

Soft Robotics & Bio-Inspired Actuators

Priya K. Sinha¹, Ashutosh Kulkarni², Javed Akhatar³

Associate Professor¹, Students^{2,3}

Department of Mechanical Engineering

Rungta College of Engineering & Technology

Email ID: Priyak12singh@yahoo.com¹, kulkarniashutosh18@gmail.com², javedak127@rediffmail.com³

DOI: <https://doi.org/10.5281/zenodo.19756158>

ABSTRACT

Soft robotics and bio-inspired actuators are rapidly growing areas that aim to mimic living organisms' flexibility and adaptive properties. Unlike traditional rigid robotics, soft robotics employs compliant materials such as elastomers, gels, and smart polymers to generate motion and force. Bio-inspired actuators take cues from nature—muscle tissues, octopus arms, plant movements—to overcome limitations in adaptability, safety, and dexterity. This review summarizes the current state of research in soft robotics and bio-inspired actuation, highlighting key material technologies, actuation mechanisms, control strategies, and applications in sectors such as medicine, manufacturing, and exploration. Challenges and future directions are discussed, especially in material fatigue, precise control, and large-scale implementation. The paper concludes with critical insights into how multi-disciplinary approaches can accelerate real-world applications of soft robotic systems.

KEYWORDS: *Soft robotics, bio-inspired actuators, compliant materials, adaptive systems, actuation mechanisms, soft sensors, soft manipulation.*

INTRODUCTION

Over the past decade, robotics has evolved from rigid metal structures to systems that incorporate deformable and flexible components. This shift was mainly driven by challenges that conventional robots face in unstructured environments, particularly where direct human interaction or delicate manipulation tasks are required. Soft robotics is a branch of this new paradigm that uses compliant materials to create machines capable of smooth deformation and

continuous motions.

Bio-inspiration, on the other hand, refers to the design philosophy of learning from natural systems to develop innovative technologies. In nature, actuation and motion are often achieved without rigid linkages or traditional motors; instead, muscular hydrostats (like elephant trunks), cellular osmotic changes (like plant movements), and soft tissue elasticity are exploited to great effect. Soft robotics and bio-inspired actuators are therefore inherently connected, as they both aim to achieve adaptability, safety, and functional robustness.

In this paper, we explore the foundations of soft robotics, classify various actuation schemes inspired by biological systems, evaluate materials and sensors, and consider applications that benefit from these approaches.

HISTORICAL BACKGROUND AND MOTIVATION

The early development of robotics during the mid-20th century was strongly influenced by the needs of industrial automation. Robots were primarily designed as **rigid, metallic manipulators** capable of performing repetitive tasks such as welding, painting, and assembly with high precision and speed. These machines operated in structured factory environments where every movement was predefined and optimized for efficiency. Safety concerns were addressed by **physically separating humans and robots** using cages and barriers, because the robots' rigid joints and powerful motors posed serious risks during accidental contact.

While this approach was effective for manufacturing, it revealed significant limitations when researchers began exploring robots for **human-centered environments** such as hospitals, homes, and rehabilitation centers. Rigid robots lacked the compliance needed to safely interact with delicate objects or human bodies. Even minor positioning errors could lead to damage or injury. Additionally, traditional robots were poorly suited for navigating **unstructured environments** where terrain, obstacles, and object shapes vary unpredictably.

This gap led researchers to rethink the fundamental design philosophy of robots. Instead of focusing solely on precision and rigidity, attention turned toward **flexibility, adaptability, and safety**. This shift was made possible by advances in **materials science**, particularly the development of highly elastic polymers, gels, and smart materials capable of large deformation.

At the same time, progress in **biomechanics and biological studies** provided valuable insights into how living organisms achieve complex motion without rigid skeletons or motors. The merging of these disciplines laid the foundation for what is now known as **soft robotics**.

The motivation for **bio-inspired actuation** came directly from observing nature's efficient solutions to movement and manipulation. Many organisms perform tasks that are extremely difficult for rigid robots:

- An **octopus** can twist, elongate, and compress its arms to pass through tiny openings, all without bones.
- An **earthworm** moves forward through soil using peristaltic waves of muscle contraction, adapting to irregular surfaces.
- **Elephant trunks** and **human tongues** operate as muscular hydrostats, capable of delicate grasping and powerful lifting without rigid support.
- Certain **plants** move using changes in internal fluid pressure (turgor pressure), demonstrating actuation without muscles at all.

These biological systems share a common characteristic: they rely on **continuous deformation** rather than discrete joints. Movement is smooth, adaptable, and inherently safe when interacting with surroundings. Engineers realized that by mimicking these principles using soft materials and fluidic or electrically responsive actuation, robots could achieve a level of versatility that rigid mechanisms cannot provide.

Thus, soft robotics emerged not merely as a new type of robot, but as a **paradigm shift** in how motion, force, and interaction are conceptualized in engineered systems. The goal changed from building stronger and faster machines to creating systems that are **compliant, resilient, and capable of operating**

MATERIALS FOR SOFT ROBOTICS

Materials are the foundation of soft robotics. Unlike conventional robots built from steel, aluminum, and rigid plastics, soft robots depend on **highly compliant materials** that can undergo large deformation while still returning to their original shape. The choice of material directly affects flexibility, strength, response time, durability, and the type of actuation that can be achieved. Because of this, material science plays a central role in the design of soft robotic

systems.

Soft robotic materials must generally satisfy a few important requirements: **elasticity, fatigue resistance, light weight, biocompatibility (in medical uses), and ease of fabrication**. Researchers often combine multiple materials in layered or embedded structures to achieve desired properties.

1. Elastomers and Silicone Rubbers

Elastomers are the most widely used materials in soft robotics. Silicone rubbers such as **Ecoflex, Dragon Skin, and PDMS (Polydimethylsiloxane)** are popular because they offer:

- High stretchability (can extend several times their length)
- Excellent flexibility and recovery
- Ease of casting into molds or 3D printing
- Chemical stability and biocompatibility

These materials are ideal for creating **soft grippers, artificial fingers, and flexible chambers** used in pneumatic actuation. Their transparency also allows visual inspection of embedded channels or sensors. However, elastomers generally have **low load-bearing capacity** and can tear under excessive stress, limiting their use in heavy-duty tasks.

2. Hydrogels

Hydrogels are networks of polymer chains that can absorb large amounts of water. They are extremely soft and can undergo **significant volume changes** when exposed to environmental stimuli such as:

- Humidity
- Temperature
- pH changes
- Electric fields

This swelling and shrinking behavior makes hydrogels suitable for **stimuli-responsive actuators** inspired by plant movements. In medical robotics, hydrogels are valuable due to their **tissue-like softness and biocompatibility**. For example, hydrogel-based actuators can be

used in drug delivery systems or minimally invasive surgical devices.

The drawback is that hydrogels usually respond **slowly** and may suffer from dehydration over time, which affects long-term reliability.

3. Shape Memory Alloys (SMAs)

Shape Memory Alloys, such as **Nitinol (Nickel-Titanium alloy)**, are metals that return to a predefined shape when heated. Although they are metallic, they are used in soft robotics as embedded actuation elements because they can produce **large force with small size**.

When electric current passes through SMA wires, they heat up and contract, creating motion similar to muscle fibers. SMAs are often embedded inside elastomer bodies to create **bio-inspired muscle-like actuators**.

Advantages include:

- High actuation force
- Compact size
- Silent operation

Limitations include:

- Slow cooling time (limits speed)
- High energy consumption
- Fatigue after repeated heating cycles

4. Dielectric Elastomers

Dielectric elastomers are smart polymers that deform when subjected to high voltage electric fields. They consist of a soft elastomer film placed between two compliant electrodes. When voltage is applied, electrostatic forces compress the thickness and expand the surface area, causing motion.

These materials are attractive for soft robotics because they offer:

- Very large strain (over 100%)
- Fast response time
- Lightweight structure

They are often referred to as **artificial muscles** due to their similarity to biological muscle movement. However, they require **high voltages**, which can be challenging for portable and safe operation.

5. Pneumatic Networks (PneuNets)

PneuNets are not a material by themselves but a **design strategy** used with elastomers. Internal air channels are molded into silicone structures. When air is pumped into these channels, uneven expansion causes bending or twisting motions.

This approach is one of the most common in soft robotics because:

- It is simple to design and fabricate
- Produces large and controllable deformations
- Is relatively low cost

PneuNets are widely used in soft grippers, crawling robots, and bending actuators. The main disadvantage is the need for **external air pumps or compressors**, which reduce portability.

Table 1: Common Soft Robotic Materials and Properties

Material Type	Key Benefits	Limitations	Typical Use Cases
Elastomers	High stretchability	Limited load-bearing	Soft grippers
Hydrogels	Biocompatible, large swelling	Slow response	Medical robots
SMA	High actuation stress	Heating required, slow	Bio-actuators
Dielectric Elastomers	Large strain with voltage	High voltage needed	Fast actuators

Material Type	Key Benefits	Limitations	Typical Use Cases
Pneumatic Networks	Simple, high deformation	Bulky pumps	Soft limbs

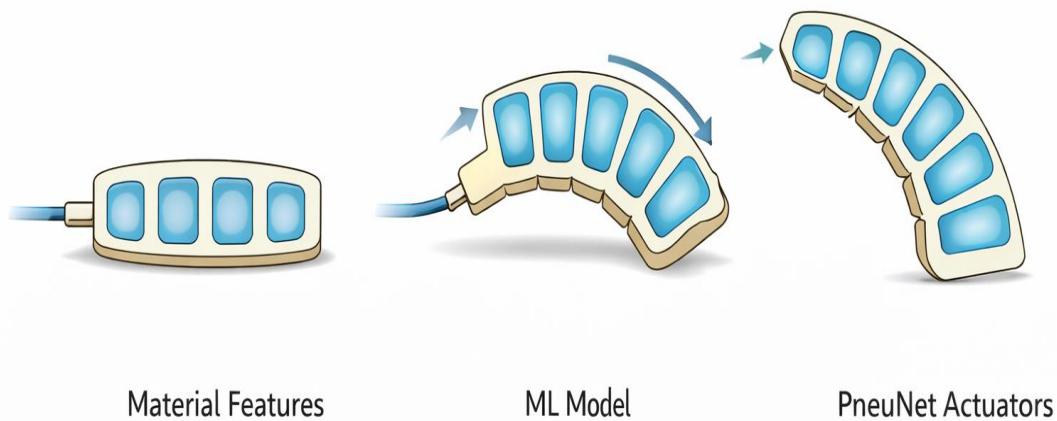


Figure 1: Illustration of PneuNet actuators showing multiple internal chambers that bend when pressurized.

BIO-INSPIRED ACTUATION MECHANISMS

Bio-inspired actuators aim to replicate biological motion:

1. Muscular Hydrostat Actuators

Muscular hydrostats (like octopus arms) use constant volume muscle groups oriented differently. Engineers have replicated this with soft structures containing internal fluid and contractile fibers. These actuators bend and extend without rigid skeletons.

2. Peristaltic Actuation

Seen in worms and digestive systems, peristalsis involves sequential contraction waves. Soft robotic segments inflate in sequence to generate locomotion. This is common in soft crawlers used for inspection in constrained environments.

3. Osmotic and Stimuli-Responsive Actuation

Plants often move using turgor pressure changes. Hydrogels that respond to humidity, pH, light,

or temperature have been used to replicate slow but large deformation motions.

4. Electroactive Polymer Actuators

These include dielectric elastomers and ionic polymer-metal composites that deform when electrically stimulated. They often offer faster response than fluidic systems.

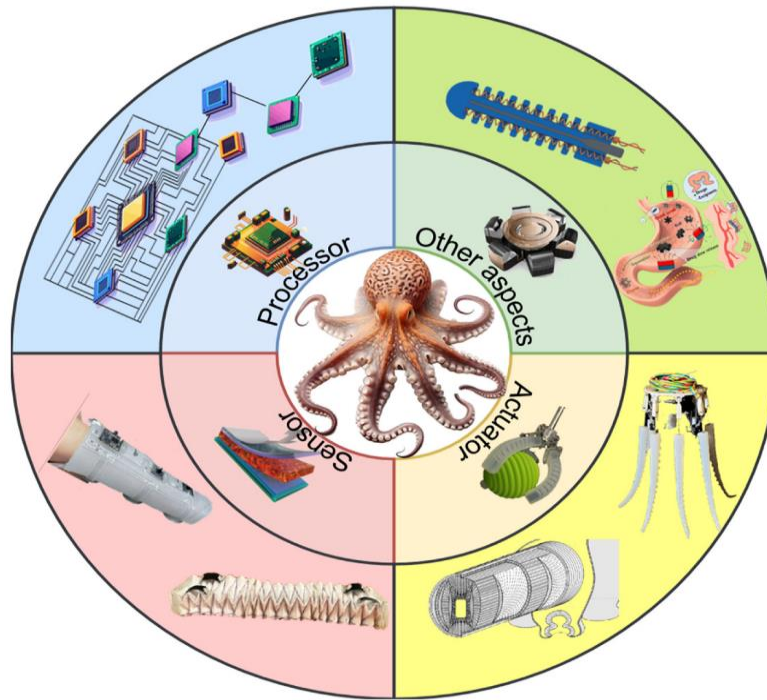


Figure 2: Comparison of biological actuation (e.g., octopus arm) and soft robotic analogs with internal fluid chambers.

SENSING AND FEEDBACK IN SOFT SYSTEMS

For meaningful interaction with the environment, soft robots require specialized sensing:

- **Stretch Sensors:** Embedded resistive or capacitive sensors measure deformation.
- **Pressure Sensors:** Detect contact forces to enable safe gripping.
- **Embedded Soft Electronics:** Flexible circuits allow signal transmission without compromising compliance.

Integration of sensors in soft materials is non-trivial, as rigid electronics can create stress concentrations. Some designs use liquid metal circuits in microchannels or conductive yarn stitched through fabric-like elastomers.

CONTROL STRATEGIES

Controlling soft robots is challenging due to their infinite degrees of freedom:

- **Model-based Control:** Uses mathematical models of continuum structures; often computationally heavy.
- **Learning-based Control:** Machine learning (ML) methods map inputs to desired motion without explicit models.
- **Hybrid Control:** Combines simplified physics with ML for faster real-time control.

A difficulty is that soft materials show hysteresis and non-linear response, which makes traditional PID controllers less effective.

APPLICATIONS

Soft robotics and bio-inspired actuators have many promising uses:

1. Medical and Rehabilitation Devices

Soft exosuits can assist patients with limited mobility without restricting comfort. Soft surgical tools navigate delicate tissues without damage.

2. Grippers for Delicate Manipulation

Soft grippers inspired by octopus suckers and human hands can gently pick fruits, fragile electronics, or irregular objects.

3. Exploration and Inspection

Soft crawlers adapt to uneven terrain in disaster zones, underwater environments, or narrow pipes.

4. Wearable Assistive Technology

Soft actuators can create haptic garments for rehabilitation or virtual reality feedback.

Table 2: Key Application Domains

Application Area	Benefits	Challenges
Medical Robotics	Safety, adaptability	Sterilization & durability
Industrial Manipulation	Gentle handling	Integration with automation
Search & Rescue	Navigation in complex terrain	Robustness in harsh conditions

Application Area	Benefits	Challenges
Wearables	Comfort, light weight	Power & control integration

CASE STUDIES

1. Soft Gripper for Fragile Objects

A research team developed a pneumatically actuated soft gripper with three fingers. Each finger had PneuNet chambers; by individually controlling pressure, it could conform to objects of varied shape. The gripper lifted fruits, delicate glassware, and even eggs without damage. Control was achieved with open-loop pressure commands and simple feedback from pressure sensors.

2. Octopus-like Arm with Hydrostatic Actuation

Another prototype mimicked an octopus arm with fluidic chambers oriented longitudinally and transversely. By adjusting fluid volumes in these chambers, the arm could bend, elongate, and twist. The arm was controlled using reinforcement learning, enabling it to reach targets in cluttered spaces.

CHALLENGES AND OPEN PROBLEMS

Although soft robotics has made significant advances, several issues remain:

1. Material Durability

Soft materials suffer from fatigue, tearing, and creep. Repeated use can degrade performance rapidly, especially in demanding environments.

2. Complex Control

Accurate control of soft bodies with many degrees of freedom remains a tough problem. Real-time control algorithms are still under development.

3. Integration with Traditional Systems

Often, soft components need to work with rigid elements (sensors, pumps, batteries). Seamless integration without losing compliance is difficult.

4. Power and Portability

Soft robots that rely on pneumatics require heavy pumps or compressors. Reducing the weight and size of power systems is necessary for mobile applications.

FUTURE DIRECTIONS

Promising future research includes:

- **Multi-functional Materials:** Combining sensing, actuation and self-healing properties in one material.
- **Biohybrid Robots:** Integrating living cells with soft structures to achieve autonomous growth and repair.
- **Advanced Manufacturing:** 3D printing of multi-material soft systems for better performance.
- **Adaptive Control:** AI-driven control systems that learn in real time and adjust actuation strategies.

CONCLUSION

Soft robotics and bio-inspired actuators represent a transformative shift in robotic design, from rigid and predetermined movements toward systems that mimic nature's adaptability and resilience. With advancements in materials, actuation mechanisms, and control strategies, soft robotics is gradually overcoming existing challenges. Broader adoption in healthcare, industry, and exploration is becoming feasible. However, durability, control complexity, and energy sources still limit widespread deployment. A multidisciplinary approach that combines biology, materials science, control theory, and machine learning will be crucial to fully realize the potential of soft robotic systems. Ongoing research should focus on integrating multiple functionalities into soft structures while ensuring reliability and scalability.

REFERENCES

1. Shepherd, R. F., et al. "Soft Robotics: A Bio-Inspired Evolution in Robotics." *Advanced Materials*, 2016.
2. Kim, S., et al. "Bio-Inspired Soft Actuators for Robots." *Journal of Soft Robotics*, 2018.
3. Laschi, C., et al. "Design and Control of Soft Robotics Systems." *IEEE Transactions on Robotics*, 2017.
4. Majidi, C. "Soft-Material Engineering for Soft Robotics." *Advanced Materials Technologies*, 2019.
5. Rus, D. & Tolley, M. T. "Design, Fabrication, and Control of Soft Robots." *Nature*, 2015.
6. Ilievski, F., et al. "Pneumatic Networks for Soft Actuation." *Science Robotics*, 2019.

7. Tolley, M. T., et al. "A 3D-Printed Soft Actuator Mechanism." *Soft Matter Journal*, 2018.
8. Wang, T., et al. "Sensor-Integrated Soft Robotic Actuators." *Sensors and Actuators A: Physical*, 2020.
9. Cianchetti, M., et al. "Biomedical Applications of Soft Robotics." *Annual Review of Biomedical Engineering*, 2021.
10. Trivedi, D., Rahn, C. D., Kier, W. M., & Walker, I. D. "Soft Robotics: Biological Inspiration, State of the Art, and Future Research." *Applied Bionics and Biomechanics*, 2022.

Cite as:

Priya K. Sinha, Ashutosh Kulkarni, Javed Akhatar(2026). Soft Robotics & Bio-Inspired Actuators, Journal of Research in Mechanical Engineering and Applied Mechanics, 11(1), 53-64.

<https://doi.org/10.5281/zenodo.19756158>