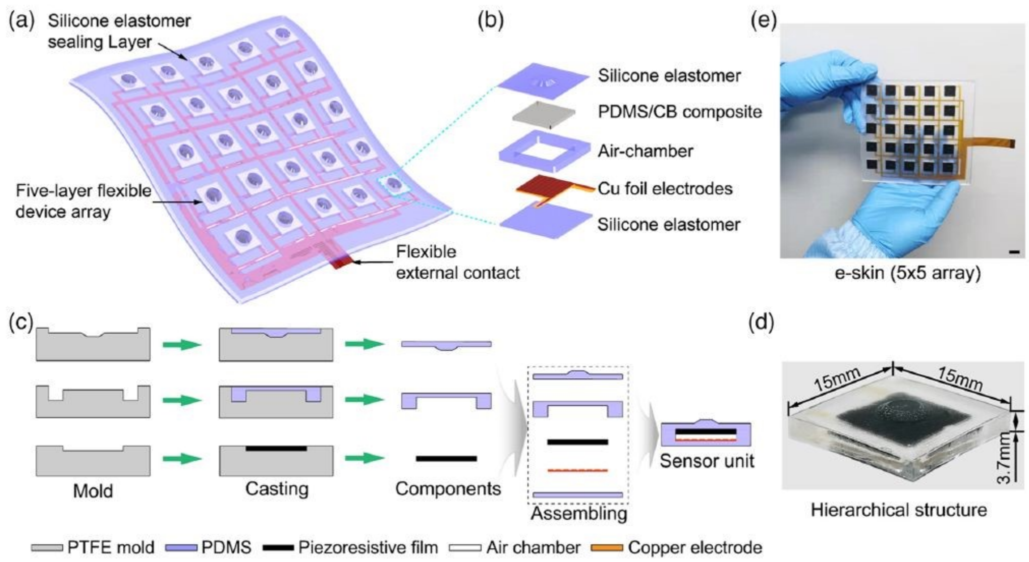

Figure 4 – Hybrid sensor preparation array. A) Schematic illustration of hybrid sensor array; b) view of structure of each single node; c) construction method through molding of PDMS and PDMS/CB composite; d) sensor dimensions and respective aspect; and e) prepared e-skin with complete sensing array [66].

Further, manufacturing processes are typically cost-effective, which promotes wider adoption in robotics, especially in unstructured environments, where flexibility is requires [67].

Some material innovations have been rising throughout the last decade, which include silicone elastomers, including Ecoflex, Polydimethylsiloxane (PDMS), which is widely used for its stretchability (>300% strain) and compatibility with fillers like carbon nanotubes or magnetic particles [68]. Other approaches include smart composites, hydrogels and liquid crystal elastomers (LCEs) [69].

Magnetic-responsive composites such as NdFeB within elastomeric materials have been applied for the development for soft pressure sensors [70] and pressure keys [71]. These

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composite materials enable conformal contact with irregular objects, while providing durable and stretchable designs, displaying constant performance in over 1000 compression cycles with minimal hysteresis (2 % - 6 % at 1 Hz) [70]. Additionally, the fabrication method by deposition enables encapsulation (Figure 5), which ensures stability while retaining elasticity, further enabling applications on wearables, healthcare [70, 72] and robotics [71, 73].

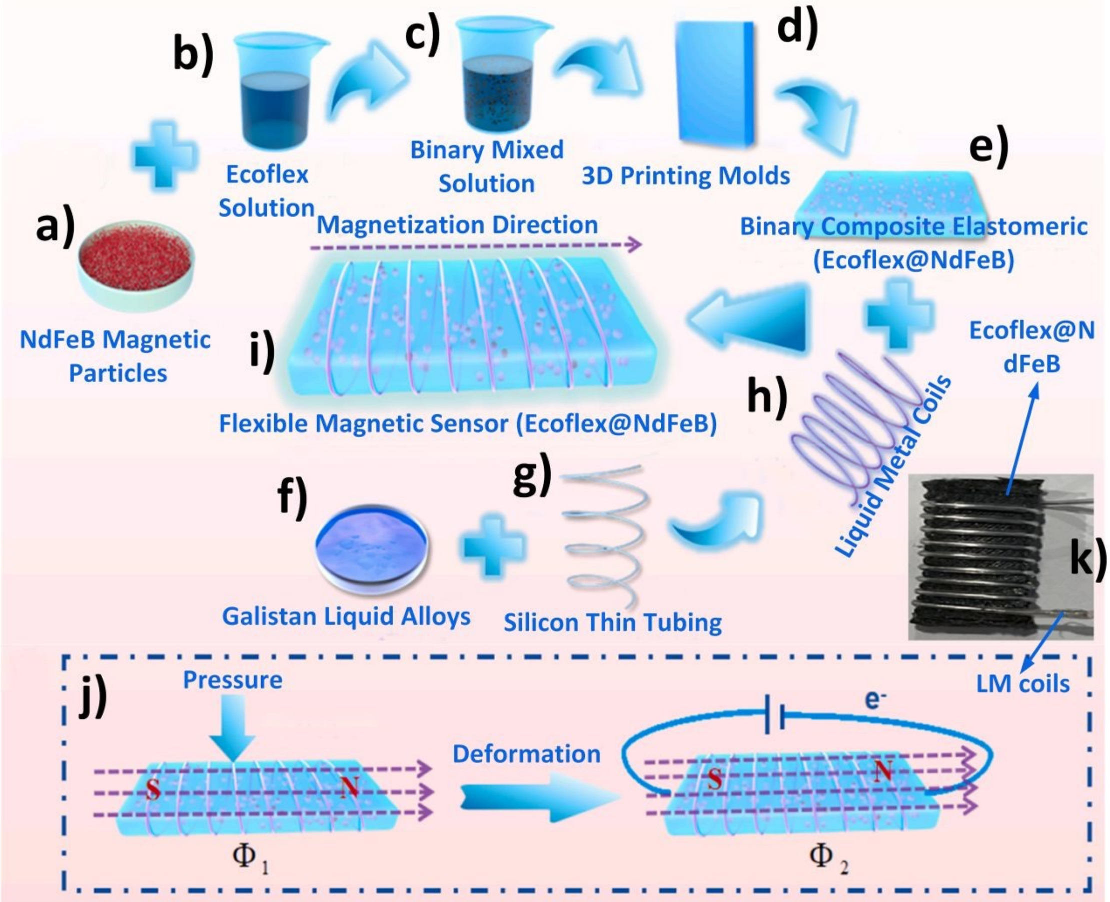

Figure 5 - Illustration of the fabrication steps for the magnetoelectric sensor: (a) NdFeB magnetic particles, (b) Ecoflex solution, (c) combined binary solution, (d) 3D-printed molds, (e) binary composite elastomers (Ecoflex@NdFeB), (f) galinstan liquid metal, (g) thin silicone tubing, (h) formation of liquid metal coils, (i) final flexible magnetic sensor (LM/Ecoflex@NdFeB), (j) operating principle of the flexible magnetoelectric sensor and (k) magnetoelectric flexible sensor physical aspect [73].

Regarding some manufacturing techniques towards sensors fabrication and integration, 3D printing and photolithography allow the design of complex geometries for application with helical microrobots and LCE actuators. Lithography is a very adaptable method to embed magnetic particles into elastomeric materials, which is used to engineer LCEs with programable actuation [74]. Furthermore, the advent of printed electronics and respective

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thermal conformation of printed circuits, enable robotic components to be directly imprinted on irregular surfaces [75].

Regarding flexibility and adaptability, the key challenges from Table 2 are being tackled currently in the state of the art, however, further research and development is yet required to suitably use these solutions towards final applications with longer reliability. It must be taken into consideration that the prospects in robotic flexibility and adaptability are reachable, bearing in mind the combination of material science with artificial intelligence driven control and modular design. These are suitable techniques to develop systems that excel in unstructured environments. These advancements are paving the way for robots to operate with human-like dexterity and resilience. Future breakthroughs will center on closing the loop between sensing, actuation, and embodied intelligence.

Table 2 - Key Challenges and Future Directions

Challenge	Emerging Solutions	Ref.
Durability	Self-healing polymers, fatigue-resistant composites	76-78
Biocompatibility	Biohybrid materials (e.g., cell-laden hydrogels)	79-81
Localization	Magnetic resonance imaging (MRI)/US/CT-compatible markers for *in vivo* tracking	82, 83
Energy Efficiency	Triboelectric / piezoelectric energy harvesting; flexible thermoelectric generators based on polymer composites	84-87
Scalability	Federated learning for distributed multi-robot systems	88, 89

By considering the accomplished evolution on flexible materials and printed electronics, there is a clear transformation being enabled on robotics achieving unprecedented adaptability, tactile intelligence and increased leaning towards integration with artificial intelligence. Thus, innovations with multi-modal sensors, hybrid piezoresistive/capacitive solutions and magnetically active composites, are gradually equipping human-like touch and dexterity in robots. Further, cost-effective manufacturing methods like 3D printing and photolithography are accelerating adoption

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despite the ongoing challenges regarding durability, biocompatibility and scalability. Dynamic and unstructured environments are becoming a decreasing challenge when considering the synergies between advanced materials, sensor fusion and AI-driven control. AI and corresponding methods are increasingly employed to process the large volumes of data generated by multimodal tactile sensors. Machine learning and deep learning algorithms can identify complex patterns in pressure, vibration and texture signals, which enables improved object recognition and adaptive grasp control. Finally, the integration of neural networks with sensor arrays in robotic systems, the learning to adjust grip force in real time can be also achieved, which enables anomaly detection and material classification based on tactile signatures. Thus, this capability enhances sensors' performance beyond what is considered conventional so far regarding signal processing methods. As further research is performed, the gap between robotic and human capabilities gets closer, fostering new possibilities throughout fields such as healthcare, industry and beyond.

3.2. Improved Sensing, Actuation and Adaptability

Soft robotics with integrated actuation and sensing, take advantage of materials like shape memory polymers, dielectric elastomers (DEs) and others relying on magnetic principles, while simultaneously using those integrations for proprioception and interaction with its surroundings. When studying sensors integration, robot body-surface integration must be considered, as well as internal embedment aiming towards closed-loop mechanisms for adaptative control, through multiple mechanical locations. Applications that require extreme adaptability capabilities such as medical, rescue operations and ocean or space exploration, can take huge advantage of this type of systems in robotics [90].

To address these requirements, studies have been conducted to develop new designs and methods to achieve proprioception in a robot using a pneumatic fiber-reinforced actuator functioning as a proprioceptive sensor [91]. This sensor utilizes two parallel conductive microfibers, allowing it to operate both as a bending sensor and a radial expansion limiter, as shown in Figure 6. The authors were able to simultaneously enable sensing and actuation, achieving bending motions up to 240º while providing high sensitivity of 1.2 pF/rad, thereby reducing system complexity [91].

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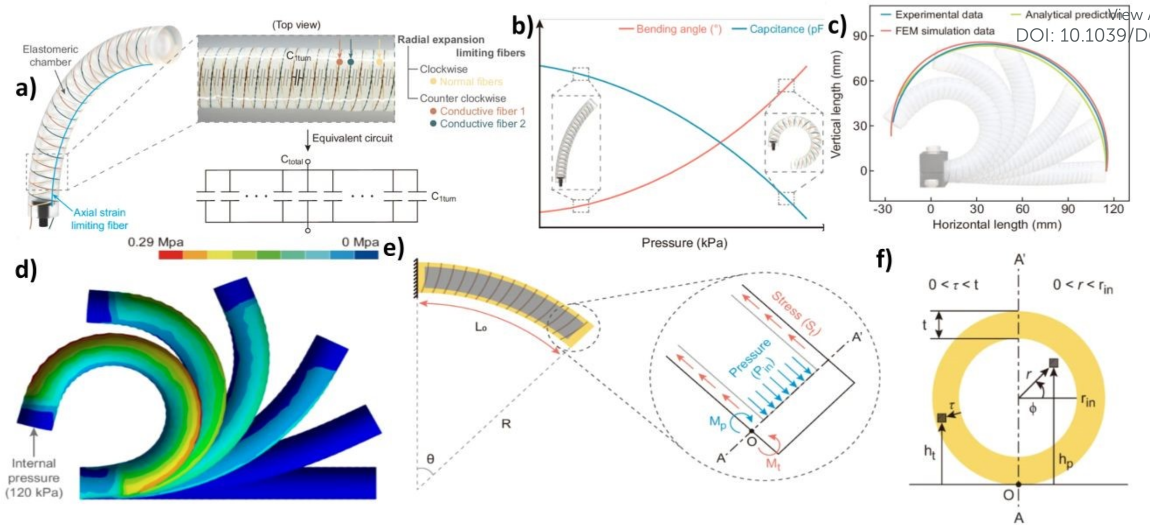

Figure 6 – a) Fiber-reinforced pneumatic soft actuator scheme; b) conceptual graph showing the bending of the soft actuator and correspondent capacitance response; c) distal tip trajectory displaying the bending angle from 0 to 250°; d) superimposed FEM images of the soft actuator at different bending angles; e) body diagram of the soft actuator under bending actuation; f) respective cross section of the actuator including inner surface of its distal tip [91].

Further methods comprehend retrofitted design sensing, aiming for a versatile, non-invasive strategy for soft fluidic robots that does not require embedded sensors or design modification [92]. The authors focus on measuring fluidic input that are required to activate the respective soft actuators while linking it to the respective deformed states of the soft grip fingers during contact with its environment. The objectives of this study were to assess how effective this technique was regarding its feasibility, accuracy and robustness across a variety of actuators for closed-loop control tasks. A robotic system able to discern object size, shape, object stiffness and even surface roughness was achieved, without embedded electronics as can be seen at Figure 7. This strategy can be retrofitted to various existing pneumatic soft actuators and grippers, which can enhance their functionality without complex modifications. It also provides closed-loop control and its inherent robustness to applications in object sorting, fruit picking (tomato) and ripeness detection, results in a simple system that relies on the natural shape changes of objects. However, it presents some hardware disadvantages while not addressing all sensing requirements, especially when considering the requirements of high precision or multimodal sensing, as it was explored in [93]. The retrofitting sensing strategy with liquid-driven actuators relies on air compressibility to balance the actuator and an air tank during interactions, although

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as liquids are not compressible, it requires a flexible air tank to mimic the compression through the elastic deformation. Additionally, resolution variability may happen due to the relationship between actuator deformation and fluidic input, as they may present inconsistencies due to liquids incompressibility, resulting in individual calibration requirements. Further, to access a comparable sensing resolution, the air tank size may be required to be reconfigured as well as other components. The lack of a closed-loop results in the simplicity of these liquid-driven actuators, allowing to avoid additional components such as valves and feedback sensors [94]. In Figure 7c the larger error bars observed at higher approach distances (e.g., h = 30 mm) arise from the increased variability in the contact condition between the actuator and the surface near the contact threshold. In this regime, small variations in actuator deformation or experimental conditions may lead to fluctuations in the measured equilibrium pressure. Furthermore, the nearly constant response observed for small object diameters (Figure 7f, D < 20 mm) reflects the regime in which the gripper does not yet significantly deform around the object. In consequence, the internal geometric volume of the actuator remains largely unchanged, leading to minimal variation in the equilibrium pressure. Therefore, once the object diameter exceeds this threshold, mechanical interaction between the gripper and the object increases, producing a measurable and approximately linear pressure response. Additionally, when compared with embedded electronic sensors, this retrofitted version sensing approach offers a simpler and less invasive strategy, which avoids additional integration complexity and potential reliability issues that are associated. However, embedded sensing architecture usually provides higher spatial resolution and improved multimodal sensing capabilities.

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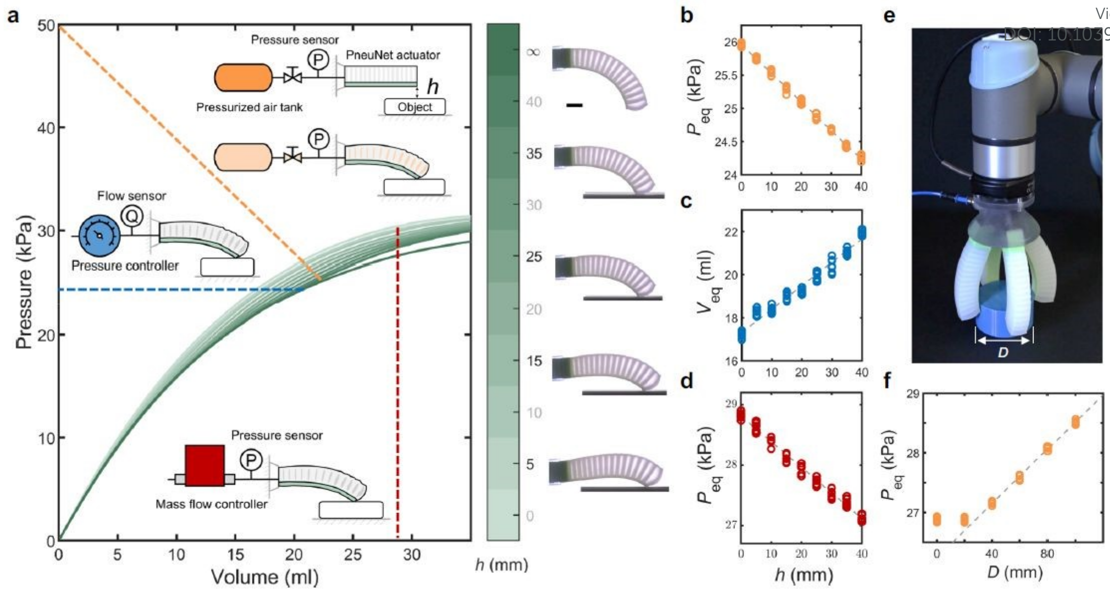

Figure 7 – a) Overview of fluidic sensing methodology e) soft gripper with four PneuNet actuators gripping a cylindrical object with a D diameter.

When considering carbon-based sensors and actuators, materials such as carbon nanotubes, graphene, or graphite among others, are widely used due to their high sensitivity to stimuli and precise actuation at micro and nano scales, finding applications on biomedicine and wearable robotics [95].

Regarding the application on exoskeletons, flexible integrated sensors enhance human-robot interaction by improving safety and comfort, where elastic actuators combined with force-sensing elements deliver control for support operations. Research in the field already reports sensitivities on the order of Gauge factors exceeding 1200 with hysteresis suppression also reaching over 80%, which stem from nanocomposite designs (e.g., MoS_2- direct laser writing (LIG) [96]) and multimodal sensing through piezoresistive-capacitive coupling [97]. Thus, developments to address the critical limitations of wearable and robotic applications, which constantly struggle with cyclic loads and environmental variations, are reaching new prospects.

The reported developments demonstrate the importance of many types of measurement natures within the robotics field, and flexible materials and their respective integrations are required to foster applicability. When considering the recent advancements in robotic sensing and actuation technologies, these are mostly found in alternative methods beyond the traditional rigid ones, to reach healthcare, agriculture, manufacturing and wearable applications, which without flexible sensing and actuation cannot be performed.

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Therefore, soft robotics leveraging on materials such as shape memory polymers and DEs enable proprioceptive feedback and closed-loop control, while retrofitted fluidic sensing and carbon-based sensors, expand robotic capabilities, allowing simpler designs and enhanced human-robot collaboration.

3.3. Sustainability and Energy Efficiency

Recent advancements in soft robotics and flexible sensing/actuation systems have displayed increased prospects bringing together energy efficiency and sustainability.

Regarding sustainable material innovations, biodegradable and recyclable materials comprehending multifunctional composites like LCEs, thermoplastic polyesters and biopolymers for environmental impact attenuation have been proposed. These materials may enable reduced tech waste by following a development approach that focus how they are disposed [98].

Additionally, carbon-based nanomaterials such as graphene and carbon nanotubes, also provide sensing/actuating features while enabling recyclability. Furthermore, to support zero-waste manufacturing, the 3D printing of biodegradable hydrogels is a field currently prompting further research [99, 100]. Thus, solutions are being explored such as the upcycling of plastic waste into nanomaterials, such as graphene and CNTs, which would provide both a solution for resource scarcity and plastic pollution. Recent advances on processes such as flash joule heating and pyrolysis also offer a possibility for improved waste management towards circular economy goals [101, 102].

When considering energy efficient actuation, the state of the art already provides examples of systems that rely on piezoelectric systems such as the eViper robot that uses piezoelectric actuators achieving locomotion with a single watt, taking advantage of the vibrations transducing them into energy efficient motion [103]. There are also similar pneumatic actuators with worm-like locomotion to reduce internal energy consumption by more than 30% through simplified single air path designs [104]. Furthermore, regarding tunable stiffness, magnetic soft actuators and shape-memory polymers (SMPs) provide adaptative responses with reduced energy input, being key in the development of grippers and medical devices [105].

Self-powered sensing relying on piezoelectric and pneumatic systems also delivers sustainability when considering the powering of sensors by photovoltaic cells or piezoelectric materials. Other sources such as thermoelectric sensors can convert

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temperature gradients into electricity in applications such as human bio-wearable sensors or building management systems [106]. Additionally, soft grippers equipped with fluidic sensing can infer object features and shapes through pressure gradients [107], and triboelectric nanogenerators are able to harvest motion mechanical energy [108]. In [87], the authors demonstrate how energy harvesting can be achieved by the integration of titanium-based metal-organic framework (MIL-125) with flexible triboelectric nanogenerators. This integration on robotic soft grip, as in Figure 8, resulted in high electrical output (150 µW/cm^2), robust mechanical flexibility and actual self-powered sensing, demonstrating high feasibility. Considering Table 3, higher power densities are achievable by using other material composites, however, this method offers unique advantages in durability and environmental adaptability. For applications prioritizing mechanical robustness over peak power, such as soft robotics, it presents a competitive alternative to piezoelectric systems.

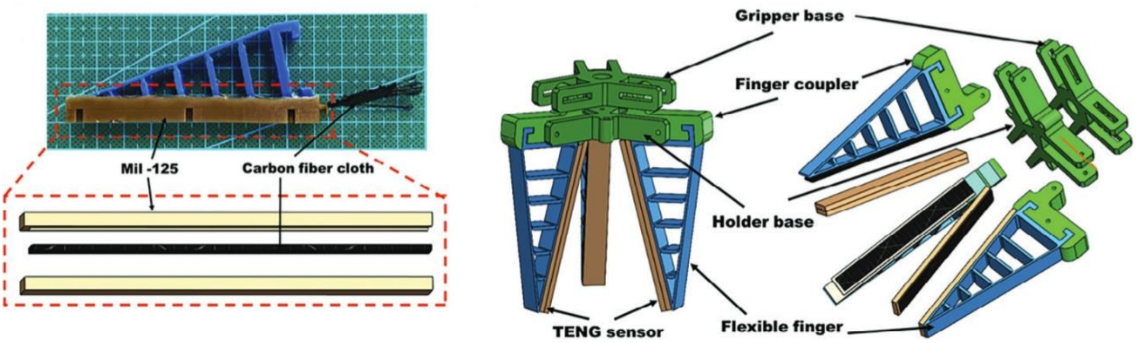

Figure 8 - Flexible gripper with embedded self-powered tactile sensor from MIL-125/Ecoflex triboelectric energy nanogenerator (TENG) [87].

Applications for sustainability such as urban farming and ocean preservation with soft robots with biodegradable grippers enable precise crop harvesting (e.g. lettuce, raspberries) and marine debris removal, supporting sustainable development goals [98].

Other critical applications emerge when considering adaptable sensors powered by renewable energy. For instance, in health monitoring, it would reduce the frequent replacements of batteries while providing continuous, real-time data. Additionally, the integration of these sensors into soft robots for search-and-rescue operations can significantly reduce risks on human workers, while enabling autonomous exploration and hazard detection in dangerous environments [109].

When considering the integration strategies, monolithic integration and modular designs reduce assembly complexity, thus these approaches are recommended, for easy assembly, replacement and customization of sensor and actuator units in larger systems [110]. Finally,

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by merging sustainable materials, energy-harvesting technologies, and bio-inspired designs, soft robotics is poised to revolutionize industries while aligning with global climate and sustainability goals.

Table 3 - Power densities of recent energy harvesters capable of being integrated into robotic applications

Energy Harvester Technology	Device Area	Reported Power Value	Normalized Power Density ($\mu W/cm^2$)	Ref.
Flexible GaN:Mg nanowire (PENG)	~0.5 cm^2	13 mW/cm^2	13000	111
Flexible 1D Nanorod Piezoelectric	9 cm2	400 $\mu W/9\ cm^2$	44.4	34
Hydrogel-based stretchable (TENG)	24 cm^2	444.44 mW/m^2	~44.4	113
Ferroelectric metal–ligand cage (1–PDMS composite) (PENG)	1.3x2 cm^2	14.85 $\mu W/cm^2$	14.85	114
Flexible Metal-Ligand Cage/PDMS Piezoelectric	1.3x2 cm^2	14.6 $\mu W/cm^2$	14.6	115
MXene-reinforced hydrogel (TENG)	10 cm^2	54.24 mW/m^2	~5.4	116
Highly Flexible Organic (PENG)	0.0625 cm^2	2.48 $\mu W/cm^2$	2.48	117
Freestanding single-crystal PZT membrane (PENG)	Volume provided (estimated with 250 nm thickness)	63.5 mW/cm^3	~1.59	112
PVDF-BaTio3 Nanofiber (PENG)	4 cm^2	4.07 mW/m^2	0.407	119

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Soft robotics and flexible sensing/actuation systems recent advancements are paving the way for more energy-efficient and sustainable technologies. Environmental impact can be mitigated through the application of biodegradable and recyclable materials such as LCEs, thermoplastic polyester and carbon-based nanomaterials, driving towards circular economy goals. Simultaneously, energy-efficient and self-powered sensors, such as piezoelectric, pneumatic and triboelectric systems, reduce power consumption while leaning into autonomous operation. These achievements may have deep impact where sustainability and adaptability are relevant, such as in applications including urban farming, ocean preservation and health monitoring. While challenges still lie in scalability and integration, sustainability/energy-efficiency is a required synergy that positions soft robotics as a transformative force aligned with the technological, energy and sustainability goals of our time.

3.4. Smart Materials, Artificial Intelligence and Advanced Manufacturing

Smart polymer materials, artificial intelligence and advanced manufacturing technologies are converging together, driving large expectations for the next generation of adaptive robotic systems. Additive manufacturing and printed electronics that enable complex flexible sensor architectures fabrication are becoming key in a field where machine learning algorithms allow robots to interpret multimodal sensor data and adapt their behavior in real time. Considering this growing synergy, it further enables intelligent robotic systems to be self-adaptable, while featuring predictive maintenance and improved interaction with dynamic environments and humans.

4. Representative Applications

Smart materials are used in areas such as medical robotics and prosthetics, as well as in industrial and space applications.

4.1. Medical Robotics and Prosthetics

The advances provided by polymeric sensors and actuators in the soft robotics field are revolutionizing medical grips and prosthetics by offering several advantages over the conventional rigid ones. Their ability to adapt to complex surfaces and provide safety to delicate tissues avoiding physical damage has become key features for their success.

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Thus, those advances are enabling robot surgery to undergo a rapid evolution, finding a variety of applications in both in-vivo and in-vitro medical operations [88].

Multifunctional tactile sensors can pave the path into more autonomous systems, where the ones based on nanowire materials, carbon nanotubes and ionic gels provide both sensitivity and durability [120]. These materials enable electrical responses from mechanical deformations, usually employed as printed electrical tracks, building many of the circuit blocks. Further, they enable the application of multiple layers with multi-type electrical responses. Thus, sensors with dual-mode design, can operate independently, attenuating interference between pressure and temperature measurements, improving accuracy on data gathering [121]. In literature, it is possible to find research using a combination of conductive silver paste as electrode, TPU particles doped with ionic liquid for pressure sensing and carbon nanotube NP ink doped with single layer graphene for temperature sensing. The performances achieved has been impressive, reaching in this particular work a sensitivity of 804.27 kPa^{-1} with response times as low as 17 ms over 5000 cycles, which ensures reliability [120]. These systems are already reaching ~94% material recognition accuracy when combined with neural networks for adaptative control [122].

Other materials such as piezoelectric polymers like Polyvinylidene Fluoride (PVDF) are one of the most responsive polymers that provide response on impacts and temperature gradients, offering flexibility and biocompatibility in prosthetics [41].

Fluidic sensors that enable object properties evaluation using the pressure gradients in soft grippers, as has been already mentioned, are also key features to consider on prosthetics [69]. Further, including TENGs to harvest the mechanical energy from motion, reducing external power requirements contribute for improved efficiency on powering locally these types of contact sensors [41].

A good example of research efforts is the development of low-cost flexible textile-based force sensors, having as objective to retrofit existing prosthetics to enhance their features. They were able to demonstrate that can reliably detect object contact and slippage during grasping tasks, where the results suggest this solution can indeed be implemented into prosthetic hands to provide tactile feedback and improve grip control to t amputees [123]. However, there is still the need to detect multiple spatiotemporal tactile stimuli, which consists of static and dynamic forces/frictions/vibrations that enable the identification of shape, hardness and texture of a gripped object. Thereby, further efforts tackling this issue have been performed in slip detection mechanisms such as in [124], where a finger-skin-inspired model has been developed such as in Figure 9a), reaching detection of 8 N

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normal forces and 4 N shear forces with 160 mV/N sensitivity and response time of 10 ms. It was possible to detect slip events with low speeds such as 5 mm/s, demonstrating effective real-time feedback, and due to the thin nature of this sensor of ~1 mm, it enables conformal integration on robotic fingers. Although, it still presents a limited force range and is still difficult to handle the signal accuracy and repeatability resulting from any small deformation, light source drift or fiber misplacement, it is still a very useful approach to work upon.

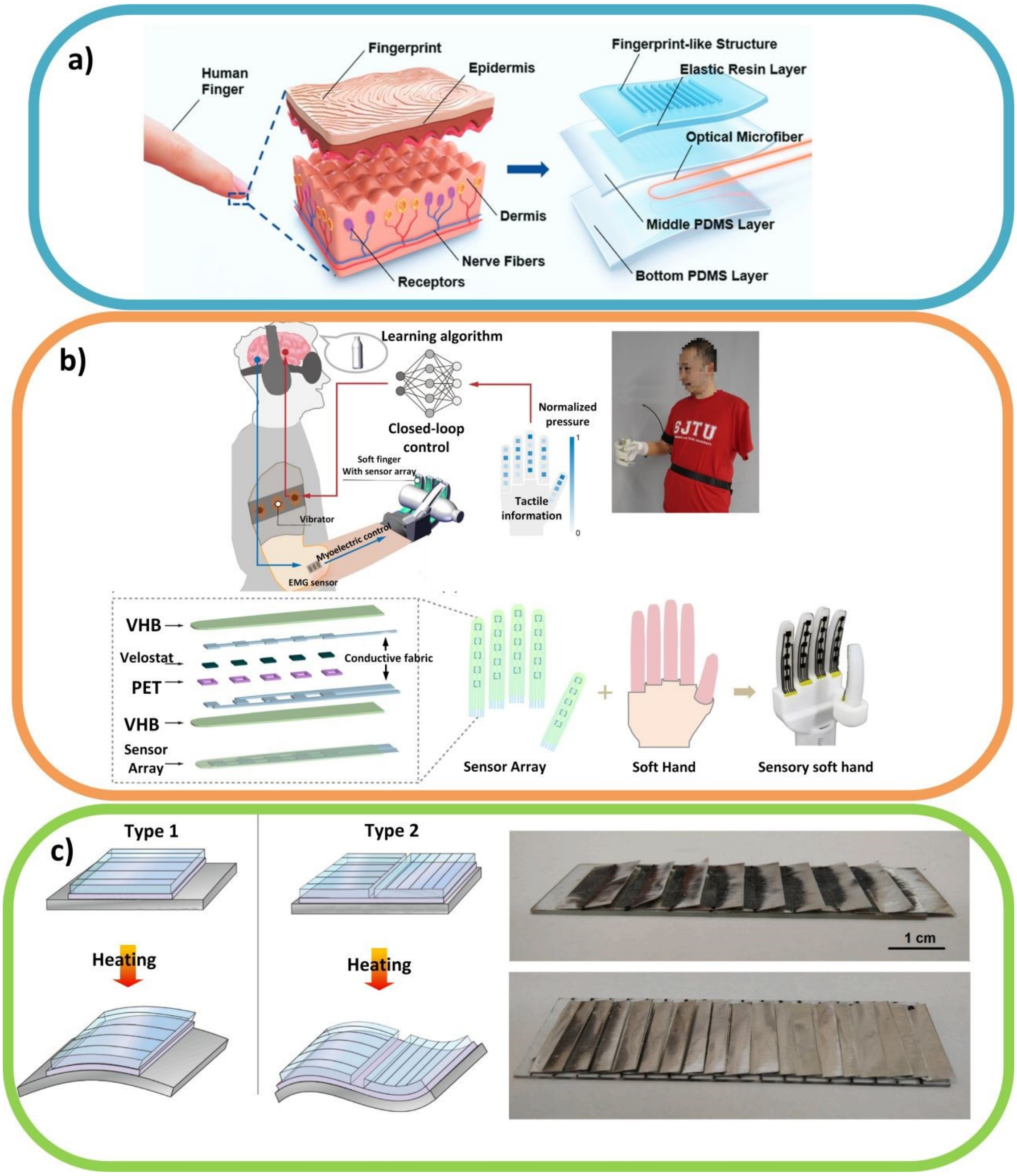

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Figure 9 – a) Finger skin-inspired optical sensor composed by multiple of PDMS, resin and optical microfiber [124], b) Exploded view of flexible piezoresistive sensor array construction used on prosthetic hand for learning algorithm development on object discrimination [125] and c) schematics of the two-layers actuator design principles and Ratchet surfaces in the form of alternating metal plates with 7 and 3.5 mm [126].

Furthermore, when pursuing force analysis on prosthetics, sensing feedback has been designed on three axes by using molded silicone injected with Galinstan liquid metal, assembled with the respective wiring. This system achieved a sensitive of 1.557 mV/N (x-axis), 0.944 mV/N (y-axis), and 1.412 mV/N (z-axis), with a drift of 14.5 to 26.5 µV, which assures stability and suitability for slippage detection during grasping tasks [127]. Galinstan liquid metal method has also been explored in [128], in which a force measurement resolution of 0.29 N^{-1} was achieved, although limited to a range between 0.2-10 N, but also temperature measurements within 20 to 80 ºC with resistance variations between 0.21 % to 0.55 % per ºC stating good linearity, repeatability and durability in the cyclic tests of both physical parameters. Regarding the application of conventional designs as represented in Figure 9b), an untethered soft prosthetic hand was developed based on a piezoresistive sensor array, enabling pressure magnitude and distribution detection, using a simple approach with Velostat, conductive fabric electrodes and laminated PET/VHB layers, and were able to achieve a fast response of 12 ms and high classification accuracy (~97%) for finger/object recognition through machine learning. Furthermore, the user gets vibrotactile feedback through the band, providing an integrated sensing, learning and feedback system [125].

When considering actuators on these type of robotic applications, LCEs and DEs can mimic natural muscle offering strains up to 300% and forces in the range of 34 MN/m^2 with direct integration on prosthetic hands for improved natural grip motions [41]. Furthermore, SMPs enable programmable actuation, working like muscle-memory storing previous configurations for delicate object grasping [69].

Regarding bending angle improvements, tendon-driven origami pumps in soft grippers enable up to 240º without external compressors being key for minimal invasive surgeries [129]. There are also fluidic fabric muscle sheets, which achieve strains over 100% while exerting forces 115 times their weight, being suitable for prosthetic limbs or wearable compressions garments [130].

Some bi-layer polymer actuators are capable of locomotion when activated by thermal stimulation, which can mimic soft motion by combining two polymer layers with

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different thermal expansion coefficients (Figure 9c). The bonding of two polymer layers films, which upon heating the differential expansion results on the actuator to bend or curl results in motion. This approach revealed controllable, repeatable locomotion through a distance of up to 10 cm, upon thermal activation [126].

The integration of machine learning with flexible sensing and actuating solutions, by trial-and-error the electrical feedback can be interpreted in an improved way, which brings all the features required for material recognition on prosthetics, while on surgery, internet-of-things (IoT) achieves real-time monitoring of the robotic grip forces [41].

Thus, when considering the applications of merging advanced polymers, intelligent systems with medical robotics and prosthetics, these research fields are on the verge of achieving: hand natural functions restoration; remote surgery for higher clean-room efficacy; and even wearable robotics for therapeutic compression or assistive forces through garments conforming to body contours among others (Table 4) [131].

Table 4 – Summary of integration examples of different technologies

Combined Technologies	Integrated Application Example	Refs
Origami Pumps + LCEs/DEs + SMPs + Bi-layer Actuators	Smart prosthetic limbs with adaptive, programmable grip	132, 133
	Soft surgical manipulators for minimally invasive procedures	132, 133
Fluidic Muscle Sheets + LCEs/DEs + SMPs	Wearable exosuits for rehabilitation and assistance	134, 135
LCEs/DEs + Origami Pumps + Fluidic Muscle Sheets	Adaptive grippers for delicate industrial or healthcare tasks	134, 136
Bi-layer Actuators + SMPs + Fluidic Muscle Sheets	Bio-inspired crawling/exploring soft robots	134, 137

Soft multifunctional materials enable delicate interactions with tissues providing reliable feedback and efficient energy harvesting, which are essential features for the next generation of surgical tools and prosthetic devices. The integration of intelligent systems such as machine learning and IoT, further advances the self-government and functionality of these solutions, increasing the feasibility for more natural hand movements, remote surgical capabilities and wearable therapeutic devices. Therefore, restoration of natural

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functions through innovations like these will lead to an improvement of the quality of life.

4.2. Industrial, Agricultural and Space Applications

Polymer based sensors and actuators are driving innovations in robotics across industrial, agricultural, and space applications by combining flexibility, durability, and energy efficiency.

In industry, high performance actuators such as piezoelectric polymers (PVDF-TrFe), enable micro-robotic deflections with precision up to 250 µm at low voltage levels (3.3 – 4 V), finding application on automated assembly lines that requires delicate tasks such as micro-component placements [138].

Ionic polymer-metal composites enable flexible grippers with carbon nanotubes enhanced electrodes, which provide an adaptable force control, reducing manufacturing damage when handling irregular objects [139].

Commercial solutions such as VICTREX™ PEEK/PAEK polymers offer a durable solution aiming to replace metal gearboxes and bushings, promising to offer 10 times more durability of polyamide and twice the lifespan of steel in high-wear environments to apply in collaborative robots with lightweight and corrosion resistance joints.

When considering some examples, which could be used for industrial applications, some grippers follow a conformable design based on polymers such as TPU, which can be 3D printed with conventional systems. There are however, some interesting solutions for force measurement such as in [140], in which a conformable grip (Figure 10 a and b) has been developed which employs a rope entangled through the grippers and connected to angle measurement units, using algebra to calculate the respective force. This method does not use TPU as sensing element but demonstrates that its mechanical properties and processability allows to take suitable roles in these applications.

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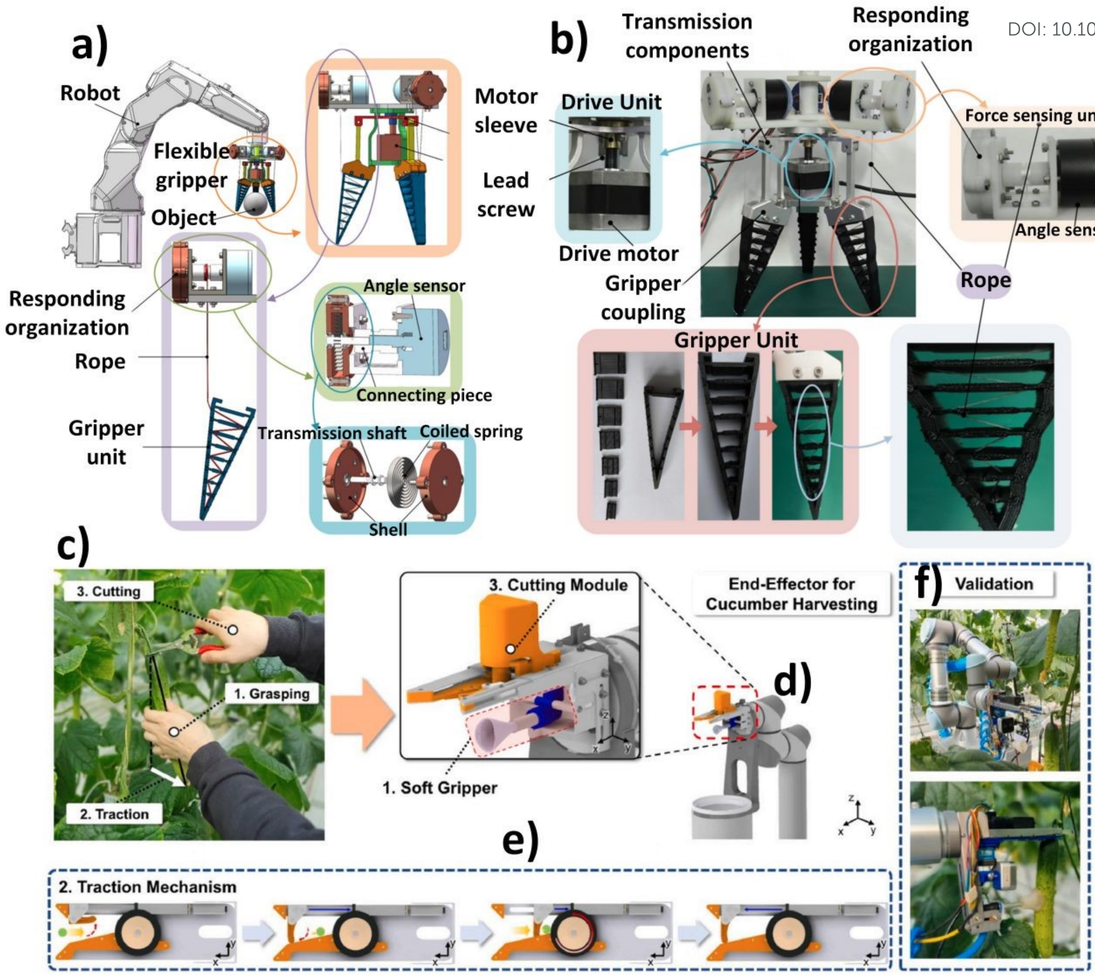

Figure 10 – a) Schematic structure of grip and measurement system and prototype developed with a b) conformable 3D printed TPU grip [140]; c) Robotic system inspired by the human harvesting process which mimicked with a d) harvesting robotic arm that grasps and cuts with the aid of e) mechanical traction mechanism system, and f) a validation on commercial cucumbers in real farm conditions under controlled harvesting an size criteria [141].

In agricultural robotics, fluidic fabric muscle sheets enable soft gripping, which enable actuators to exert forces of 115 times their weight, as previously mentioned, that suits the harvest of delicate crops without bruising [130].

Further, DEs actuators and their ability to reach over 100% strain, allow to achieve variable shapes and sizes, through adaptable fruit sorting while leveraging on low-energy electrostatic forces [69].

Additionally, carbon nanotubes sensors also play a role in the monitoring of soil moisture and crop health in real-time, which bring a total new depth when integrated into robotic arms, enabling precision irrigation or pesticide delivery [139].

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Concerning the harvesting itself, promising solutions are appearing that aim to mimic human behavior when grabbing and cutting by precisely analyzing each phase of the method regarding grasping, traction and cutting the vegetable or fruit. This was achieved with a single robotic arm equipped with a suction soft contact mechanism and an integrated cutting module as shown in Figure 10 c-f) [141].

In the space application area, new materials that are in need are related to lightweight, thermal and radiation-resistance. Thus, the high-performance polymer PEEK™ comes into consideration due to the wide temperature resistance (-70 ºC to +260 ºC). These materials are already being used on planetary rovers within joint actuators and sampling tools [142, 143].

However, furthermore materials such as shape memory polymers bring further possibilities by enabling deployments of structures such as solar panels that provide memory within their intrinsic configurations after being exposed to heat, which reduces the payload volume during launch [144].

Furthermore, PDMS embedded with NdFeB particles, work as a magnetic actuator that generates precise movements in microgravity, suitable for manipulation of regolith samples and antenna alignment adjustments through deflections up to 9.16 µm under 0.98 mT fields [139]. Regarding the supra-cited application fields, every one of them requires further energy efficiency and biodegradable/recyclable materials Thus, using polymers such as piezoelectric actuators enable reduced power consumption by 70% compared to static systems for antenna or solar array deployment and vibration damping mounts for instruments and optics [145, 146].

Finally, regarding recyclability, carbon nanotubes are excellent development alternatives for sustainability purposes, which aligns with eco-friendly initiatives for mass production sensors for both agriculture and industry [69, 139].

Thus, polymeric sensors and actuators are at the vanguard of robotics innovation, enabling considerable advancements across industrial, agricultural, and space sectors.

They provide a unique combination of flexibility, durability, and energy efficiency, which is driving the replacement of traditional materials and mechanisms. In industry, precision, adaptability and longevity in robotic components are being enhanced by polymers such as PVDF-TrFe and PEEK/PAEK, while soft and conformable designs are improving safety and adaptability.

In agriculture, polymer-based actuators and sensors mimic human hands motion, which enables soft crop harvesting, real-time monitoring, and precision tasks.

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For space applications, high-performance polymers like PEEK™ and shape memory materials are already achieving the demands for lightweight, radiation-resistant, and thermally stable components, while also supporting compact and energy-efficient system designs.

Additionally, the integration of recyclable and biodegradable materials, such as carbon nanotubes, underscores a growing commitment to sustainability being present in all of the three application branches (Table 5). Collectively, these advances are not only boosting the performance and functionality of robotics but are also paving the way for more sustainable and intelligent solutions towards many fields, which can benefit from those advancements.

Table 5 – Summary of materials integrated in industrial, agriculture and space robotic applications

Technology	Industry	Agriculture	Space	Ref
Piezoelectric polymers (PVDF-TrFE)	Micro-robotic actuators for precise component placement; reduced power consumption for vibration damping mounts	—	Energy-efficient vibration damping mounts; actuator systems for antenna/solar array deployment	147-150
VICTREX™ PEEK/PAEK polymers	Durable, lightweight, corrosion-resistant joints; metal gearbox/bushing replacement in collaborative robots	—	Lightweight, radiation- and temperature-resistant actuators and joints for planetary rovers	143, 151
TPU (3D-printed conformable grips)	Conformable, soft, 3D-printed grips; force measurement systems	—	—	152, 153
Fluidic fabric muscle sheets	—	Soft robotic grippers for delicate crop harvesting (forces up to 115× their weight)	—	130, 154
DEs	—	Adaptive fruit sorting; actuators	—	155-157

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Technology	Industry	Agriculture	Space	Ref
		handling variable shapes and sizes		
CNTs-based sensors	Flexible grippers with adaptable force control for handling irregular objects	Real-time soil moisture and crop health monitoring; precision irrigation/pesticide delivery	Eco-friendly, recyclable sensors for sustainable systems	158-160
Shape memory polymers	—	—	Deployable structures (e.g., solar panels) with memory for compact launch and autonomous deployment	161, 162
PDMS embedded with NdFeB particles	—	—	Magnetic actuators for precise movement/manipulation in microgravity (e.g., regolith sampling, antenna align)	163, 164
Ionic polymer-metal composites	Precision end-effectors in electronics assembly (sub-mm accuracy)	Electroactive grippers for weed removal (low-voltage, 5–10% strain)	Low-power actuators for Mars rover mobility (radiation-tolerant)	165, 166

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4. Conclusion, challenges and future directions

Polymer-based smart materials for sensor and actuator applications are paving the way for the next generation of robotic systems, replacing conventional rigid technologies with adaptable, multifunctional, and responsive solutions. Their intrinsic flexibility, stretchability, and tunable properties are enabling soft and intelligent robots capable of performing complex interactions in dynamic and unstructured environments.

However, despite the significant progress achieved, several challenges persist regarding performance, durability, integration, scalability, cost-effectiveness, and modeling accuracy. Furthermore, the production and assembly of flexible sensors and actuators still present challenges on scalability and integration as well as energy autonomy. Some solutions may rely on the use of printing technologies such as inkjet-, screen- and roll-to-roll printing, which represent as key methods for the mass-production of flexible sensors and actuators, which, when allied with compatible materials that can be processed at low temperatures, results in lower-energy consumption and lower emissions.

Currently, the performance of many polymer-based smart devices remains at the proof-of-concept level. Nevertheless, continued advances in materials design and processing, hybrid composites, and multi-layer integration are expected to deliver signal stability, thermal resilience, high SNR, and sensitivity required for real-world deployment.

Adaptable and multifunctional sensors will drive the next phase of evolution, overcoming the constraints of traditional rigid systems. Flexibility, adaptability, and, in some cases, transparency have become the focus of research and development to overcome installation limitations and enable further capabilities in robotics systems.

In extreme applications, such as space exploration, the convergence of flexible electronics, smart polymers, and soft robotics will be crucial for designing systems that operate reliably under harsh conditions.

Looking forward, research will increasingly emphasize the creation of high-performance hybrid systems, where the combination of different smart material classes enables synergistic improvements in actuation strength, sensitivity, and energy efficiency. The emergence of self-healing materials capable of autonomously repairing structural damage, as well as functional materials that can execute basic logic operations, represents another frontier in intelligent material design.

To meet the growing need for environmentally sustainable and biocompatible robotic technologies, future material development must adopt sustainable-by-design and safe-by-design principles, ensuring both high performance and minimal ecological footprint.

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Furthermore, the integration of AI-enhanced design and control will play a central role, leveraging machine learning and generative algorithms to optimize material architecture, predict performance, and enable real-time adaptive control of flexible robotic systems. Overall, the synergy between polymer-based smart materials, artificial intelligence, and advanced manufacturing will define the next generation of highly efficient, autonomous, and interactive robotic systems—capable of transforming applications across healthcare, industry, and space exploration through unprecedented levels of adaptability, sustainability, and intelligence.

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Data Availability Statement

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The data that support the findings of this study are available from the corresponding author upon reasonable request.