

# Tactile Sensing Technologies in Robotics: A Review of Sensors, Materials, and Applications

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## Abstract

*Tactile sensing, which closely resembles the human sense of touch, is an essential capability in modern robotics. It enables robots to detect and interpret physical interactions with objects, surfaces, and living beings, thereby allowing them to operate more intelligently and adaptively in complex environments. Unlike visual or auditory sensors, tactile sensors provide direct feedback about contact, pressure, texture, force, temperature, and even vibration. These sensory cues are vital for improving the dexterity, safety, and precision of robotic systems, especially in tasks involving manipulation, exploration, and physical interaction. In recent years, there has been significant progress in the field of tactile sensing, driven by innovations in materials science, nanotechnology, and flexible electronics. Developments in artificial skin, soft and stretchable materials, and sensor miniaturization have opened up new possibilities for integrating tactile sensors into robotic hands, grippers, limbs, and even full-body robotic platforms. These advancements have made tactile sensing more reliable, compact, and energy-efficient, making it feasible to deploy in both industrial and service-oriented robotics. This review article provides a comprehensive overview of the current landscape of tactile sensing technologies. It focuses on various sensor types—such as capacitive, piezoresistive, piezoelectric, optical, and magnetic sensors—and evaluates their principles of operation, benefits, and limitations. In addition, the review explores a wide range of materials used in sensor design, from conventional polymers and conductive composites to emerging smart materials like hydrogels and piezoelectric polymers.*

**Keywords:** Tactile sensors, capacitive sensing, piezoresistive materials, artificial skin, human-robot interaction, flexible electronics, robotic manipulation

## INTRODUCTION

Tactile sensing is a cornerstone of advanced robotics, particularly in scenarios where physical interaction with the environment is necessary. In contrast to vision and auditory sensors, which operate at a distance and interpret external stimuli through light and sound, tactile sensors operate through direct contact. They provide crucial real-time feedback regarding parameters such as force, pressure, vibration, temperature, and texture. These sensory inputs allow robotic systems to understand their surroundings more intuitively and respond precisely. As robots are increasingly being deployed in dynamic and unstructured environments, the role of tactile sensing has become more vital.

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One of the primary motivations for developing tactile sensing technologies is to replicate the functionality of the human skin, which is capable of detecting a wide range of stimuli with remarkable accuracy and spatial resolution. Human skin senses touch and enables adaptive and protective responses. Translating this sensory capability into robotic systems opens the door to more dexterous,

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responsive, and intelligent machines capable of performing complex tasks, such as grasping delicate objects, navigating tight spaces, or interacting safely with humans.

Modern robotic systems are used in a variety of sectors, including healthcare, manufacturing, agriculture, logistics, and even domestic settings. The ability to interact safely and effectively with objects and people is a critical requirement in these domains. For instance, in surgical robotics, tactile sensors enable tools to detect tissue stiffness, thereby improving the surgical outcomes. In assistive and prosthetic devices, tactile feedback provides users with a natural and intuitive control experience. Similarly, in industrial automation, tactile sensors help robotic arms adjust their grip dynamically based on an object's shape, weight, or texture [1].

In recent years, significant progress has been made in the development of tactile sensing technologies, largely fueled by advances in materials science, microfabrication, and flexible electronics. Sensors are smaller, more durable, and more adaptable than ever before. Innovations in soft materials such as stretchable polymers and conductive elastomers have enabled the creation of electronic skins (e-skins) that can conform to curved surfaces and deform under stress without losing function. In addition, new sensor designs incorporate multimodal sensing, allowing for the simultaneous detection of pressure, temperature, and strain.

## **CLASSIFICATION OF TACTILE SENSORS**

Tactile sensors are typically classified according to their sensing mechanisms, signal output characteristics, and structural designs. Each type of sensor is optimized for specific applications based on factors such as sensitivity, range, form factor, cost, and compatibility with flexible or rigid substrates. This classification also reflects how mechanical stimuli are converted into electrical signals that can be interpreted using robotic systems. As robotic applications become more sophisticated, the choice of tactile sensing technology must align with the task precision, environmental conditions, and required response time. This section elaborates the key categories of tactile sensors commonly used in robotic systems, including capacitive, resistive, piezoelectric, piezoresistive, optical, and magnetic sensors. Each sensing principle has unique advantages and trade-offs that influence its suitability for specific scenarios, such as wearable devices, industrial automation, medical tools, and prosthetics. Understanding these distinctions is critical for researchers and engineers seeking to integrate tactile functionality into next-generation robotic platforms [2–4].

### **Capacitive Sensors**

Capacitive tactile sensors operate based on the principle of capacitance variation between conductive plates when an external force causes a mechanical deformation. These sensors typically consist of two conductive layers separated by a dielectric material. When pressure is applied, the distance between the plates changes, resulting in a measurable change in capacitance. Capacitive sensors are widely used for their high sensitivity, rapid response, and low energy consumption. Moreover, they can be fabricated on flexible substrates, making them ideal for applications requiring conformal contact, such as electronic skins, robotic fingers, and wearable systems. Capacitive sensors also support multitouch detection and spatial mapping when arranged in matrix arrays. However, they are susceptible to environmental noise, such as humidity and electromagnetic interference, which can affect their accuracy.

### **Resistive Sensors**

Resistive tactile sensors function by detecting changes in the electrical resistance caused by mechanical deformation, such as pressure or bending. These sensors usually consist of two or more layers with conductive elements that come into contact under pressure, thereby altering the resistance in the circuit. The simplicity of their structures makes resistive sensors highly attractive for low-cost and scalable applications. These are commonly used in pressure-sensitive pads, flexible touch panels, and basic robotic touch systems. Despite their affordability and ease of integration, resistive sensors

tend to suffer from limitations, such as low durability, signal drift, and hysteresis, especially under repeated or long-term loading. In addition, their responses can be affected by the temperature and surface contamination. To improve their performance, researchers have explored composite materials, layered structures, and printed electronics approaches. Although not as sensitive or accurate as other tactile sensor types, resistive sensors continue to play a vital role in applications where cost constraints and moderate sensitivity are acceptable [5].

### **Piezoelectric Sensors**

Piezoelectric sensors exploit the intrinsic properties of certain materials that generate electrical charge when subjected to mechanical stress. These materials, such as quartz, lead zirconate titanate (PZT), and polyvinylidene fluoride (PVDF), enable high-frequency responses, making piezoelectric sensors ideal for detecting dynamic forces, vibrations, and rapid pressure changes. These sensors are particularly valuable in applications requiring fast, transient measurements, such as slip detection in robotic grippers or impact sensing in wearable electronics. Unlike resistive or capacitive sensors, piezoelectric sensors do not require an external power source for signal generation, which makes them energy-efficient and suitable for remote or portable systems. However, a key limitation is their inability to effectively measure static or low-frequency forces as their signal decays over time. Integration into flexible systems can also be challenging because of the brittle nature of traditional piezoelectric ceramics. Ongoing research on flexible piezoelectric polymers aims to overcome these limitations, paving the way for a broader deployment in soft robotic systems.

### **Piezoresistive Sensors**

Piezoresistive tactile sensors are based on materials that exhibit a change in electrical resistance when a mechanical strain or pressure is applied. This effect is distinct from that of purely resistive sensors in that the resistance change is a function of internal material deformation rather than just surface contact. These sensors can be fabricated using silicon-based materials or flexible composites infused with conductive particles such as carbon nanotubes (CNTs), graphene, or metallic nanoparticles. Their excellent compatibility with microelectromechanical systems (MEMS) and flexible substrates makes them ideal for integration into high-resolution tactile arrays and artificial skin systems. Piezoresistive sensors are known for their simplicity, high sensitivity, and ability to detect both static and dynamic pressure. However, they may exhibit temperature sensitivity and require careful calibration to ensure accurate signals. Recent research has focused on developing self-healing and stretchable piezoresistive materials to enhance durability and function in complex robotic environments. Their versatility makes them one of the most widely adopted tactile sensing technologies [6].

### **Optical and Fiber Bragg Grating Sensors**

Optical tactile sensors detect changes in light properties, such as intensity, phase, or wavelength, resulting from mechanical deformation. A popular subtype, Fiber Bragg Grating (FBG) sensors, uses periodic variations in the refractive index within optical fibers to reflect specific wavelengths. When mechanical strain is applied to the fiber, these wavelengths shift, providing a precise and linear measure of the pressure or deformation. One of the major advantages of optical and FBG sensors is their immunity to electromagnetic interference, which makes them ideal for medical applications, MRI environments, and high-voltage settings. In addition, these sensors offer high sensitivity, multiplexing capabilities, and long-distance signal transmission without degradation. However, they can be complex and costly to manufacture and require sophisticated readout systems. Their integration into flexible and soft robotic systems is a growing area of research, particularly in prosthetics and wearable healthcare devices, where accurate and noise-free tactile data are crucial for user feedback and control.

### **Magnetic and Hall Effect Sensors**

Magnetic tactile sensors operate based on changes in the magnetic fields caused by physical displacement, pressure, or deformation. Hall effect sensors are a specific type of sensors that detect voltage differences across a conductor in the presence of a magnetic field. These sensors often consist

of a soft magnetic layer and an embedded magnet, with the deformation altering the magnetic field distribution, which is then measured by the sensor. Magnetic sensors are highly durable and resistant to environmental factors such as dust, moisture, and temperature changes. They are well-suited for applications requiring robust tactile feedback under harsh or variable conditions, such as industrial automation or heavy-duty robotic manipulation. Additionally, magnetic sensors can function through noncontact mechanisms, offering advantages in terms of sensor longevity and reduced wear [7–10].

## **MATERIALS FOR TACTILE SENSING**

Material selection plays a crucial role in the design and performance of tactile sensors. Material properties, such as elasticity, electrical conductivity, thermal stability, and biocompatibility, directly influence the sensitivity, response time, flexibility, and long-term durability of tactile sensing systems. Modern tactile sensors aim to mimic the versatility of human skin, which can detect minute changes in pressure, temperature, and strain. To achieve similar performance, researchers have explored a variety of materials, ranging from traditional polymers to cutting-edge smart materials. The integration of these materials into soft, stretchable, and lightweight substrates enables the development of next-generation tactile devices for wearable and robotic applications.

### **Polymers and Elastomers**

Polymers and elastomers form the backbone of many flexible tactile sensors because of their inherent mechanical flexibility, lightweight nature, and cost-effectiveness. Polydimethylsiloxane (PDMS), polyurethane (PU), and Ecoflex are the most widely used materials. In particular, PDMS is valued for its high elasticity, optical transparency, chemical inertness, and ease of fabrication. These materials often act as substrates, encapsulating layers, or dielectric spacers for capacitive and resistive tactile sensors. Their softness allows them to conform to curved surfaces or dynamic interfaces, which makes them ideal for robotic skins or wearable sensors [11].

### **Conductive Composites**

Conductive composites are engineered materials created by embedding conductive fillers, such as carbon nanotubes (CNTs), graphene, carbon black, or metallic nanoparticles, into flexible polymer matrices. These materials exhibit tunable electrical properties and are widely used in piezoresistive and capacitive tactile sensors. When subjected to external forces, the conductive network within the composite changes its resistance or capacitance, enabling the detection of pressure, bending, and strain. CNTs and graphene, owing to their exceptional electrical conductivity and high aspect ratio, allow for high sensitivity, even under low pressures.

### **Piezoelectric Polymers**

Piezoelectric polymers, such as polyvinylidene fluoride (PVDF) and its copolymers, are increasingly being used in tactile sensors because of their ability to convert mechanical energy into electrical signals. Unlike traditional rigid piezoelectric ceramics, these polymers are flexible, lightweight, and compatible with soft substrates, making them suitable for conformal and wearable applications. When mechanically deformed, the PVDF generates a voltage signal proportional to the applied pressure or strain. This feature is particularly useful in dynamic tactile sensing, where real-time feedback is needed, such as in robotic fingertips or motion-sensing wearables. PVDF also exhibits good chemical resistance and thermal stability, further enhancing its appeal in harsh environments [12].

### **Hydrogels**

Hydrogels are emerging as promising materials for tactile sensing applications, particularly in the biomedical and wearable domains. These soft, water-rich polymer networks exhibit mechanical properties similar to those of human tissues, making them ideal for skin-like or bio-integrated sensors. Their high stretchability and tunable viscoelasticity allow them to conform closely to surfaces and accommodate large deformations without structural failure. In addition, hydrogels can be engineered to possess ionic or electronic conductivity by incorporating salts, conductive polymers, or nanomaterials.

This makes them suitable for capacitive, resistive, or even hybrid tactile sensors capable of simultaneously detecting pressure, temperature, and strain [13, 14].

## FABRICATION STRATEGIES

The development of tactile sensors with high sensitivity, flexibility, and durability requires precise and scalable fabrication techniques. The key strategies that are commonly employed are as follows.

1. *Screen printing and inkjet printing*: These printing techniques are widely used for fabricating flexible tactile sensors, owing to their cost-effectiveness and compatibility with various substrates. Screen printing involves pushing conductive inks through patterned meshes onto surfaces that are suitable for batch production. Inkjet printing offers digital control and precise deposition, allowing rapid prototyping and customization. Both methods enable the production of large-area, lightweight, and stretchable sensors on flexible films that are ideal for wearable and robotic applications.
2. *Soft lithography*: Soft lithography uses elastomeric molds, typically made of PDMS, to replicate micro- and nanoscale patterns onto soft materials. It is particularly useful for creating microstructured surfaces that enhance the sensitivity and responsiveness of tactile sensors. This technique allows fine control over the geometry and pattern uniformity, making it ideal for fabricating sensors with a high spatial resolution. Soft lithography is compatible with diverse materials and is often used in combination with other processes to build multilayered tactile devices.
3. *3D printing*: Additive manufacturing (3D printing) is increasingly being used in tactile sensor fabrication owing to its design flexibility and rapid prototyping capabilities. This allows the layer-by-layer construction of complex sensor geometries, including embedded electronics and microchannels. Different materials, such as conductive inks and elastomers, can be co-printed to create integrated multifunctional sensors. 3D printing also supports personalized designs for specific robotic applications, such as prosthetic interfaces or customized grippers, with minimal material wastage and quick turnaround.
4. *Laser patterning*: Laser-based fabrication provides high precision for patterning conductive materials and cutting complex geometries. Techniques such as laser ablation, scribing, or sintering can directly modify the surface structure or conductivity of substrates without the need for masks or chemicals. This method enables fast and accurate production of micropatterns, which are ideal for creating sensor arrays or fine interconnects. Laser patterning is scalable and suitable for both prototyping and industrial-scale manufacturing of tactile sensors with complex designs.

## APPLICATIONS IN ROBOTICS

Tactile sensing technologies have become increasingly important in various robotic applications to enhance precision, safety, and adaptability.

1. *Prosthetics and assistive robotics*: Tactile sensors integrated into prosthetic limbs enable users to perceive touch, pressure, and grip forces. This sensory feedback improves motor control, allowing for more natural and intuitive movement. It also enhances the user's ability to safely interact with different objects and surfaces during daily activities.
2. *Human-robot interaction (HRI)*: In collaborative environments, tactile sensors enhance a robot's ability to detect human touch and respond safely. This promotes smoother and more intuitive interactions between humans and robots, reduces the risk of injury, and enables shared tasks, such as co-assembly or guided assistance in healthcare and service robotics.
3. *Industrial manipulators*: Tactile sensors embedded in robotic grippers allow them to dynamically adjust their grip based on the shape, texture, or fragility of an object. This results in more precise and adaptive handling of diverse items on assembly lines or packaging stations, thereby reducing damage and improving operational efficiency in manufacturing.
4. *Medical and surgical robots*: In minimally invasive procedures, tactile feedback helps surgeons sense subtle differences in tissue properties such as stiffness or texture. This capability enhances precision, reduces tissue damage, and allows for better diagnostic and therapeutic outcomes, especially in delicate surgeries, such as neurosurgery or laparoscopic interventions.

5. *Autonomous systems*: Tactile sensors improve the autonomy of robots navigating unpredictable environments by detecting contact forces, slippage, or terrain irregularities. This sensory input allows robots to make real-time adjustments, ensuring stability, safe object handling, and improved performance in tasks such as search and rescue or planetary exploration.

## CHALLENGES AND FUTURE PROSPECTS

1. *Sensor integration and miniaturization*: Integrating tactile sensors into compact multifunctional robotic systems remains a challenge. Miniaturization without sacrificing sensitivity or durability requires innovative design and materials. Future progress will depend on creating seamless interfaces between sensors, electronics, and control units to enable highly responsive, lightweight, and energy-efficient tactile sensing solutions.
2. *Signal processing and data interpretation*: Extracting meaningful information from raw tactile data is complex because of the noise, variability, and high data volumes. Advanced algorithms and machine-learning techniques are required for real-time signal processing and interpretation. Enhancing data accuracy will improve the ability of robots to make autonomous decisions based on tactile feedback.
3. *Durability and reliability*: Robust tactile sensors must withstand repeated mechanical stress, environmental factors, and wear over long periods. Achieving consistent performance under harsh conditions, such as extreme temperatures or humidity, remains difficult. Research has focused on developing self-healing, fatigue-resistant materials to extend the lifespan of sensors.
4. *Scalability and manufacturing*: Producing tactile sensors at a scale while maintaining quality and affordability poses significant challenges. New fabrication methods must support the mass production of flexible and stretchable sensors with uniform performance. Advances in printable electronics and roll-to-roll processing are promising for large-scale manufacturing applications.
5. *Future trends and opportunities*: The future of tactile sensing lies in multifunctional multimodal sensors combining pressure, temperature, and chemical detection. Integration with AI and Internet of Things (IoT) will enable smarter context-aware robotic systems. Continued innovation will expand applications in healthcare, industry, and daily life, pushing the boundaries of human–robot interaction [15].

## CONCLUSION

Tactile sensing technology has revolutionized the field of robotics by providing machines with the ability to perceive and interact with their environment in a more nuanced and human-like manner. The development of diverse sensor types and advanced materials has significantly improved the sensitivity, flexibility, and durability of tactile sensors, thereby enabling their integration into a wide range of robotic applications. From prosthetics and human–robot interaction to industrial automation and medical robotics, tactile sensing enhances the functionality, safety, and adaptability of robotic systems. Despite considerable progress, challenges remain in areas such as sensor miniaturization, signal processing, long-term stability, and seamless integration with other sensory modalities. Future research should focus on novel materials, multimodal sensing, and artificial intelligence-driven signal interpretation to overcome these limitations. As tactile sensing technologies continue to advance, they will play an increasingly critical role in the development of intelligent, responsive, and autonomous robotic systems capable of performing complex tasks in dynamic, real-world environments.

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