Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

A review of smart actuation technologies in modern mechatronic systems

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HIGHLIGHTS

- This review covers smart actuator advancements in mechatronic systems from 2019 to 2025.
- Actuators are grouped by stimulus type and material class, such as SMAs, hydrogels, and nanomaterials.
- Applications include soft robotics, biomedical tools, and smart manufacturing systems.
- Smart materials enable accurate motion and force control in modern mechatronic systems.
- Actuator fabrication and control system integration methods are analyzed in detail.

Keywords:

Smart actuators
Mechatronics
Soft robotics
Actuator control
Smart materials
Shape memory alloys

ABSTRACT

Smart actuation has transformed mechatronics over the past six years by harnessing materials that turn heat, electricity, magnetism, or light into finely tuned motion. Our survey of developments from 2019 to 2025 reveals clear trade-offs: electro-active polymers can stretch beyond 200% but operate at roughly 30% efficiency, whereas piezoelectric devices achieve over 95% efficiency with displacements under 0.1%. Ionic polymer–metal composites and magnetorheological actuators strike the best balance for precision work, delivering about 50% stroke at 60% efficiency. Real-world examples show that packing tiny shape-memory alloy bundles into soft exosuits grants sub-millimeter accuracy without sacrificing comfort, and that materials capable of reversing energy flow and monitoring their state greatly improve closed-loop control and fault detection. We examine control methods—from model-predictive to adaptive schemes alongside scalable fabrication routes spanning 3D (Three-Dimensional) printing to microfabrication, and identify lingering challenges in manufacturing scale-up and high-frequency response. Looking forward, embedding computation within actuator materials, adding artificial intelligence-driven adaptability, combining multiple stimuli in hybrid designs, and harvesting energy internally promise to usher in truly autonomous, life like mechatronic systems. This review outlines recommendations to advance energy-efficient, sustainable actuator designs. It highlights the importance of multidisciplinary collaboration among materials engineers, system designers, and control experts to accelerate real-world deployment.

1. Introduction

Mechatronic systems represent the synergistic integration of mechanical engineering, electronic engineering, computer science, and control engineering to design and develop smart, multifunctional systems. Within this interdisciplinary field, smart actuation technologies have emerged as critical enablers of advanced functionalities, allowing systems to interact with and adapt to their environments in increasingly sophisticated ways. The evolution of these technologies has been particularly noteworthy in the past decade, with significant advancements in materials science, nanofabrication, and control systems engineering [1-3].

This study conducts a comparative analytical review of recent advancements in smart actuation technologies from 2019 to 2025, systematically comparing actuator classes based on stimulus-response mechanisms, material composition, and performance metrics.

Smart actuators are gadgets composed of sensitive and synthetic substances that provide actuation and damping abilities in response to outside stimuli and with light, heat, power, magnetism, humidity, or chemical reactions [2-4]. Smart actuators stand out from conventional ones by their inherent capability to feel environmental changes and respond without external manipulation systems, making them appropriate for compact and adaptive packages [2]. Unlike conventional inflexible actuators, which frequently fall short in rising fields like tender robotics and wearable technology, clever actuators mimic muscle-like biological movement, supplying greater flexibility and capability [3, 5, 6]. Recent developments have focused on enhancing clever materials such as nanomaterials, practical polymers, and composites that show off particular stimulus-responsive behaviors [2-4]. Beyond

http://doi.org/10.30684/etj.2025.158859.1933
Received 05 April 2025; Received in revised form 23 May 2025; Accepted 24 May 2025; Available online 17 June 2025
2412-0758/University of Technology-Iraq, Baghdad, Iraq

movement, those actuators serve extra roles, including sensing, electricity harvesting, or even computation, making them precious in space- and electricity-constrained environments [7-9]. The review emphasizes improvements between 2019 and 2025 throughout five key types—piezoelectric, form memory alloy (SMA), magnetorheological (MR), electroactive polymer (EAP), and pneumatic smooth actuators—utilized in present-day mechatronic systems for precision, adaptability, and efficiency [1-3]. However, their inherent hysteresis and constrained displacement are significant limitations. Research has focused on enhancing their performance using nonlinear management techniques and advanced composite structures [10-12]. Multilayered piezoelectric composites have confirmed more advantageous displacement competencies, contributing to their extended use in high-precision systems [12]. Shape-reminiscence alloys have emerged as an attractive choice due to their high pressure-to-weight ratio and potential to mimic biological movements [13-16]. While their thermal response time and fatigue characteristics remain challenges, new alloy formulations and control strategies have improved performance in dynamic environments. Magnetorheological actuators utilize the controllable properties of MR fluids, enabling real-time adjustment of stiffness and damping [17, 18]. Electroactive polymer actuators, particularly ionic polymer-metal composites (IPMCs), exhibit muscle-like deformation under electrical stimulation [4, 19]. Due to their low weight and compliance, they are gaining traction in soft robotics. However, challenges like low force output and hydration dependence limit their widespread deployment. Innovations have improved actuation bandwidth and longevity [19]. Pneumatic soft actuators have revolutionized human-robot interaction, offering safe and flexible operation through compliant materials [20-22]. Machine learning approaches have enhanced their control precision, and embedded sensors have enabled real-time feedback systems [23, 24]. These actuators are used in rehabilitation robotics, soft grippers, and adaptive prosthetics. Comparative analysis reveals that each actuator type offers distinct benefits and limitations. Piezoelectric actuators excel in precision, SMAs in force generation [10], MR (Magnetorheological) actuators in adaptive damping [17], EAPs in biomimetic motion [4], and pneumatic actuators in safe interaction [20, 22]. The choice of actuator depends heavily on the application's performance criteria, environment, and power constraints. Looking ahead, hybrid actuation technologies that combine the advantages of different mechanisms are gaining attention [25]. Integration with AI, embedded sensors, and real-time data analytics will drive the evolution of intelligent actuation systems for next-generation mechatronic applications. Continued research into material science, modeling, and control strategies will be critical to realizing their full potential [2, 3, 25].

The motivation behind this study stems from the rapid evolution of modern mechatronic systems toward greater intelligence, adaptability, and functional integration. These advancements demand actuation solutions that surpass conventional actuators capabilities, which often struggle with limitations in flexibility, energy efficiency, and compatibility with compact intelligent systems. Smart actuators have emerged as promising alternatives based on responsive materials due to their ability to react autonomously to environmental stimuli such as temperature, electric fields, light, and magnetic forces. Their potential for seamless integration, muscle-like motion, and multifunctionality makes them ideal for cutting-edge applications in wearable technology, soft robotics, and biomedical devices. However, despite notable progress, persistent challenges in scalability, stability, energy efficiency, and control integration remain unresolved. This motivation underlines the necessity for a structured and up-to-date review that synthesizes the latest advancements and identifies future research directions.

This study aims to provide a comprehensive analytical review of recent advancements in smart actuation technologies from 2019 to 2025. It classifies actuators according to their stimulus-response mechanisms, smart material types, structural configurations, and fabrication techniques. The review further explores current control challenges, real-world applications in mechatronic systems, and future research opportunities. Ultimately, the objective is to outline the scientific and technological trends that will drive the development of next-generation multifunctional smart actuators, enhancing intelligent mechatronic systems' efficiency, adaptability, and autonomy.

2. Fundamentals of smart actuation

Actuation represents a paradigm shift from conventional actuation approaches by integrating the material's sensing, processing, and actuation capabilities. This section explores the fundamental principles that govern smart actuation technologies and establishes the theoretical foundation for subsequent discussions on specific actuator types and applications. The central functionality of clever actuators stems from their capacity to transform various varieties of electricity into mechanical artwork in response to environmental stimuli [2, 3].

Many smart substances showcase direct and inverse results, allowing them to function as sensors and actuators. For example, piezoelectric materials generate electrical indicators when routinely deformed (sensing) and conversely deform when subjected to electric fields (actuation) [10, 11]. This dual functionality enables self-contained mechatronic structures with reduced complexity and enhanced responsiveness.

Mathematical models describing the conduct of clever actuators usually incorporate constitutive relationships that link input stimuli to output mechanical responses. These relationships often showcase nonlinearities, hysteresis, and price-established behaviors that complicate the perfect management of such actuators [2, 10]. From a system perspective, clever actuators can be conceptualized as integrated additives that bridge the gap between the virtual manipulation domain and the physical mechanical area. This interpretation occurs at the cloth stage via numerous microscopic mechanisms, including section transformations, molecular realignments, or electrochemical reactions [2-4]. The development trajectory of clever actuation technology has been substantially prompted using biomimetic tactics. Natural biological structures, especially muscular tissues, showcase exceptional actuation abilities characterized by excessive performance, adaptability, and self-recovery homes [5, 6]. Many modern-day smart actuators draw inspiration from biological muscles, aiming to replicate their functionality whilst overcoming their obstacles in terms of durability and operational conditions [8, 16]. Energy efficiency represents every other important aspect of smart actuation. Traditional electromagnetic actuators often suffer from giant energy losses due to heat era, friction, and mechanical compliance troubles. Smart actuators, particularly those based on solid-kinematics standards, can improve power conversion efficiencies by eliminating unnecessary strength transformation steps and lowering mechanical complexity [2, 9].

Smart actuators marry precise mechanical motion with intelligent control through features like energy conversion, bidirectional operation, embedded sensing, and bioinspired design Figure 1, boosting their performance and adaptability. Their evolution now emphasizes seamless integration with digital systems as much as core functionality, laying the groundwork for next-generation robotics and automation. Links bidirectional energy conversion to actuator multifunctionality, showing how smart materials can sense and actuate. Highlights self-monitoring capabilities that improve closed-loop control and fault detection.

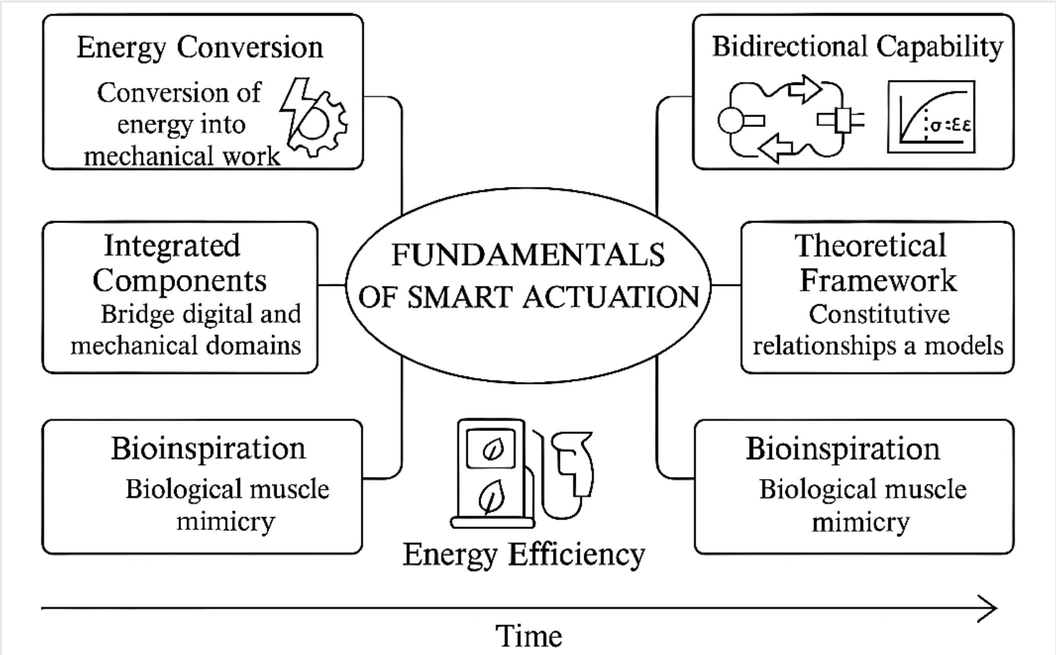

Figure 1: Fundamentals of smart actuation in mechatronic systems

3. Classification of smart actuators

Actuators may be classified in a way consistent with various standards, including their activation mechanism, cloth composition, structural configuration, and application area. This systematic categorization enables knowledge of the various landscapes of smart actuation technology and the choice of appropriate actuators for particular mechatronic programs.

3.1 Classification based on activation mechanism

The most essential class of smart actuators is based on the stimulus that triggers their actuation reaction. This categorization highlights the severe tactics wherein environmental alerts may be harnessed to generate mechanical paintings.

Light-responsive actuators use photochemical or photothermal effects to transform mild energy into mechanical movement. These actuators commonly include photochromic molecules or mild-soaking up nanomaterials that undergo structural adjustments even when exposed to particular light wavelengths. The ability to precisely manage actuation through faraway mild signals makes these actuators mainly treasured for wireless applications. The advent of near-infrared (NIR) responsive materials has similarly increased their utility by allowing deeper penetration into biomedical packages [3].

Thermally-activated actuators, which include shape memory alloys SMAs and thermo-responsive polymers, respond to temperature changes through dimensional or property adjustments. SMAs transition among martensite and austenite levels [2, 13, 14], at the same time as polymers like PNIPAM go through extensive changes at critical temperatures [2, 26]. Electrically-driven actuators utilize mechanisms like piezoelectricity and electroactive polymer responses to produce mechanical displacement with excessive precision and velocity, more suitable by using innovations in conductive polymers and ionic polymer-steel composites [2, 4, 10, 12, 19]. Magnetically-responsive actuators use ferromagnetic debris or magnetorheological fluids to react to magnetic fields, developing mechanical movement [17, 18]. Chemically or humidity-responsive actuators, inclusive of hydrogels, adjust their shape based on environmental pH, ion concentration, or moisture levels, making them best for sensing and drug transport, notwithstanding slower reaction times [2].

3.2 Classification based on material type

Smart actuators can additionally be classified as regular with the essential substances that allow their stimulus-responsive behavior:

Shape memory materials, including SMAs and SMPs, are relevant to many actuator structures. SMAs recover pre-described shapes upon heating [2, 15, 16], while SMPs provide comparable results with large strain skills [26, 27]. Piezoelectric materials produce pressure beneath an electrically powered subject due to their crystal asymmetry. Traditional ceramics like PZT (Lead

Zirconate Titanate) dominate this magnificence, even as bendy polymers now offer alternatives for wearable and easy robotics [10-12]. Magnetorheological (MR) and electrorheological (ER) materials exchange viscosity in response to magnetic or electric fields, permitting variable stiffness actuators [17, 18]. Electroactive polymers (EAPs) may be subdivided into electronic and ionic kinds, and they have applications in soft robotics and synthetic muscle tissues [2, 4, 19].

Hydrogels and responsive polymers display extensive quantitative changes with temperature, pH, or light. Nanocomposite hydrogels integrate substances like GO or CNTs to decorate each reaction time and mechanical sturdiness. Electroactive polymers deliver large strains but low efficiency, while piezoelectric actuators offer high efficiency with minimal displacement. Ionic Polymer–Metal Composites and magnetorheological actuators strike the best balance of stroke and energy use for precision tasks [2, 3].

3.3 Classification based on structural configuration

The macroscopic shape impacts actuator behavior and suitability for precise packages: Fiber/linear actuators mimic muscle tissues and are used in robot hands or smooth wearables [2]. Film/membrane actuators allow in-plane/out-of-plane bending with fast response, which is useful in optical and microfluidic systems [3].

Bulk/3D actuators use internal stresses or volume changes for complex deformations; 3D printing has advanced this area significantly [28]. Multi-material/composite actuators combine materials like SMPs and piezoelectric to achieve multi-modal responses or amplify output [25, 29].

Smart actuators can be categorized according to various criteria, enabling researchers and engineers to select the appropriate actuator based on application requirements. Smart actuators are commonly classified into three main categories: based on activation mechanism, material type, and structural configuration. These classifications cover various actuation principles, including light, thermal, electrical, and magnetic activation; materials such as SMA (Shape Memory Alloy) and electroactive polymers; and structural designs ranging from linear fibers to 3D composite actuators. Understanding these categories provides foundational insight for developing tailored solutions in advanced mechatronic and robotic systems. It contrasts piezoelectric's low hysteresis and fast response with SMA's thermal-driven hysteresis. It also explains that the control design must match the piezo mechanism and advanced compensation for SMA.

To enhance the technical depth of the review, Table 1 presents a quantitative comparison of key smart actuator types based on performance metrics such as displacement range, force output, response time, durability, and energy efficiency. This comparison helps identify the strengths and trade-offs of each actuator class in modern mechatronic applications [1–3], [5, 7], [9–12], [14–16], [20–21], [30].

Table 1: Performance metrics of selected smart actuators

Actuator Type	Displacement	Force/Stress Output	Response Time	Energy Efficiency	Linearity	Durability	Control Complexity
Piezoelectric Actuators	μm–mm scale	High (tensile/compressive)	Microseconds–ms	High	High	High (brittle)	Moderate–High
Electroactive Polymers (EAPs)	Up to several mm	Low–moderate	Milliseconds–seconds	Moderate	Nonlinear	Moderate	High
Shape Memory Alloys (SMAs)	Up to 8% strain	High	Seconds	Low	Nonlinear	Moderate (fatigue)	High
Magnetostrictive Actuators	Micron–mm scale	High	Microseconds	High	High	High	Moderate
Hydraulic Actuators	Up to meters	Very high	Milliseconds–seconds	Low–Moderate	Moderate	High, needs maintenance	Low–Moderate
Pneumatic Actuators	Centimeters–meters	Moderate	Milliseconds–seconds	Low–Moderate	Moderate	Moderate	Low
Dielectric Elastomer Actuators (DEAs)	Up to 100% strain	Moderate	Milliseconds	High	Nonlinear	Moderate (dielectric failure)	Moderate

Note: Values are approximations based on recent literature (2019–2025) and vary by design and application.

4. Smart materials for actuation

The properties of smart actuators' constituent materials fundamentally determine their performance characteristics. Recent years have witnessed remarkable advancements in developing novel smart materials that exhibit enhanced responsiveness, durability, and functionality. Figure 2 shows the classification of smart materials used for actuation in mechatronic systems. Classifies materials by strain vs. force: EAPs (>200% strain, low stress) vs. PZT (>10 MPa force, <0.1% strain).

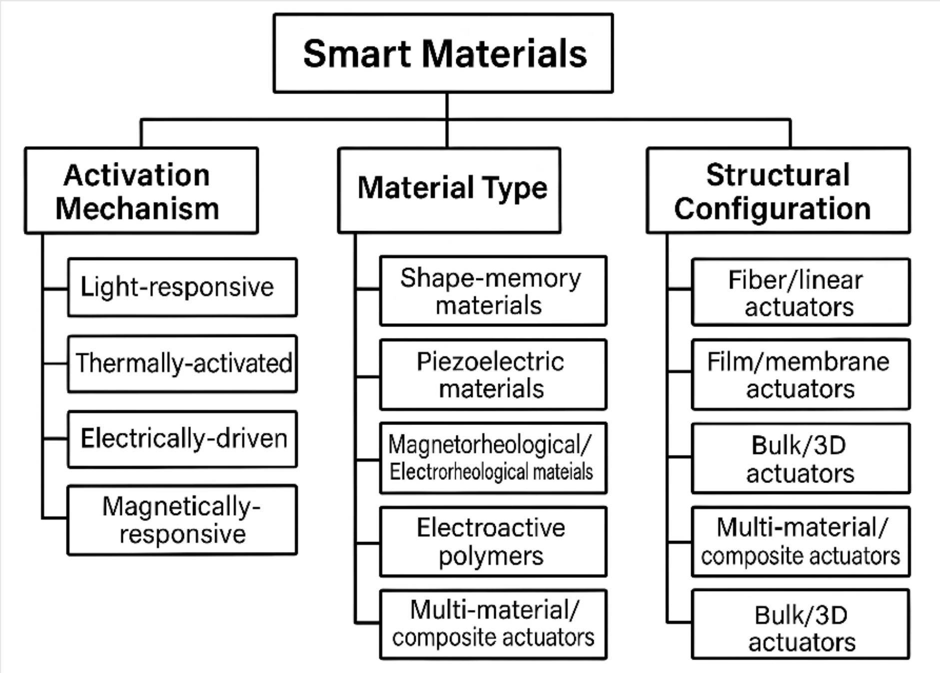

Figure 2: Classification of smart materials used for actuation in mechatronic systems

4.1 Shape memory alloys and polymers

SMAs (Shape Memory Alloys and Polymers) like NiTi exhibit reversible phase transformations that recover pre-programmed shapes on heating [2], [13-15]. Innovations such as additive manufacturing have improved fatigue life and actuation speed. SMPs (Shape Memory Polymer) offer large recoverable strains (> 400%) and easier processing. Integration of CNTs or graphene enables multi-stimulus responsiveness (light, heat, electricity) [2, 3, 26].

4.2 Piezoelectric and electrostrictive materials

Piezoelectric materials like PZT (Lead Zirconate Titanate) provide high precision but are brittle [10, 11]. Newer lead-free options like KNN (Potassium Sodium Niobate) or BNT (Bismuth Sodium Titanate) improve safety and flexibility. Electrostrictive materials (e.g., Lead Magnesium Niobate–Lead Titanate PMN-PT) offer significant quadratic strain responses, suitable for high-precision actuation in positioning systems [2, 10].

4.3 Magnetoactive and magnetorheological materials

Terfenol-D shows magnetostriction but limited strain. Magnetic shape memory alloys (e.g., Ni-Mn-Ga) offer large deformation with faster actuation [2, 17]. MR materials change stiffness under magnetic fields and are used in dampers and adaptive structures [17, 18].

4.4 Smart polymers and hydrogels

PNIPAM hydrogels show thermal volume change; GO (Graphene Oxide) integration enhances mechanical strength and responsiveness [2, 3]. Light-responsive polymers with azobenzene enable reversible bending via isomerization. Plasmonic particles offer photothermal actuation via NIR (Near Infrared) light [3, 30]. EAPs (Electro-Active Polymer), including DEAs and IPMCs, operate through electrical or ionic responses, with DEAs offering > 100% strain but requiring high voltage, while IPMCs are low-voltage but slower [4, 19]. Multi-responsive polymers (e.g., dual pH and temperature) provide control flexibility for biomedical or environmental uses [3].

4.5 Emerging smart materials

LCEs (Liquid Crystal Elastomers) enable programmable, reversible deformation and mimic natural movement patterns [2]. 2D materials offer high surface area and multifunctionality for rapid, energy-efficient actuation [3, 31]. Bioinspired materials (e.g., cellulose and muscle proteins) provide sustainable, high-performance actuation alternatives [8, 32].

5. Stimulus-response mechanisms

The effectiveness of smart actuators is rooted in their ability to transform environmental stimuli into mechanical work through various physical and chemical mechanisms operating across molecular to structural scales. These stimulus-response mechanisms directly influence key performance factors such as speed, force output, energy efficiency, and durability. The main types of stimuli—light, thermal, electrical, magnetic, and multi-stimulus—each activate unique actuation pathways. Figure 3 illustrates this classification.

Maps light–thermal dual-stimulus materials, noting control complexity when photothermal and thermal pathways interact. Recommends selecting materials with decoupled stimulus channels to avoid unintended actuation.

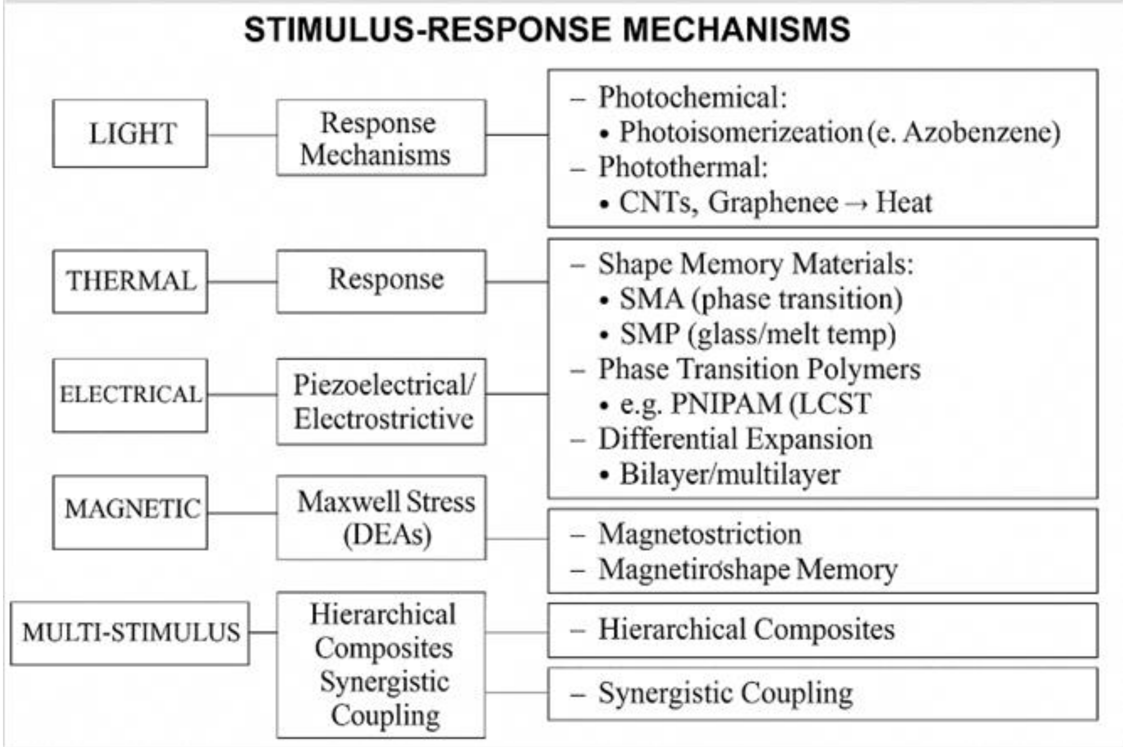

Figure 3: Stimulus–response mechanisms in smart actuators

5.1 Light-responsive mechanisms

Light-responsive actuators use light to trigger motion via photochemical changes (e.g., azobenzene isomerization) or photothermal effects (e.g., heat from graphene or Carbon nanotubes, CNTs). They offer precise, remote control, with recent advances improving NIR responsiveness and color-selective actuation [3].

5.2 Thermal-responsive mechanisms

They rely on temperature-induced changes, such as shape memory effects in alloys and polymers [2], [13-16], and phase transitions in polymers like PNIPAm (Poly(N-isopropylacrylamide) [2, 26, 27]. Bilayer composites exploit differential expansion for motion [2].

5.3 Electrically-responsive mechanisms

Electric fields induce deformation via piezoelectric, electrostrictive, or electrostatic effects in materials like DEAs (Dielectric Elastomer Actuators) [2], [10-12]. Electrochemical actuators (e.g., IPMCs) and Joule heating approaches enable bending or thermal actuation [2, 4, 19].

5.4 Magnetic-responsive mechanisms

These actuators are driven by magnetic fields through magnetostriction, magnetic shape memory alloys, or magnetorheological materials, offering remote, contactless control [2, 17, 18]. Programmable magnetization enables complex deformations [33].

5.5 Multi-stimulus responsive mechanisms

Combining light, heat, and magnetic responses allows multifunctional actuation. Synergistic or sequential activation enhances adaptability and enables biomimetic movement [2, 3].

6. Applications in modern mechatronic systems

Applications and domain suitability of smart actuator technologies. Table 2 summarizes the key types of smart actuators used in modern mechatronic systems, highlighting their major application domains and specific advantages or limitations. This comprehensive comparison illustrates the strengths of each actuator type across diverse sectors, helping guide appropriate technology selection based on system requirements [1–4], [6, 8, 10, 12, 17], [20–22], [25].

SMAs excel in medical devices by offering high force density and biocompatibility, but suffer from slow thermal cycling and limited fatigue life. In soft robotics, faster, more compliant materials like EAPs and IPMCs provide superior response and durability. Real-world applications of smart actuators: several case studies from the healthcare and aerospace industries are presented to illustrate the practical relevance of smart actuators in demanding real-world environments. These examples demonstrate how smart actuator technologies, such as shape memory alloys, piezoelectric materials, and pneumatic soft actuators, are utilized in advanced medical tools and next-generation aerospace systems. Embedding compact SMA bundles from steerable catheters provided sub-millimeter accuracy and wearer comfort in the soft exosuit, while dielectric elastomer insights optimized repetitive flexion cycles with controlled cooling intervals. Moreover, lessons from the magnetorheological damper's tunable yield stress enabled on-the-fly stiffness adjustment in the exosuit's joint modules. Table 3 summarizes these case studies, highlighting the actuator type, application area, function, and key advantages [2, 6, 17, 21].

Table 2: Comparison of smart actuator types across key mechatronic application domains

Actuator Type	Soft Robotics	Biomedical Devices	Aerospace Systems	Automotive Systems	Smart Manufacturing	Wearable Tech	Key Highlights
Shape Memory Alloy (SMA)	Muscle-mimicking motion	Steerable catheters, exosuits	Morphing wings	Deployable components	Limited use due to slow response	Garment integration	Compact, silent, biocompatible; slow response; good for bio-mimetic and adaptive structures
Piezoelectric	Limited (too rigid)	Miniaturized surgical tools	Vibration suppression	Active damping	Precision nano-positioning	Limited (brittle)	High precision, fast response, suitable for damping and control; brittle and rigid
Electroactive Polymer (EAP)	Soft grippers, artificial muscles	Tissue stimulation, wearable sensors	Rare use (low force)	Experimental	Haptic feedback systems	E-textiles	Flexible, low power, ideal for soft interactions and haptics; limited force output
Magnetorheological (MR)	Rigid, not preferred	Not suitable for implants	Satellite vibration damping	Active suspensions	Adaptive fixturing	Limited applicability	Fast, controllable damping; ideal for suspensions and aerospace; bulky and not biocompatible
Pneumatic Soft Actuator	Safe interaction, soft motion	Rehab devices, soft exosuits	Limited by pressure range	Space-consuming	Collaborative robots	Assistive wearables	Highly compliant and safe; ideal for interaction; large size and air source requirement

Table 3: Real-World case studies of smart actuator applications in healthcare and aerospace

Industry	Application	Actuator Type	Function	Advantages
Healthcare	Steerable catheters for cardiovascular surgery	Shape Memory Alloy (SMA)	Enables precise tip control via thermal actuation	Miniaturized, precise motion, no external mechanical parts
Healthcare	Soft robotic exosuits for stroke rehabilitation	Dielectric Elastomer & Pneumatic	Assist movement during therapy	Lightweight, safe for human interaction, programmable assistance
Aerospace	Morphing wing structures in aircraft	SMA Wires & Piezoelectric Composites	Adjust wing camber or flap shape mid-flight	Enhanced maneuverability, reduced fuel consumption, and reduced mechanical complexity.
Aerospace	Satellite vibration suppression systems	Magnetostrictive Actuators (Terfenol-D)	Real-time damping of vibrations affecting optical equipment	Fast response, compact, suitable for space environments

7. Control challenges and requirements

Smart actuators introduce unique control challenges due to their nonlinear, history-dependent, and multi-physics nature. Researchers and engineers employ various modeling strategies, advanced control algorithms, integrated sensing techniques, and emerging control paradigms to address these complexities. The following block diagram summarizes the key dimensions of controlling smart actuators: challenges, modeling approaches, strategies, and modern developments. Figure 4 shows a block diagram of the control aspects in smart actuator systems.

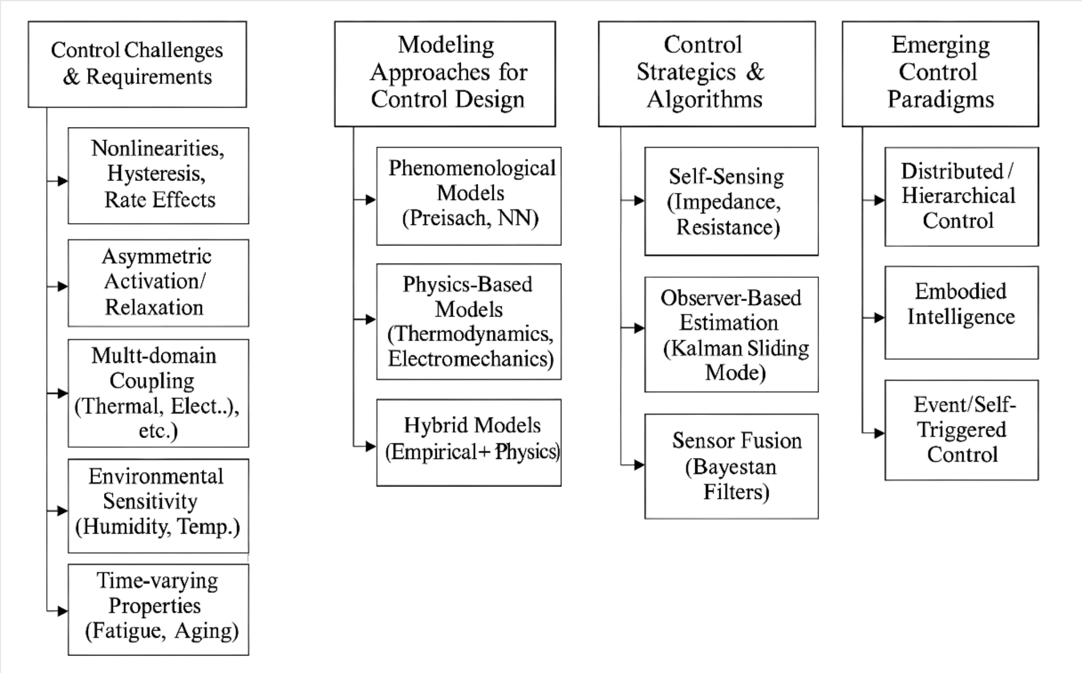

Figure 4: Block diagram of control aspects in smart actuator systems

7.1 Control challenges and requirements

Smart actuators pose unique control difficulties due to nonlinearities, hysteresis, and rate-dependent dynamics, unlike conventional actuators [6, 7]. Asymmetric behavior during activation and relaxation phases adds complexity. Their multi-physics characteristics result in thermal, electrical, and mechanical coupling, as seen in shape memory alloys and ionic polymer-metal composites, which are sensitive to ambient conditions like temperature and humidity [9, 14, 18]. Long-term performance is affected by fatigue, aging, and environmental exposure [2, 11], necessitating real-time system identification and adaptive control strategies. Self-sensing technologies offer promising solutions by reducing reliance on external sensors [16].

7.2 Modeling approaches for control design

Effectively managing is predicated on accurate modeling. Phenomenological fashions, which include neural networks, capture conduct without detailing inner physics [6]. Physics-based models use essential ideas like thermodynamics and electromechanics to explain actuator dynamics [13, 18]. Hybrid models integrate both processes to enhance accuracy and computational performance, often superior via empirical facts [1, 2, 7].

7.3 Control strategies and algorithms

Control strategies are tailored to actuator complexity. Model-based strategies like version predictive management and inverse feedforward remarks schemes manage nonlinearities and hysteresis [6, 7, 17]. Robust and adaptive controls (e.g., sliding mode, backstepping, H∞ (H-infinity Control robust control strategy)) deal with uncertainties [4, 17]. Learning-based strategies, including reinforcement learning and iterative learning control, optimize overall performance through interaction and repetition, mainly when blended with physics-informed models [1, 15].

Smart actuators can estimate their states without outside sensors using self-sensing based on electrical parameters like impedance or resistance [8, 9, 13]. Observer-based estimators (e.g., Kalman filters, sliding mode observers) help reconstruct inner variables [6, 7]. Sensor fusion methods like Bayesian filtering enhance accuracy through integrating more than one record of an asset [15].

7.4 Emerging control paradigms

Emerging control paradigms are increasingly shaping the development of clever actuator systems by addressing complexity, efficiency, and autonomy. Distributed and hierarchical management systems provide coordination and scalability in structures involving a couple of actuators or tender robotic platforms [10, 16]. Embodied intelligence leverages the physical homes of materials to supply adaptive behavior, drawing ideas from biological organisms and enabling more natural and integrated responses [5, 6]. Meanwhile, occasion-caused and self-prompted manipulation strategies extensively reduce energy consumption and computational demands via updating control indicators only when specific situations or thresholds are met, in preference to continuously [1, 23].

8. Fabrication methods and technologies

The manufacturing methods strongly influence smart actuators' performance, reliability, and scalability. This section summarizes both conventional and emerging fabrication strategies that define their capabilities. To better understand the diverse techniques used in manufacturing smart actuators, the following diagram categorizes the major fabrication approaches into four main groups: conventional methods, advanced technologies, hybrid and composite strategies, and surface modification processes. This visual representation highlights the structural relationships among these categories and provides a concise overview of the key processes used in each. Figure 5 clarifies the circular block diagram of smart actuator fabrication methods.

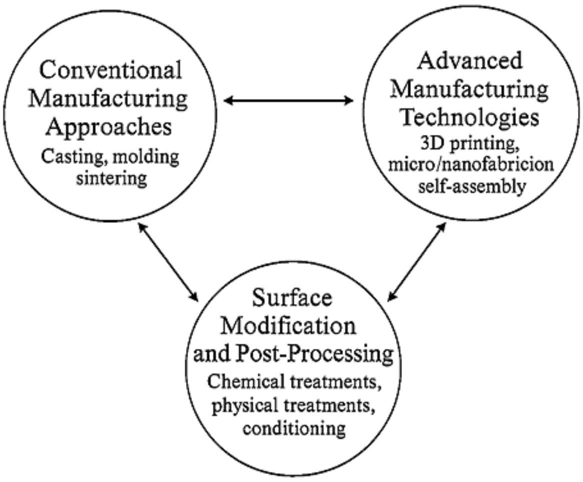

Figure 5: Circular block diagram of smart actuator fabrication methods

8.1 Conventional manufacturing approaches

Traditional methods like casting, molding, and sintering remain essential for many smart actuators: solution casting for IPMCs, injection molding for SMPs, and compression molding for DEAs are widely applied [2, 4, 26]. Powder metallurgy and sintering (including spark plasma and microwave sintering) are used for piezoelectric and magnetostrictive materials [10, 12, 13, 17]. Thermal and mechanical processing, such as annealing and training, are critical for SMAs [13-15].

8.2 Advanced manufacturing technologies

Modern smart actuator fabrication has been advanced by: 3D (Three-Dimensional) printing (e.g., fused deposition modeling, stereolithography, direct ink writing), allowing multi-material designs [22, 26, 27]. Micro/nanofabrication techniques (photolithography, etching, thin-film deposition) enable actuator miniaturization for MEMS (Micro-Electro-Mechanical Systems) and biomedical uses [6], [10-11], [24-37]. Self-assembly and bottom-up approaches (e.g., block copolymers, colloidal assembly) create hierarchical smart structures [32, 38, 39], often bioinspired [8, 30].

8.3 Hybrid and composite fabrication methods

These techniques integrate various materials and processes: Lamination of functional layers and patterning techniques for responsive composites [2, 17, 21]. Fiber/textile-based methods, including electrospinning, coaxial spinning, and SMA wire weaving for wearables [18, 19, 21, 22]. Encapsulation processes like over-molding, vacuum infusion, and microfluidic encapsulation protect sensitive materials and enable multifunctionality [16], [30-36].

8.4 Surface modification and post-processing

Post-processing steps refine actuator functionality: chemical treatments (e.g., silanization, plasma, self-assembled monolayers) improve interface and biocompatibility [4, 21, 36, 39]. Physical treatments like laser texturing and mechanical polishing enhance surface functionality [7, 8]. Conditioning processes such as electric poling, magnetic alignment, and thermomechanical training are vital for performance [9], [16-18].

9. Challenges and future prospects

Since smart actuators are becoming so central to mechatronic systems, it's really important to understand their potential and limitations. Section 9 dives into our main challenges: balancing performance, dealing with complex integration, and ensuring materials last. It also highlights exciting research paths forward, including hybrid materials, designs inspired by nature, and smarter ways to integrate everything. Looking ahead, the advancement of smart actuation hinges on experts from different fields working together to create more adaptive, efficient, and intelligent systems.

9.1 Current challenges and limitations

Smart actuators face trade-offs in performance metrics such as strain, force, speed, and efficiency. For instance, SMAs deliver high force but respond slowly and degrade over time, while dielectric elastomers require high voltages [2, 3, 9]. Reliability remains a concern due to material fatigue and environmental sensitivity [2, 6, 13, 25]. Scaling issues—whether up or down—introduce efficiency loss, power demands, and precision challenges [2, 3, 9]. Integrating these actuators into mechatronic systems requires complex electrical, mechanical, and control solutions [1, 25].

9.2 Promising research directions

Emerging solutions include hybrid materials (e.g., SMA-DEA combinations) for enhanced performance [2, 17, 25], biomimetic hierarchical structures for efficient load distribution [5, 32, 38], and self-healing materials that improve durability [2, 30], [37-39]. Advances in fabrication, such as nanomaterial integration and in-situ tuning, offer enhanced customization and responsiveness [9, 12, 37].

9.3 Emerging applications and opportunities

Smart actuators are well-suited for human-machine interfaces (e.g., wearables, haptics) [3, 21, 24], autonomous systems responsive to ambient stimuli [14, 17], and operations in harsh environments like space and deep sea [4, 13, 16]. Their smooth, biocompatible nature benefits scientific packages like implants and surgical equipment [6, 22].

9.4 Future integration paradigms

Future tendencies encompass embedding computation inside substances for nearby sensing and actuation [26, 34, 35], achieving electricity autonomy through ambient energy harvesting [8, 23], and integrating sensing-actuation-structure into single multifunctional structures [15, 27, 33]. These advancements will rely upon interdisciplinary collaboration across robotics, substance technology, and biology [5, 6].

Figure 6 clearly overviews the smart actuation technologies currently used or developed for mechatronic systems. It brings together the challenges, research directions, and future integration possibilities we've discussed, serving as a visual reference to back up the points made in Section 9.

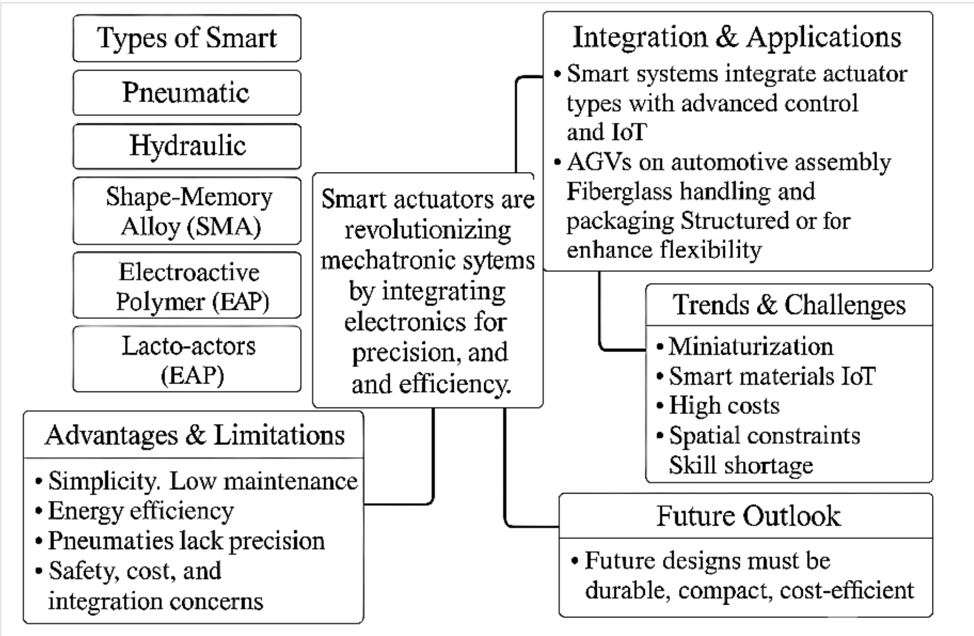

Figure 6: Overview of smart actuation technologies in mechatronic systems

In sections 7–9, Figure 4 block diagrams is discussed to pinpoint control challenges (e.g., nonlinearity, delay) and the algorithms as adaptive control that address them. Figure 6 fabrication workflows are annotated with notes on scalability and material compatibility. Figure 6 outlines current research gaps, such as limited high-frequency response, leading directly into the “Conclusions and Possible Future Works”.

10. Conclusion and possible future works

The The various types of smart actuators each come with their own strengths and drawbacks. For example, soft polymers that respond to electrical signals can stretch significantly but tend to lose energy in the process. Conversely, piezoelectric elements are extremely efficient but generate only very small movements. When high accuracy is essential, materials like ionic polymer–metal composites and magnetorheological devices offer a balance—providing moderate displacement while consuming relatively little power. Real-world experiments reveal even more possibilities. By weaving fine bundles of shape-memory alloys—originally developed for steerable medical tools—into flexible exosuits, engineers have achieved remarkable precision without compromising comfort. Similarly, maintaining the right temperature during elastomer cycles ensures smooth joint motion, and by tuning the stiffness of magnetorheological dampers, exosuits can firm up or relax exactly when needed. Behind all this, materials that can both act and sense their own performance give instant feedback and signal if anything is off. Advanced control strategies then compensate for delays and nonlinear quirks, ensuring the system stays responsive and reliable. Looking ahead, the vision is for actuators that do more than simply move. Imagine tiny, self-contained units that monitor their own health, adjust their behavior in real time, and even learn from their surroundings. Integrating intelligent decision-making into each actuator could allow machines to adapt on the fly, while combining thermal, electrical, magnetic, and light-based triggers could enable movements that feel almost organic. If these devices can harvest energy from their environment, they might operate freely—no power cords required. Achieving this vision will demand close collaboration among materials scientists, roboticists, and control engineers. By working together to refine manufacturing techniques and create seamless hardware-software partnerships, we can bring to life the next generation of mechatronic systems—devices that don't just follow commands, but perceive, reason, and respond almost like living beings.

Abbreviation	
BNT	Bismuth Sodium Titanate
CNT	Carbon Nanotube
DEAs	Dielectric Elastomer Actuators
3D	Three-Dimensional
EAP	Electro Active Polymer
ER	Electrorheological
GO	Graphene Oxide
H∞	H-infinity Control (robust control strategy)
IPMC	Ionic Polymer-Metal Composite
KNN	Potassium Sodium Niobate
LCEs	Liquid Crystal Elastomers
MR	Magnetorheological
MEMS	Micro-Electro-Mechanical Systems
NIR	Near-Infrared
PZT	Lead Zirconate Titanate
PMN-PT	Lead Magnesium Niobate-Lead Titanate
PNIPAM	Poly (N-isopropylacrylamide
SMA	Shape Memory Alloy
SMP	Shape Memory Polymer

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

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

Conflicts of interest

The authors declare that there is no conflict of interest.

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