

Light – Driven Soft Microrobots Based Smart Materials: Development and Prospects

Rishwin Alwin¹, Raphael Joshua A², Rakesh R³

¹Student, St. Joseph's College of Engineering, Nagercoil, Tamil Nadu-600119, India

²Student, St. Joseph's College of Engineering, Chennai, Tamil Nadu-600119, India

³Student, Sholinganallur, OMR, Chennai, St Joseph's College of engineering, Chennai, Tamil Nadu- 600119, India

ABSTRACT

From biomedical devices to industrial automation, light-driven soft microrobots based on smart materials are transforming soft robotics by allowing flexible, adaptable, and bioinspired movement, therefore rendering them indispensable for advanced applications. By providing increased compliance, lightweight design, and enhanced functionality, these actuators—which use smart materials and innovative technologies—overcome the constraints of conventional rigid actuators. Still major obstacles to their general acceptance, nevertheless, are energy economy, durability, and exact control. Focusing on their mechanisms, materials, and uses in soft robotics, this research attempts to offer a thorough assessment of the most recent developments in artificial actuators in biomedical applications. Using secondary data gathered from websites such as IEEE Xplore, ScienceDirect, and SpringerLink using a qualitative approach, the study Examining publications from 2018 to 2025 guarantees a current assessment of technical trends, new materials, and innovative actuation methods in the literature. Recent developments in biomedical applications have underlined notable progress in using dielectric elastomers, electroactive polymers, shape memory alloys, and fluid-driven actuators, stressing their potential in wearable robotics, assistive technologies, biohybrid robots, and industrial automation. Mostly by photothermal and photomechanical phenomena, light-driven soft microrobots actuate using optical energy. Promising uses in biomedical and micro-manipulation applications, hydrogel and liquid crystal elastomer (LCE)-based microrobots leverage these mechanisms for controlled motion. This work investigates their driving systems, benefits, and drawbacks, so advancing micro-scale robotics. Notwithstanding these developments, outstanding problems of response time, power consumption, and integration with real-time sensors call for more creativity. By integrating current advancements and pointing up important issues and future prospects in artificial actuator research, this review adds to the increasing body of knowledge. The results have major ramifications for soft robotics development, encouragement of automation innovation, and improvement of applications in manufacturing, healthcare, and other sectors.

Keywords: *Artificial Actuators, Applications, Soft Robotics, Shape Memory Alloy, Electroactive Polymer.*

INTRODUCTION

The development of soft robotics depends on light-driven artificial actuators, which provide flexible, adaptable, biomimetic movement exceeding traditional rigid actuators. Unlike conventional actuators depending on rigid mechanical components, these sophisticated systems use smart materials, integrated control mechanisms, and energy-efficient designs to replicate the natural motions of living entities [1, 2]. The shift from rigid to soft actuation is crucial in advancing biomedical

devices, assistive robotics, industrial automation, and autonomous exploration, where adaptability and safe interaction with dynamic environments are essential. Over the past decade, significant advancements in electroactive polymers (EAPs), dielectric elastomers (DEAs), shape memory alloys (SMAs), fluidic actuators, and biohybrid systems have propelled the field forward [3, 4]. However, challenges such as energy efficiency, durability, scalability, response time, and precise control continue to limit widespread practical deployment [3]. Light-driven soft microrobots, utilizing photo-

responsive smart materials like liquid crystal elastomers (LCEs) and nanocomposite polymers, offer precise, remotely controlled motion. By converting light energy into mechanical deformation, these actuators facilitate soft robotics applications in microfluidic systems, autonomous biomedical functions, and microrobotic operations. Figure 1 illustrates the schematic representation of soft bio-microrobots, highlighting their design principles, energy sources, and biomedical applications. Remote control features and adaptability of soft microrobots driven by light have attracted a lot of interest. Whereas the photomechanical effect depends on molecule rearranging for motion, the photothermal effect causes heat-based deformations. Focusing on hydrogel and LCE-based microrobots and their possible uses in several domains, this work investigates these mechanisms.

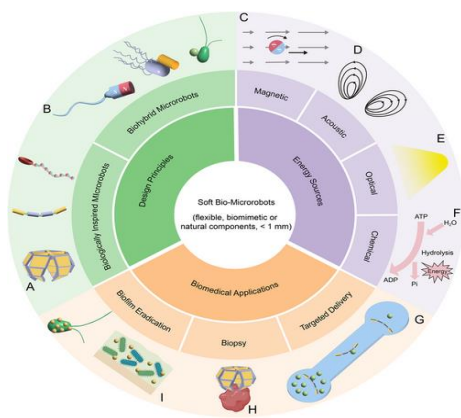


Fig 1. Illustration of soft bio-microrobots, covering design, energy, and biomedical uses¹.

This review seeks to examine the advanced advancements in artificial actuators, emphasizing their mechanics, material advances, and various applications in soft microrobotics. This work synthesizes previous discoveries to identify major trends, appraise novel actuation approaches, and highlight unresolved difficulties that must be addressed to improve actuator performance in soft microrobotics for biomedical applications. The primary objective is to offer insights that will propel future research, promote interdisciplinary collaboration, and enable the incorporation of

artificial actuators into advanced soft robotic systems, hence improving their efficiency, functionality, and practical applications.

MATERIALS AND METHODS

Soft and biocompatible polymers are essential for actuators intended for biomedical applications, prostheses, and human-interactive robotics. These materials must be non-toxic, pliable, and able to integrate with biological tissues without eliciting undesirable reactions. Silicone-based elastomers, Polydimethylsiloxane (PDMS), Thermoplastic Polyurethanes (TPUs), and biohybrid hydrogels are some of the most prevalent materials in this area. They demonstrate significant elasticity, robustness, and biostability, rendering them suitable for applications like soft robotic implants, artificial cardiac muscles, and assistive devices [5, 6]. The goal is to create polymers that preserve their structural integrity in biological settings, resist degradation, and offer precise actuation control [7, 8]. Researchers are investigating bioengineered proteins and self-assembling peptides to develop actuators that merge smoothly with live tissues. The efficacy of artificial actuators is generally assessed using critical parameters like force output, reaction velocity, energy efficiency, durability, and adaptability. Elevated force output guarantees efficient load management, while accelerated response times facilitate instantaneous motion control [9, 10]. Furthermore, energy-efficient actuators promote sustainability and extend battery longevity in portable robotic applications [11]. Through the optimization of these parameters, artificial actuators are transforming next-generation soft robotic systems, enhancing their efficiency, functionality, and practical applicability.

Soft microrobots have transitioned from rigid materials, including metals and plastics, to highly flexible substances such as hydrogels and liquid crystal elastomers (LCEs). These new materials offer exceptional flexibility, scalability, and biocompatibility, facilitating the creation of revolutionary microrobots with improved

1

<https://advanced.onlinelibrary.wiley.com/doi/full/10.1002/aisy.202300093>

functionality in biomedical and environmental applications.

Hydrogel-Based Soft Microrobots

Hydrogels are three-dimensional polymeric networks that retain water while preserving structural integrity. Their capacity for substantial deformation renders them optimal for the fabrication of soft microrobots. A primary benefit of hydrogels is their environmental responsiveness, enabling them to react to stimuli such as temperature, pH, humidity, and pressure. Poly(*n*-isopropylacrylamide) (PNIPAM), a thermoresponsive hydrogel, experiences phase transitions in reaction to temperature variations, rendering it advantageous for targeted drug administration and bioengineering applications. Researchers have employed PNIPAM-based bilayer actuators to create soft microrobots proficient in gripping, crawling, and jumping for biomedical and environmental monitoring applications [29, 12]. Moreover, photoresponsive hydrogel crawlers infused with gold nanoparticles provide directed locomotion via asymmetric friction, permitting the manipulation of microscopic entities. Notwithstanding their benefits, hydrogels exhibit inadequate mechanical strength and reliance on watery environments, constraining their uses.

LCE-Based Soft Microrobots

Liquid crystal elastomers (LCEs) are distinctive polymers that possess properties of both liquid crystals and elastomers, providing superior mechanical flexibility and shape adaptation. In contrast to hydrogels, LCEs function effectively in arid conditions, rendering them appropriate for various applications. LCE-based microrobots utilize stimulus-responsive characteristics, wherein external stimuli like light, heat, or voltage modify their molecular configuration to facilitate movement. Researchers have developed voltage-driven liquid crystal elastomer actuators for multi-gait locomotion across diverse surfaces, allowing microrobots to ascend barriers and traverse restricted areas [29, 13]. Moreover, photoresponsive liquid crystal elastomers combined with carbon-based light absorbers facilitate fast deformation, resulting in self-oscillating microrobots for autonomous functions. LCE-based microrobots exhibit enhanced durability,

flexibility, and adaptability in intricate settings relative to hydrogels.

Target Tracking Algorithm

The real-time navigation of magnetic-activated microrobots depends much on target tracking. Advanced tracking systems increase accuracy and efficiency by using vision-based approaches and deep learning methodologies. In this field, the two main methods are the Binocular Stereo Vision Algorithm and the Monocular Vision Algorithm; both have different benefits in microrobot localization and movement prediction.

Monocular Vision Algorithm

The monocular vision-based target tracking system tracks the microrobot in real-time from one camera. Deep learning models—including convolutional neural networks (CNNs)—are used in this method to process visual data from a single viewpoint. To estimate the position of the microrobot, the method captures texture, colour, and form elements. Li et al. [28] presented a strong monocular vision tracking system with enhanced real-time detection by means of deep neural networks combined with Monocular vision tracking, however, suffers from depth perception restrictions and needs further model-based estimating methods to deduce three-dimensional spatial orientation. The figure 2 below illustrates the imaging principle of magnetically controlled microrobots based on a binocular vision algorithm in detail.

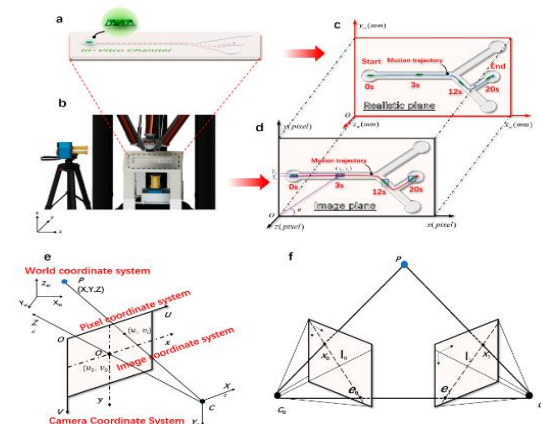


Fig 2. Imaging principle of magnetically controlled microrobots based on a binocular vision algorithm [28]

In the above figure, (a) Customized microrobot motion trajectory shows above. (b) Binocular imaging and tracking experimental apparatus magnetically operated. (c) A real plane schematic of the monocular target tracking system. (d) A monocular target tracking algorithm image plane target tracking diagram (e) The spatial distribution map of the four coordinate systems developed and the geometric model of camera imaging. (f) The polar geometry of two matching camera views.

Binocular Stereo Vision Algorithm

By means of two synchronized cameras to get depth information, the binocular stereo vision algorithm improves tracking accuracy. Computation of disparity maps from stereo image pairings allows this approach to precisely three-dimensional localization of the microrobot. Under dynamic environmental settings, Li et al. [28] showed that integrating deep learning with stereo vision greatly enhances microrobot tracking. With better spatial resolution than monocular techniques, the method uses feature matching approaches to recover depth data. Although computational complexity and calibration needs define the main difficulties of this method, it is nonetheless a strong tool for real-time microrobot tracking.

For tracking magnetic-activated microrobots, both monocular and binocular vision systems offer useful solutions. Although bilateral stereo vision provides improved depth perception and is more suited for high-precision uses even if monocular vision is computationally efficient.

Driving Mechanisms

Light-driven soft microrobots use optical energy to accomplish microscale mobility and functional tasks. Two basic processes define its actuation: the photothermal effect and the photomechanical effect. Soft microrobots are quite useful for biomedical applications, environmental sensing, and micro-manipulation since these systems provide exact and remote control.

Driven by the Photothermal Effect

When light is absorbed by a medium, localized heating and thermal expansion results from which movement is induced. Soft microrobots based on

hydrogels and liquid crystals often use this phenomenon.

Hydrogel Soft Microrobot Driven by Photothermal Effect

By means of the light-induced heating of implanted nanoparticles or photothermal agents, hydrogel-based soft microrobots generate localized swelling or shrinking. Photothermal conversion materials (like gold nanoparticles or carbon-based materials) absorb energy from near-infrared (NIR) or visible light, therefore inducing a phase transition in the hydrogel matrix. This change in the hydrogel's volume causes either contraction or directed bending or expansion. Highly fit for biomedical uses like targeted drug delivery and minimally invasive surgery, Gao, Wang, and Chen [29] underlined the benefits of hydrogels in terms of biocompatibility and fast response times. Achieving exact motion control and stability under different environmental circumstances is therefore the main difficulty. The figure 3 below illustrates the shape of the double-layer hydrogel bands varies with different sections and lengths in detail.

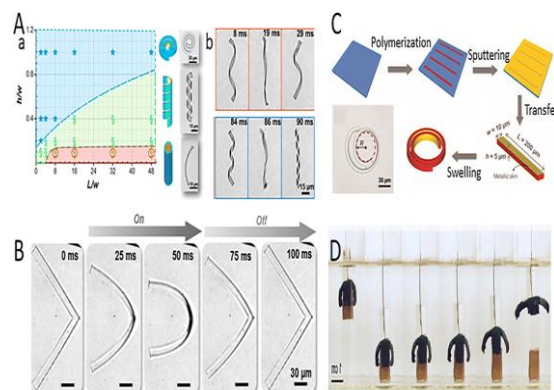


Fig 3. Shape of the double-layer hydrogel bands varies with different sections and lengths – An Overview [29]

LCEs Soft Microrobot Driven by Photothermal Effect

Another family of soft microrobots using the photothermal effect for motion are liquid crystal elastomers (LCEs). Cross-linked liquid crystalline polymers make up LCEs; they phase-transform with heating to cause reversible shape changes. Photothermal elements buried in the LCE matrix cause localized heating upon light exposure, hence inducing a nematic-to-isotropic phase shift. The

LCE molecular structure's alignment determines whether this transition produces bending, twisting, or rolling deformations. Promising for biomedical micromanipulation and soft robotics, Gao et al. [29] showed that LCE-based microrobots show exceptional mechanical flexibility and programmed actuation. But their efficiency relies on material composition, light intensity, and homogeneity of heat distribution. A light-driven millimetre-scale crawling robot was demonstrated in figure 4 below.

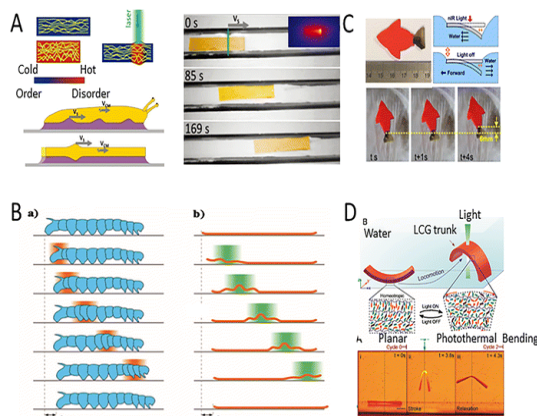


Fig 4. A light-driven millimetre-scale crawling robot [29]

Driven by Photomechanical Effects

Unlike the photothermal effect, which depends on heat creation, the photomechanical effect straight transfers light energy into mechanical deformation by molecular rearrangements. Materials having photoresponsive molecular components, such as LCEs and polymers based on azobenzene, show this mechanism especially.

Motion is obtained in photomechanical-driven microrobots by use of light-induced molecular conformational changes. For example, materials based on azobenzene experience mechanical deformation by means of cis-trans isomerization under various light wavelengths. Applications needing controlled and repeatable motion depend on very accurate and reversible actuation made possible by this phenomenon. Reversible changes in the shape of liquid crystal polymer chairs is illustrated in figure 5 below.

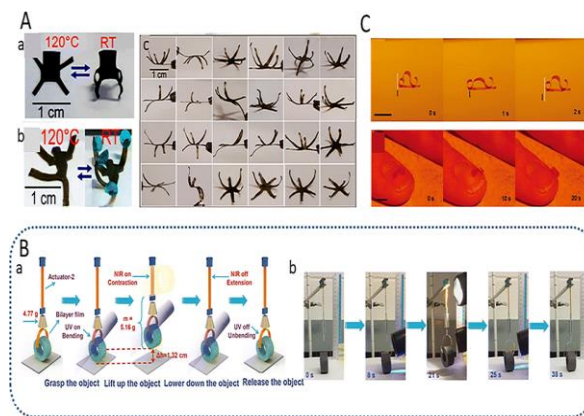


Fig 2. Imaging principle of magnetically controlled microrobots based on a binocular vision algorithm [28]

LCE-based soft microrobots also show photomechanical reactions, in which case light exposure changes the alignment of liquid crystalline molecules to cause reversible deformations without appreciable heat generation. Faster response times and lower heat dissipation follow from this, so photomechanical actuation is quite effective for micro-scale uses.

By use of photothermal and photomechanical effects, light-driven soft microrobots provide several actuation techniques for micro-scale motion. Photothermal conversion helps hydrogel and LCE-based microrobots to move under control and efficiency. Photomechanical effects, meantime, offer direct, heat-independent actuation, so improving responsiveness and accuracy. Together, these drive systems help soft microrobotic systems for industrial and healthcare uses advance. The figure 6 below illustrates the potential application of artificial muscles and bionic soft robots in detail.

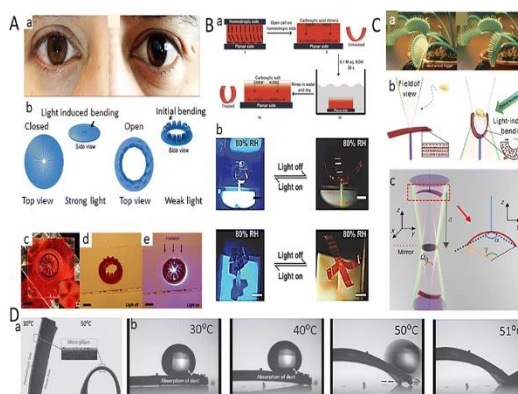


Fig 6. Potential application of artificial muscles and bionic soft robots [29]

Advanced Materials for Artificial Actuators

The efficacy and efficiency of artificial actuators are fundamentally dependent on the choice of sophisticated materials that determine their mechanical characteristics, energy efficiency, and reaction time. In contrast to conventional rigid actuators, artificial actuators utilize intelligent, flexible, and adaptive materials to facilitate intricate, bioinspired motions. The development of responsive polymers, conductive composites, biocompatible materials, and nanotechnology has greatly enhanced the potential for soft robotic applications. These materials facilitate the creation of actuators that are lightweight, flexible, resilient, and self-repairing, rendering them appropriate for use in wearable robots, biomedical devices, and advanced automation [14, 15, 16]. The figure 7 below illustrates the details of soft actuators.



Fig 7. Soft Actuators – An overview²

Intelligent and responsive materials are essential in artificial actuation, as they respond to external stimuli including heat, light, electric fields, and magnetic fields. The materials encompass SMAs, SMPs, LCEs, and hydrogels, each possessing distinct attributes that facilitate accurate and programmable motion. SMAs and SMPs experience phase changes upon exposure to thermal energy, facilitating shape recovery and regulated deformation. LCEs, influenced by the alignment characteristics of liquid crystals, demonstrate

programmable shape transformation in response to temperature and light exposure, rendering them suitable for soft grippers and robotic exoskeletons. Hydrogels, which expand or contract in reaction to variations in humidity and pH, are progressively utilized in biological applications and drug delivery systems [17]. Nevertheless, issues including sluggish response times, energy consumption, and material fatigue must be resolved to enhance their practical applicability.

Conductive and flexible materials are crucial for electrically operated actuators, including DEAs and EAPs. These materials must integrate high conductivity, flexibility, and mechanical toughness to enable seamless and consistent actuation cycles. Significant advancements in this domain encompass stretchy metallic composites, carbon-derived nanomaterials (such as graphene and carbon nanotubes), and ionic-conductive hydrogels. Graphene and carbon nanotubes (CNTs) are notably advantageous owing to their remarkable electrical conductivity, mechanical strength, and lightweight characteristics. Conductive elastomers, including silver nanowire-infused polymers and PEDOT: PSS (poly(3,4-ethylenedioxythiophene) polystyrene sulfonate), provide an optimal combination of stretchability and electronic performance, rendering them ideal for wearable artificial muscles and electronic skin applications [17, 18]. Nonetheless, guaranteeing long-term durability, reliable conductivity under stress, and economical production continues to pose significant research problems.

Nanotechnology has revolutionized artificial actuators by enhancing molecular mechanical, electrical, and thermal properties. Actuator designs use graphene, CNTs, boron nitride Nano sheets, and metallic nanoparticles to improve conductivity, strength, and responsiveness. Micro-robotic systems, haptic feedback devices, and soft grippers can use CNT-based actuators for efficient electrically powered motion. Magneto-responsive nanomaterials, such as iron oxide nanoparticles, provide magnetic field-controlled remote actuation. These advances enable compact, high-

performance actuators for biomedical Nano robots, drug delivery systems, and precision surgical instruments [18, 19]. Nanomaterials' main drawbacks include scalability, reproducibility, and high synthesis costs.

Self-healing and adaptable actuator materials can repair damage and resume operation without external intervention. These materials are inspired by biological healing mechanisms and are vital for increasing the lifespan of dynamic soft robotic systems. Supramolecular polymers, ionic hydrogels, and dynamic covalent networks can self-heal cracks and fractures, extending durability. Adaptable materials that change stiffness and actuation in response to environmental changes are being studied for wearable robotics, autonomous prosthetics, and space exploration [17, 19]. The use of microcapsule-based healing agents and reversible cross-linking polymers has improved self-repairing actuators. However, balancing mechanical strength, healing velocity, and operational stability remains a research priority.

Next-generation soft robotics, biomedical applications, and intelligent automation systems are being developed by improving artificial actuator materials. Increased responsiveness, conductivity, biocompatibility, and self-healing are helping researchers overcome fundamental limits and improve artificial actuation technology.

Actuation Techniques in Soft Microrobotics

Soft robotics depends on novel actuation methods to facilitate adaptive, flexible, and biomimetic movement. In contrast to conventional rigid systems, soft robots necessitate actuators that emulate natural muscle movement, function effectively under fluctuating situations, and blend harmoniously with their surroundings. A variety of actuation solutions have developed to improve the performance, adaptability, and autonomy of soft robotics, such as distributed and embedded actuation, multi-modal actuation approaches, energy harvesting, and sophisticated sensing and control systems [20, 21]. These methodologies guarantee accuracy, longevity, and energy efficiency, rendering soft robots appropriate for applications in healthcare, industrial automation, and exploration technologies.

Distributed and Embedded Actuation

Soft robotics requires distributed and embedded actuation for uniform force distribution and fine motion control. Distributed actuation uses several tiny actuators inside the soft structure to enable smooth, flexible, and detailed deformations, unlike centralized motor-based robotic systems. Soft robots can bend, stretch, and twist organically using pneumatic networks (PneuNets), fluidic elastomer actuators, and integrated electroactive polymer layers. This approach is useful in biomedical soft robotics, prosthetics, and wearable assistive devices, where localized deformation and flexibility must be controlled [21]. Miniaturization, actuator synchronization, and reaction time minimization are challenges for compact designs. Future advances will use microfluidic systems and nanoscale actuators to include intelligence for accuracy and real-time adaptability.

Multi-Modal Actuation Strategies

Multi-modal actuation solutions increase soft robotics' versatility and adaptability by incorporating multiple actuation mechanisms. These solutions use pneumatic, hydraulic, dielectric elastomer, SMA, and magnetoactive actuation to create complex movements. Depending on the application, hybrid actuators that combine electroactive polymers (EAPs) with shape memory materials allow robots to act sequentially or simultaneously. This technology is ideal for bioinspired robots that mimic octopus's movement, self-adapting structures, and robotic exoskeletons. Multi-modal actuation improves flexibility and redundancy but complicates control, actuation coordination, and power consumption [22]. To improve integration, research is underway on self-regulating systems, AI-based actuation control, and energy-efficient hybrid materials.

Energy Harvesting for Sustainable Actuators

Actuators in soft robotics require continual power, making energy efficiency a major concern. Energy harvesting converts ambient energy into power to improve operational independence. Piezoelectric energy harvesting, triboelectric Nano generators (TENGs), biofuel cells, and solar-powered soft actuators are potential energy sources.

Piezoelectric soft actuators can harness body energy for wearable robots and prosthetics. Sun-responsive polymers and light-driven soft actuators are sustainable solutions for autonomous field robotics and space exploration [23]. Despite these benefits, energy-collecting devices face low conversion efficiency, integration complexity, and intermittent power generation. To promote sustainability, future technologies focus hybrid energy storage, flexible super capacitors, and AI-optimized energy management.

Control and Sensing Mechanisms for Soft Actuators

Soft robotic actuators need advanced control and sensing methods for motion execution and feedback regulation. Soft robots need adaptive, real-time control systems to accommodate nonlinear deformations and variable force outputs, unlike rigid robots that need accurate kinematics. Sensors include embedded strain sensors, capacitive touch sensors, fibre optic sensors, and flexible piezo resistive materials measure actuator

position, force, and environmental interactions. Closed-loop control systems use these sensors to adjust soft robots' movements to ambient inputs. To improve self-calibration, predictive control, and automatic fault rectification, soft robotics is using machine learning and AI-driven control frameworks [21, 24]. However, lowering sensor complexity, improving unstructured durability, and optimizing signal processing for real-time applications are major issues. Soft robotic actuators will benefit from wireless, self-sustaining, and bioinspired sensing networks for autonomous adaptation and interaction.

Soft robotics actuation approaches are improving intelligence, adaptability, and efficiency. Using distributed actuation, multi-modal approaches, sustainable energy sources, and AI-driven sensing mechanisms, researchers are developing next-generation soft robotics for dynamic, human-centric environments with greater precision and autonomy.

Applications of Artificial Actuators in Soft Microrobotics

The following table provides an explanation of the various applications of artificial actuators in soft robotics [20, 23, 24, 25, 26].

Table 1. Applications of Artificial Actuators in Soft Robotics

Application Area	Description & Use Cases	Key Actuation Technologies	Challenges & Future Directions
Soft Grippers and Manipulators	Used for gentle and adaptive grasping in food processing, pharmaceutical handling, agriculture, and electronics. They conform to different object shapes for handling delicate and irregularly shaped objects.	Pneumatic actuators, DEA, SMA, EAP, bioinspired adhesives	Enhancing grip strength while maintaining flexibility, improving energy efficiency for portable use, integrating AI-driven adaptive grasping and feedback mechanisms.
Wearable and Assistive Devices	Found in prosthetic limbs, rehabilitation exoskeletons, assistive gloves, and mobility aids. These devices mimic biological muscle	Hydrogel actuators, shape memory polymers (SMP), soft pneumatic actuators, magnetoactive materials	Reducing device weight for comfort, enhancing durability and power efficiency, developing real-time sensory

	contractions to help users regain movement.		feedback for user adaptability.
Biohybrid and Biomedical Applications	Integrated with biological tissues for biohybrid robots, implantable medical devices, drug delivery systems, and surgical tools, improving minimally invasive procedures.	Biocompatible polymers, ionic EAPs, nanomaterial-based actuators, self-healing materials	Ensuring long-term biocompatibility, miniaturizing actuators for seamless implantation, enhancing response time for biological applications.
Autonomous Soft Robots for Exploration	Designed for disaster response, space missions, and deep-sea exploration. These robots navigate challenging terrains with high adaptability and resilience.	Dielectric elastomers, SMP, flexible electromagnetic actuators, bioinspired soft actuators	Improving locomotion efficiency on rough terrains, enhancing energy independence, developing damage-resistant and self-healing materials.
Industrial and Manufacturing Applications	Used in robotic co-workers, self-adapting production tools, and automation, improving human-robot collaboration for precise and safe assembly lines.	Pneumatic actuators, SMA, magnetorheological actuators, soft tendon-driven actuators	Increasing load-bearing capacity, reducing maintenance costs, improving sensor integration for precise control.
Underwater and Aerospace Soft Robotics	Enables bioinspired underwater robots for ocean exploration and adaptive aerospace robots for flexible movement in extreme environments.	Hydrodynamic elastomers, magnetoactive materials, artificial muscles, electroactive polymers	Improving pressure resistance in deep-sea applications, enhancing structural integrity for space environments, developing energy-efficient propulsion mechanisms.
Soft Robots for Agricultural Applications	Supports precision farming, autonomous harvesting, and pollination robots, minimizing crop damage and improving efficiency in delicate crop handling.	Soft pneumatic actuators, dielectric elastomers, magnetoactive materials, bioinspired gripping mechanisms	Enhancing dexterity for handling different crop types, improving weather resistance, integrating automated control systems for optimized farming.
Medical Rehabilitation and Therapy Robots	Soft robotic actuators help in physiotherapy and movement assistance, supporting rehabilitation exercises	Shape memory polymers, pneumatic actuators, electroactive materials, haptic	Enhancing real-time patient feedback mechanisms, reducing material fatigue for

	for patients with motor impairments.	feedback-enabled actuators	prolonged use, improving user comfort.
Soft Robotics in Consumer Electronics	Used in foldable devices, adaptive touch interfaces, and soft robotic accessories, enhancing interaction and ergonomic design.	Flexible EAPs, shape memory polymers, self-healing polymers, conductive elastomers	Developing ultra-thin actuators for wearables, improving material flexibility, ensuring durability in daily use applications.
Tactile and Haptic Feedback Systems	Enhances user experience in virtual and augmented reality (VR/AR) by providing realistic haptic sensations through soft actuators.	Electroactive polymers, dielectric elastomers, piezoelectric materials, fluidic actuators	Improving response speed and precision, integrating wireless control, enhancing energy efficiency for prolonged usage.

Artificial Actuators in Biomedical Applications Using Soft Microrobotics

Particularly in robotics and microrobotics for focused diagnosis and treatment, artificial actuators in soft robotics have transformed biotechnology. Li et al. [28] pointed out the developments in magnetic-activated microrobots using deep learning for real-time tracking and detection, therefore providing a viable biomedical use. Driven by external magnetic fields, these microrobots can negotiate challenging biological conditions with great accuracy, thereby facilitating minimally invasive treatments including localized therapy, targeted drug delivery, and tumour biopsies. Soft robotics uses extremely flexible and biocompatible materials unlike traditional robotic

systems, guaranteeing adaptation to sensitive tissues without generating appreciable damage. For uses in precision medicine, magnetic actuation combined with AI-driven trajectory prediction improves the controllability and responsiveness of these microrobots. The work of Li et al. [28] emphasized the need of AI-enhanced control systems in maximizing microrobot movement and interaction inside dynamic biological environments, thereby enhancing efficiency in biomedical diagnostics and treatment interventions. The figure 8 below illustrates the schematic diagram of the fabrication and the self-curling principle of magnetically controlled microrobots.

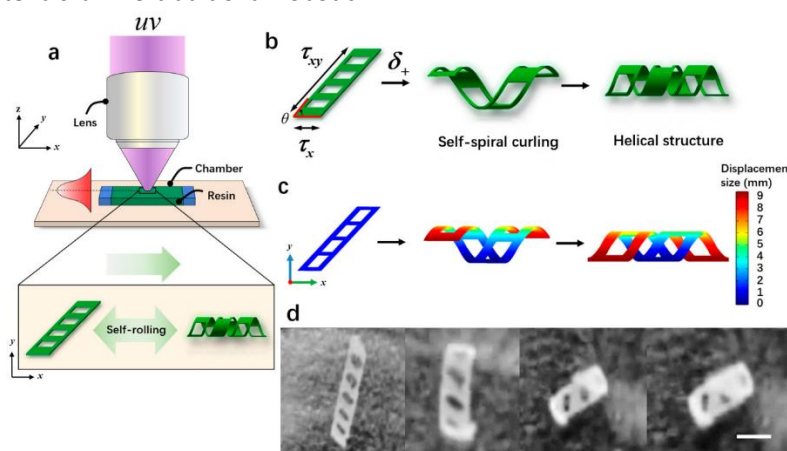


Fig 8. Fabrication and the self-curling principle of magnetically controlled microrobots

Moreover, the use of soft robotics in targeted diagnostics is changing the field of biosensory imaging. With hitherto unheard-of accuracy, magnetic microrobots can be used in vivo imaging, real-time biomarker detection, and early illness diagnosis. Deep learning is underlined by Li et al. [28] as essential for improving microrobot tracking, thereby enabling improved spatial resolution in diagnostic processes. These developments greatly support regenerative medicine, in which stem cells

and tissue engineering benefit from microrobotics. Notwithstanding their possibilities, in physiological settings biocompatibility, energy efficiency, and exact actuation remain very vital. To fully utilize artificial actuators in soft robotics for biotechnology uses, future studies should concentrate on optimizing material properties, improving AI algorithms, and removing clinical translating obstacles. The figure 9 illustrates an example of targeted diagnosis using soft robotics.

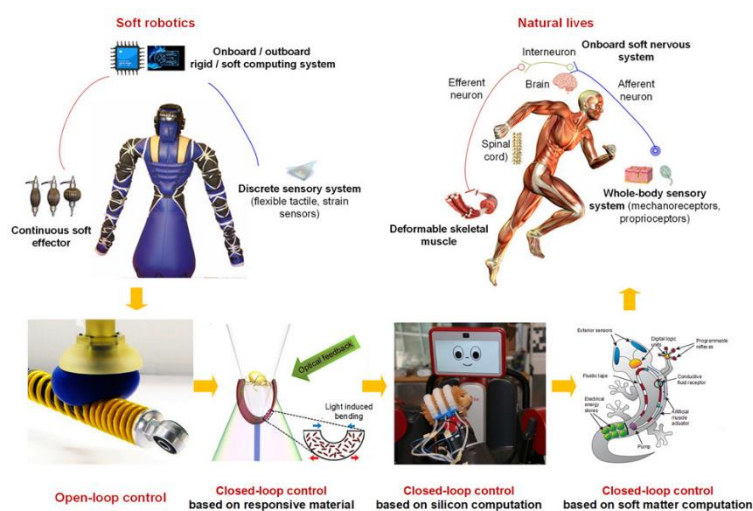


Fig 9. applications of soft robotics in biotechnology applications³

Here is a detailed table 2 focusing on soft robotics in biotechnology.

Table 2. Soft Microrobotics applications in Biomedical Applications [28]

Category	Mechanisms	Materials	Applications
Actuation Mechanism	Magnetic-controlled microrobots	Soft and biocompatible materials	Targeted drug delivery in biomedicine
Control Approach	Real-time tracking via deep learning	Nanocomposite-based polymers	Minimally invasive surgical procedures
Motion Strategy	External magnetic field manipulation	Shape-memory alloys	Endoscopic interventions and micromanipulations
Energy Source	Magnetic field-induced actuation	Hydrogel-based actuators	Smart tissue engineering and regenerative medicine

³ <https://www.sciencedirect.com/science/article/pii/S2589004221010439>

Responsiveness	Adaptive response to environmental changes	Bioinspired elastomers	Dynamic cell culture systems
Precision & Accuracy	AI-based trajectory prediction	Hybrid soft-hard materials	Real-time monitoring of biomolecular interactions
Integration with AI	Deep learning for microrobot localization	Graphene-based flexible actuators	Automated biosensing for disease diagnostics
Biocompatibility	Minimizing cytotoxicity and immune response	Non-toxic polymer matrices	Implantable microdevices
Scalability	Miniaturization for micro-scale medical tasks	Stretchable and flexible composites	Personalized medicine and on-demand therapeutic delivery

Light-Driven Soft Microrobots: Advancing Smart Materials for Adaptive and Intelligent Systems

A novel concept in smart materials, light-driven soft microrobots enable intelligent and adaptive systems with uses in healthcare, environmental, and industrial sectors via means of Mostly made of advanced smart materials such liquid crystal elastomers (LCEs), photo-responsive polymers, and nanocomposite hydrogels—which show dynamic and reversible shape alterations in response to light stimuli—these microrobots are Smart materials provide remarkable flexibility, responsiveness, and tenability unlike conventional rigid materials, therefore enabling exact, non-contact actuation [29]. For example, LCEs undergo photomechanical deformation under particular light wavelengths due to molecular realignment, therefore allowing programmable motion. This motion is illustrated in figure 10 below.

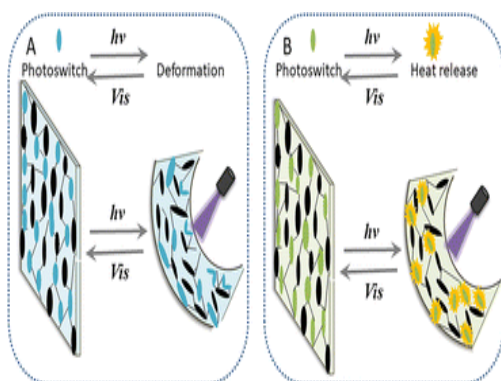


Fig 10. An illustration of (A) Opto-mechanical drive. (B) Photothermal drive [29].

Analogous volumetric changes mediated by photo thermal effects enable self-regulated expansion and contraction in photo-responsive hydrogels. By removing the need for cumbersome power sources or outside mechanical forces, these components improve the scalability and efficiency of microrobotic systems. Moreover, the use of nanoscale photothermal agents—such as carbon-based materials or gold nanoparticles—helps to increase the responsiveness of smart materials by absorbing light. This development greatly increases the operational range of microrobots, therefore enabling their fit for uses including environmental sensing, microfluidic control, minimally invasive surgery, and targeted medication delivery. Figure 11 illustrates an example of smart materials in Developed Diagnostics and Therapeutic applications.

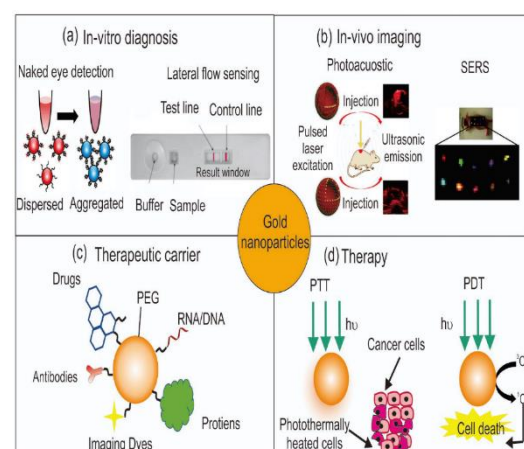


Fig 11. An example of smart materials in Developed Diagnostics and Therapeutic applications [30].

Certain smart materials' self-healing and biodegradable qualities help to advance sustainability and biocompatibility, which makes them perfect for usage in biomedicine. Still under active study, though, are concerns include maximizing material stability, accelerating response speed, and overcoming light penetration limits in biological tissues. Through constant improvement of the design and synthesis of smart materials, scientists aim to create more autonomous, efficient, multifarious microrobots competent of functioning in dynamic and complicated surroundings. The future of light-driven soft microrobotics depends on the development of next-generation smart materials with enhanced optical sensitivity, mechanical resilience, and energy economy, so enabling revolutionary developments in robotics, healthcare, and nanotechnology.

Challenges and Limitations of Artificial Actuators in Soft Microrobotics

Artificial actuators for soft robots have made great strides, but they still face many obstacles that preclude their widespread adoption and performance enhancement. Energy efficiency and power supply are key topics. Many soft actuators, such as DEA and SMA, require high working voltages or energy inputs, limiting their portability and usability. To improve practical applications, energy-efficient power sources and energy optimization are still needed. Another challenge is soft actuator durability and lifespan. Soft materials like elastomers and hydrogels can tire, rip, and degrade. This is especially true in stressful situations. The goal of ongoing research is to ensure operational stability while maintaining flexibility and responsiveness. Many artificial actuators are limited by response time and actuation speed [20, 27]. Unlike pneumatic actuators, which have slow response times due to air compression and release delays, certain EAP and magnetoactive materials have trouble actuating quickly for dynamic applications like robotic locomotion. Soft robots in biomedical applications are limited in long-term clinical use by material durability, biocompatibility

problems, and sophisticated control needs. Their response time and accuracy in delicate medical chores still need work as well.

Precision and control concerns arise because soft actuators often lack the structural support needed for accurate motion execution. Variations in material quality, external environmental conditions, and non-linear responses confound these control systems. To improve actuation accuracy, these actuators must be integrated with sensing and feedback systems, however coordinating soft actuators and real-time sensor technologies is problematic. Scalability and manufacturing restrictions limit soft actuator mass production. The fabrication process is complicated, because materials and qualities vary. Finally, material cost and availability remain major issues. Complex materials like nanocomposites and conductive polymers are expensive and scarce. To overcome these constraints, multidisciplinary research is needed to improve materials, energy efficiency, and control systems.

CONCLUSION AND FUTURE SCOPE

Next-generation smart materials with increased flexibility, energy economy, and responsiveness will define artificial actuators in soft robots going forward. By allowing adaptive, real-time reactions, artificial intelligence and machine learning will transform actuation control. While miniaturizing will drive developments in micro-scale actuators for medical and wearable uses, hybrid actuation systems incorporating pneumatic, electric, and biohybrid technologies will increase functionality. Biohybrid actuators and sustainable materials will inspire environmental advances. Developing more robust, biocompatible materials and enhancing control methods for maximum responsiveness and precision would help soft robotics in biomedical uses to flourish. Advancements in AI-driven actuation and seamless human-robot interaction could further expand their use in personalized healthcare and minimally invasive procedures. Light-driven soft microrobots with artificial actuators and smart materials provide precise, wireless, and adaptive motion control for various applications. Integration into biological, microfluidic, and environmental systems improves efficiency and functionality. Intelligent,

autonomous robotic systems will benefit from material stability and responsiveness improvements. By means of photothermal and photomechanical phenomena, light-driven microrobots show effective, under control actuation. In biomedical and commercial uses, hydrogel and LCE-based designs improve accuracy and flexibility. Future developments should solve motion stability, energy economy, and environmental adaptability so guaranteeing wider application of these soft robotic systems in practical environments. Finally, developments in materials, control techniques, and manufacturing will increase the potential for soft robotics by enabling new directions in space exploration, automation, and healthcare as well as by addressing challenges.

REFERENCES

1. Lalegani Dezaki, M., & Bodaghi, M. (2023). A review of recent manufacturing technologies for sustainable soft actuators. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 10(6), 1661-1710.
2. Mahmood, A., Akram, T., Shenggui, C., & Chen, H. (2023). Revolutionizing manufacturing: a review of 4D printing materials, stimuli, and cutting-edge applications. *Composites Part B: Engineering*, 266, 110952.
3. Abdelmaksoud, S. I., Al-Mola, M. H., Abro, G. E. M., & Asirvadam, V. S. (2024). In-depth review of advanced control strategies and cutting-edge trends in robot manipulators: analyzing the latest developments and techniques. *IEEe Access*.
4. Qu, J., Yu, Z., Tang, W., Xu, Y., Mao, B., & Zhou, K. (2024). Advanced technologies and applications of robotic soft grippers. *Advanced Materials Technologies*, 9(11), 2301004.
5. Carrico, J. D., Tyler, T., & Leang, K. K. (2017). A comprehensive review of select smart polymeric and gel actuators for soft mechatronics and robotics applications: fundamentals, freeform fabrication, and motion control. *International Journal of Smart and Nano Materials*, 8(4), 144-213.
6. Rothmund, P., Kellaris, N., Mitchell, S. K., Acome, E., & Keplinger, C. (2021). HASEL artificial muscles for a new generation of lifelike robots—recent progress and future opportunities. *Advanced materials*, 33(19), 2003375.
7. Liang, W., Liu, H., Wang, K., Qian, Z., Ren, L., & Ren, L. (2020). Comparative study of robotic artificial actuators and biological muscle. *Advances in Mechanical Engineering*, 12(6), 1687814020933409.
8. Zhang, Y., Xie, S., Zhang, D., Ren, B., Liu, Y., Tang, L., ... & Zheng, J. (2019). Thermo-responsive and shape-adaptive hydrogel actuators from fundamentals to applications. *Engineered science*, 6.
9. Li, M., Pal, A., Aghakhani, A., Pena-Francesch, A., & Sitti, M. (2022). Soft actuators for real-world applications. *Nature Reviews Materials*, 7(3), 235-249.
10. Pustavrh, J., Hočevár, M., Podržaj, P., Trajkovski, A., & Majdič, F. (2023). Comparison of hydraulic, pneumatic and electric linear actuation systems. *Scientific reports*, 13(1), 20938.
11. Omid, S. O., Goudarzi, Z., Kangarshahi, L. M., Mokhtarzade, A., & Bahrami, F. (2020). Self-expanding stents based on shape memory alloys and shape memory polymers. *Journal of Composites and Compounds*, 2(3), 92-98.
12. Youn, J. H., Jeong, S. M., Hwang, G., Kim, H., Hyeon, K., Park, J., & Kyung, K. U. (2020). Dielectric elastomer actuator for soft robotics applications and challenges. *Applied Sciences*, 10(2), 640.
13. Rahman, M. H., Werth, H., Goldman, A., Hida, Y., Diesner, C., Lane, L., & Menezes, P. L. (2021). Recent progress on electroactive polymers: Synthesis, properties and applications. *Ceramics*, 4(3), 516-541.
14. Yunas, J., Mulyanti, B., Hamidah, I., Mohd Said, M., Pawinanto, R. E., Wan Ali, W. A. F., ... & Yeop Majlis, B. (2020). Polymer-based MEMS electromagnetic actuator for biomedical application: A review. *Polymers*, 12(5), 1184.
15. Wei, S., & Ghosh, T. K. (2022). Bioinspired structures for soft actuators. *Advanced Materials Technologies*, 7(10), 2101521.
16. Jiao, Z., Zhang, C., Wang, W., Pan, M., Yang, H., & Zou, J. (2019). Advanced artificial muscle for flexible material-based reconfigurable soft robots. *Advanced Science*, 6(21), 1901371.
17. Wu, G., Wu, X., Xu, Y., Cheng, H., Meng, J., Yu, Q., ... & Chen, S. (2019). High-performance hierarchical black-phosphorous-based soft electrochemical actuators in bioinspired applications. *Advanced Materials*, 31(25), 1806492.

18. Le, X., Lu, W., Zhang, J., & Chen, T. (2019). Recent progress in biomimetic anisotropic hydrogel actuators. *Advanced science*, 6(5), 1801584.
19. Yao, D. R., Kim, I., Yin, S., & Gao, W. (2024). Multimodal soft robotic actuation and locomotion. *Advanced Materials*, 36(19), 2308829.
20. Khalid, M. Y., Arif, Z. U., Tariq, A., Hossain, M., Khan, K. A., & Umer, R. (2024). 3D printing of magneto-active smart materials for advanced actuators and soft robotics applications. *European Polymer Journal*, 205, 112718.
21. Rodinò, S., & Maletta, C. (2024). Design considerations and applications of shape memory alloy-based actuation in morphing structures: A systematic review. *Progress in Engineering Science*, 100021.
22. Raza, A., Hassan, W., & Jeon, S. (2024). Pneumatically Controlled Wearable Tactile Actuator for Multi-Modal Haptic Feedback. *IEEE Access*.
23. Nie, Z. Z., Wang, M., & Yang, H. (2024). Self-sustainable autonomous soft actuators. *Communications Chemistry*, 7(1), 58.
24. Kim, H., Na, H., Noh, S., Chang, S., Kim, J., Kong, T., ... & Lee, J. (2024). Inherently integrated microfiber-based flexible proprioceptive sensor for feedback-controlled soft actuators. *npj Flexible Electronics*, 8(1), 15.
25. Matharu, P. S., Singh, A. P., Song, Y., Gandhi, U., & Tadesse, Y. (2024). Single layered soft skin actuated with twisted and mandrel coiled actuators for soft robotics. *Journal of Polymer Science*, 62(10), 2071-2093.
26. Gunawardane, P. D. S. H., Cheung, P., Zhou, H., Alici, G., de Silva, C. W., & Chiao, M. (2024). A versatile 3d-printable soft pneumatic actuator design for multi-functional applications in soft robotics. *Soft Robotics*, 11(4), 709-723.
27. Sarker, A., Ul Islam, T., & Islam, M. R. (2024). A Review on Recent Trends of Bioinspired Soft Robotics: Actuators, Control Methods, Materials Selection, Sensors, Challenges, and Future Prospects. *Advanced Intelligent Systems*, 2400414.
28. Li, H., Yi, X., Zhang, Z., & Chen, Y. (2024). Magnetic-controlled microrobot: Real-time detection and tracking through deep learning approaches. *Micromachines*, 15(6), 756.
29. Gao, Y., Wang, X., & Chen, Y. (2024). Light-driven soft microrobots based on hydrogels and LCEs: development and prospects. *RSC advances*, 14(20), 14278-14288.
30. Kumar, P. P. P., & Lim, D. K. (2023). Photothermal effect of gold nanoparticles as a nanomedicine for diagnosis and therapeutics. *Pharmaceutics*, 15(9), 2349.