# Soft Robotics: From Basic Technologies to Real-world Applications

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**Abstract.** Soft robotics has emerged as a revolutionary field that overcomes the limitations of traditional rigid robotics. While rigid robots are specialized for jobs that require high force, excellent precision, and high speed, they cannot handle delicate objects or adapt to unstructured environments. Soft robotics, on the other hand, is made of stretchable materials and can deform its shape to adapt to dynamic environments. This paper focuses on the key enabling technologies and application fields of soft robotics. In the technology section, the paper introduces new actuation methods, novel soft materials, and intelligent control systems for soft robotics. In the application section, this paper presents the application fields of soft robotics: manufacturing, medical, deepwater exploration, rescue, and environmental monitoring. Moreover, in the discussion section, this paper examines the limitations of soft robotics from both technological and cost perspectives. The paper then provides a roadmap for future soft robotics research based on what scientists are currently exploring.

**Keywords:** Soft robotics, Smart materials, Actuation systems, Bio-inspired design, Adaptive control.

## 1. Introduction

Rigid robotics are well known for their great force and precision. Nowadays, rigid robotics is indispensable in manufacturing. That said, traditional rigid robots still encounter multiple limitations in practice. First, rigid robotics is inflexible; they are strictly coded to perform specific tasks. This property makes them difficult to work in an unstructured environment. Moreover, their high stiffness makes them dangerous for jobs that require handling delicate objects [1].

Nowadays, soft robotics has emerged as a solution to these challenges. Soft robots are typically made of stretchable materials and actuators that can interact with the natural world. Moreover, soft robotics' bio-inspired mechanism and embedded sensing technology make them tolerant to low accuracy, low speed, and low force applications. All these properties make soft robots adaptive to unknown dynamic environments and capable of manipulating fragile objects.

Soft robots are applied in many fields. Despite their typical applications in manufacturing and surgery, soft robots are also used in previously inaccessible areas, including pipe actuation, wearable rehabilitation devices, deep-sea exploration, and urgent rescue [2].

This paper provides an overview of soft robotics' current status, and it is split into two parts. In the first part, the paper discusses the key technologies that enable soft robotics to function. In the second part, the paper discusses the application fields of soft robotics. The paper does not discuss any topics in depth; instead, it provides a wide-ranging introduction to soft robotics.

## 2. Key Enabling Technologies

### 2.1. Advanced Actuation Technology

### 2.1.1. Pneumatic-based Soft Actuator

An external compressed air supply powers conventional pneumatic actuators via hoses. It can only generate rigid motion and thus lacks flexibility. Pneumatic-based soft actuators, on the other hand, demonstrate strong flexibility [3].

A pneumatic-based soft actuator is composed of stretchable materials, such as silicone rubber. It has an elastomeric network of small chambers; all these chambers are connected to a central region where a chemical reaction occurs. When an internal chemical reaction occurs, the fluid turns to gas, inflating the chambers [4]. As a result, the inflated chambers can stretch the skin of soft robots and produce movements. For example, Harvard University uses a pneumatic-based soft actuator in its design of a bio-inspired octopus. The octopus has hydrogen peroxide inside its body. Once hydrogen peroxide flows through the platinum, a chemical reaction begins, generating oxygen. The octopus uses soft microfluidic logic circuits composed of microchannels and valves to direct gas into specific chambers, producing movements [5, 6].

#### 2.1.2. Hydraulic Actuators

The core principle of hydraulic actuators is Pascal's law. When a pump pressurizes the hydraulic fluid, the fluid is directed to the actuators through tubes. McKibben Muscle (MM), a type of artificial muscle, uses hydraulic actuators. The McKibben muscle consists of two main parts: the inner bladder and the outer sheath. The inner bladder is a flexible rubber that contains hydraulic fluid, and the outer sheath is a tubular inextensible fiber surrounding the bladder [7]. When hydraulic fluid is pumped into the bladder and pressurized, the internal pressure causes the bladder to try to expand radially. The outer sheath, with its fixed length, shortens as it expands. That's how the hydraulic actuator mimics the contraction and relaxation of real muscles.

#### 2.1.3. Electroactive Polymers (EAPs)

There are two types of EAPs, dielectric elastomers and ionic EAPs. Structurally, dielectric elastomers consist of a thin elastomeric dielectric film sandwiched between two compliant electrodes. When an external electric field is applied, the film is squeezed by electrostatic forces, thereby expanding. Different from dielectric elastomers, ionic EAPs' deformation is caused by the mobility or diffusion of ions. When a voltage is applied, ions in an electrolyte move to the oppositely charged electrode and accumulate there. The ion-rich side increases in volume, and the ion-deficient side contracts and loses volume. The resulting asymmetric stress gradient across the material's thickness forces the strip to bend. As time goes on, this accumulation of ions creates a diffusive force that acts to move the ions back to the middle or opposite side, counteracting the initial bending [8].

### 2.2. Novel Soft Materials

#### 2.2.1. Liquid Crystal Elastomers (LCEs)

LCEs are materials that can change shape when heated, exposed to light, or exposed to an electric field [9].

The chemical structure of LCEs is a lightly cross-linked polymer network with embedded liquid-crystalline units, called mesogens. Mesogens are molecules that possess anisotropy and align along a common axis; polymer backbones are polymer chains that form the material's network; they are elastic and flexible; cross-links are covalent bonds that connect the polymer chains. Because of the low density of cross-links, the material can easily maintain its elastomeric nature.

When LCEs are heated over their liquid crystal-to-isotropic transition temperature, the mesogens lose their anisotropy and become randomly oriented. The polymer chains, without being stretched by the aligned mesogens, can now relax back to their preferred random-coil conformation. This relaxation causes a contraction along the original direction of the mesogens' alignment and a corresponding expansion perpendicular to it.

LCEs can also be actuated by light if photo-response molecules like azobenzene are added to the LCE network. When LCEs are irradiated with an appropriate wavelength of light, mesogens such as azobenzene undergo a reversible shape change, leading to the same polymer chain relaxation and contraction as thermal actuation.

LCEs can also be actuated by a strong electric field. A strong electric field can exert a torque on mesogens, causing them to reorient. This reorientation results in a macroscopic shape change.

#### 2.2.2. Magnetorheological Elastomers (MREs)

MREs are mainly composed of an elastomer matrix (like silicone) with magnetizable particles embedded. Once an external magnetic field is applied, magnetic particles become polarized, leading to an interparticle force. This attractive force makes the material stiffer. The strength of the magnetic field determines the material's stiffness [10].

#### 2.2.3. Shape-Memory Polymers (SMPs)

SMPs have a dual-component molecular structure — a fixed phase and a soft phase. The fixed phase acts like the SMPs' memory, maintaining their permanent shape. The soft phase is responsible for keeping the SMPs' temporary shape; it must be sensitive to stimuli such as light and heat [10].

The shape memory effect occurs through a two-step process called programming and recovery. In the programming step, SMPs are heated above their switching temperature to allow easy deformation. Then, mechanical stress is applied to the SMPs to deform them into their temporary shape, generating elastic energy. Finally, the SMPs are cooled, and the elastic energy is locked.

In the recovery step, the SMPs receive an external stimulus that raises their temperature above their switching temperature, making them soft again. The elastic energy is therefore released, pulling the SMPs back to their initial shape.

### 2.3. Intelligent Control Systems

#### 2.3.1. Reinforcement Learning (RL)

Soft robotics learn by directly interacting with the environment and accumulating data. For example, if a robot adjusts its actuator inputs (e.g., pressure, voltage) and produces a desirable output (e.g., a gesture, a shape), it receives a reward of +1. The accumulation of rewards can teach the robot the relation between actuation inputs and resulting robot behaviors. As a result, without using a model as an instruction, the robot can act based on its data [8].

#### 2.3.2. Distributed Control Systems

Each segment of soft robotics has its own sensor, and the sensors typically communicate only with their nearby neighbors, minimizing wiring. The advantage of a distributed control system becomes apparent as the robot becomes longer and more complex. This is because a decentralized structure can reduce communication and thus save power. Moreover, when a small part of a decentralized system fails, the rest can still function without being affected [6].

## 3. Application field

### 3.1. Manufacturing Automation

Manufacturing automation often adopts soft grippers. Soft grippers are often made from materials such as silicone and elastomers. Therefore, the grippers can readily deform to grasp objects of various shapes. Moreover, soft grippers often incorporate stiff mechanisms, such as embedded air chambers or pneumatic actuators. This feature enables them to grasp different objects with varying stiffness levels based on their fragility, minimizing the risk of damaging delicate items.

Soft grippers are emerging as an alternative to the human hand for farmers harvesting fruit and vegetables. This is because soft grippers can harvest fruit and vegetables efficiently without damaging them. For example, Companies like Mifood and MTC have already deployed soft grippers, especially for strawberry packaging. Human hands can easily damage strawberries, and the damage would not be visible immediately. In contrast, soft grippers avoid such damage.

### 3.2. Medical and Healthcare

#### 3.2.1. Soft RRobotic Endoscopes

First, the deformability of soft robotic endoscopes makes them suitable for navigating through the digestive system without damaging tissue. Moreover, if they are integrated with tactile sensors, they can perform tissue palpation, which helps diagnose non-polypoid tissues, as healthy tissues are softer than cancerous tissues.

Second, soft robotic arms equipped with soft endoscopes and a suction cup can be used in surgery to help the doctor manipulate the targeted tissue. Once the endoscopes locate the tissue, the suction cup can help hold it in place.

#### 3.2.2. Soft Robotic Exosuits

Soft exosuits are designed to help paralyzed people move again. For example, soft robotic gloves are widely used by people who have experienced a stroke and have lost grip strength. Soft robotic gloves can use healthy people's hands as templates and guide patients in moving their hands.

### 3.3. Deepwater Exploration

Soft robotics used for underwater applications can withstand high pressure due to their high compliance. Marine creatures, such as octopuses, inspire them. When under pressure or in tight spaces, they can change shape to adapt. For example, soft robotic grippers can dive down to 1000 meters underwater. They can use pneumatic artificial muscles for precise control to collect delicate sea creatures. Moreover, the pneumatic artificial muscles can also be used to explore underwater historical sites and collect artifacts.

### 3.4. Search and Rescue

#### 3.4.1. Vine Robots

The vine robotics' growing mechanism allows them to travel through narrow and twisted slits by expanding their body length without creating friction with the slits. The robot's internal pressure actuates this growing mechanism, and the robot controls its growing direction by controlling the chambers along its body (e.g., if the chamber on the left of the robot is inflated, the robot will turn right).

Nowadays, if a building collapses, it can trap some victims. In that case, rescue personnel need first to use cameras or other detection devices to identify spatial pockets within the pile of collapsed material before they enter the building. However, these tools are challenging to use in tortuous spaces, and they must operate for several hours while the victims remain in danger. As a result, the vine robots are designed as a new tool for rescue personnel. Vine robots can navigate through 3D space and use the camera installed at their tips to record their surroundings. The recording can help the personnel plan the rescue route.

#### 3.4.2. Magnetically Actuated Micro-robots

Those magnetically actuated micro-robots are composed of magnetic materials. An applied magnetic field remotely controls them. The field can cause them to bend, twist, and crawl.

Nowadays, researchers at Penn State have developed this type of magnetically controlled robot to search for trapped victims amid earthquake rubble.

### 3.5. Environmental Monitoring

The paper-seed project published a soft robot called Acer paper-seed. This robot is inspired by the Acer campestre seed, which can be dispersed by wind over long distances after detaching from the tree. Acer paper-seed has a shape similar to that of an Acer campestre seed, and it is made from biocompatible materials. Once drones disperse the Acer paper-seed robots, they can use the wind to travel and cover a large area. After a short period, they will be decomposed by the environment. The Acer paper-seed's function is to monitor soil temperature by becoming luminescent. The researchers are also considering adding fluorescent particles sensitive to humidity or CO2 levels into the robot in the future.

## 4. Results

By examining innovations in actuation, materials, and control systems, this paper provides an overview of the key enabling technologies underpinning soft robotics. First, pneumatic and hydraulic actuators allow soft robots to perform controllable deformation, and electroactive polymers enable soft robotics to achieve electrically driven motion. Second, novel materials such as liquid crystal elastomers, magnetorheological elastomers, and shape-memory polymers enable soft robotics to be sensitive to a range of environmental stimuli. Third, intelligent control systems, such as reinforcement learning and distributed systems, allow soft robotics to better adapt to the complex, dynamic world.

After discussing key technologies, the paper goes on to discuss the application fields of soft robotics. Nowadays, soft robotics is mainly applied in manufacturing, medical, rescue, exploration, and monitoring fields. Although soft robotics for rescue and exploration missions is still underdeveloped, projects like Acer paper-seed still demonstrate the strong potential of soft robotics.

## 5. Discussion

This paper demonstrates that soft robotics has excellent potential in manufacturing, exploration, and medical applications. However, the development of soft robotics still faces several challenges. First, and most importantly, soft robotics are difficult to model due to their infinite degrees of freedom. Therefore, it is hard to predict how soft materials will deform in response to a given command. Also, soft robotics can’t be controlled to perform tasks that require high precision. This limitation of precise control can challenge soft robotics applications in surgery and delicate assembly.

Second, soft materials (like silicones and elastomers) lack durability. Compared to metal and steel, soft materials are more flexible and cheaper. However, soft materials can’t sustain long-term operations as well as rigid robots do. Soft materials are susceptible to fatigue, tearing, and punctures. Moreover, because soft materials are soft, they can’t exert high force or operate at high speed, which further limits their industrial use.

Third, soft robotics' actuation systems are often not portable. The most common actuating method for soft robotics is to use fluidic power. This method requires connecting soft robotics with a heavy pump or compressor. This connection limits soft robotics’ mobility, rendering it unsuitable for exploration and rescue.

In conclusion, to maximize soft robotics’ potential in its application fields, scientists should focus on three objectives in the future: creating advanced control algorithms that enable precise control, creating durable soft materials, and inventing lightweight external actuation systems or developing an internal actuation method.

## 6. Conclusion

In conclusion, the rise of soft robotics represents a shift in the robotic world from rigid, precision-based systems to flexible, safe systems. Soft robotics can perform tasks that rigid robotics cannot, such as deep-sea exploration and rescue. Moreover, soft robotics enables safe manipulation in delicate assembly and surgery. In recent experiments, scientists are also using soft robotics for environmental monitoring.

However, soft robotics is still in development rather than in widespread use. This is because soft robotics lacks precise control, durable materials, and portable actuation systems. Those technological limitations, on the other hand, demonstrate the high potential of soft robotics. In the future, scientists should focus on developing advanced algorithms and inventing new soft materials and actuation systems.

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