

Sensor Technologies in Robotics: A Review of Vision, Tactile, and Proximity Sensing Systems

Prashant Roy^{1,*}

Abstract

Robotics has undergone remarkable advancements in recent decades, largely driven by the integration of cutting-edge sensor technologies. Sensors serve as crucial for allowing robots to precisely logic, interpret, and react to the world around them. Among the most essential sensor types used in robotics are vision sensors, tactile sensors, and proximity sensors. These technologies strengthen a robot's capacity for successful navigation, for example, object manipulation, and contact with people and other systems. Vision sensors, including cameras and light detection and ranging (LiDAR) systems, provide robots with the ability to recognize objects, detect motion, and interpret their surroundings through image processing and artificial intelligence techniques. Tactile sensors, on the other hand, mimic the human sense of touch, allowing robotic systems to detect force, texture, and pressure, which is particularly valuable in delicate handling tasks such as medical robotics and industrial automation. Proximity sensors, including ultrasonic and infrared sensors, enable collision avoidance, safe human-robot interaction, and efficient environmental mapping. Notwithstanding those advances, a number of obstacles still stand in the way of the creation and use of detection technologies in robots. Issues such as sensor accuracy, data processing speed, environmental adaptability, and integration with artificial intelligence continue to be active areas of research. Furthermore, ensuring the affordability and scalability of advanced sensors remains a key concern, especially for large-scale industrial and consumer applications. This review examines the latest innovations in vision, tactile, and proximity sensors and their impact on robotic performance. Additionally, it discusses emerging trends, such as sensor fusion, neuromorphic sensing, and artificial intelligence-driven perception systems, which have the potential to revolutionize the next generation of robotics. By addressing current challenges and exploring future research directions, this article highlights the essential role of sensor technology in advancing robotic capabilities across various domains.

Keywords: Sensor fusion, robotic perception, autonomous navigation, tactile feedback, multi-modal sensing, bio-inspired robotics

INTRODUCTION

Recent advances in the fields of artificial intelligence, machine learning, and sensor technologies have led to substantial advances in automated machinery. Sensors are crucial for activities such as navigation, recognizing objects, and environmental adaptability because they allow robots to observe and communicate about their environment. By collecting and processing data from their surroundings, sensors can help robots make informed decisions, execute precise movements, and respond dynamically to changing conditions.

*Author for Correspondence

Prashant Roy
E-mail: royprashant0007@gmail.com

¹M.Tech. Student, Department of Engineering, Banaras Hindu University, Varanasi, Uttar Pradesh, India

Received Date: May 19, 2025

Accepted Date: June 02, 2025

Published Date: June 10, 2025

Citation: Prashant Roy. Sensor Technologies in Robotics: A Review of Vision, Tactile, and Proximity Sensing Systems. International Journal of Robotics and Automation in Mechanics. 2025; 3(1): 31–37p.

Vision, tactile, and proximity sensors are among the most important categories of sensors used in robotics. Each of these technologies makes a

distinct contribution to improving the autonomy and practicality of a robot. Vision sensors, including cameras, depth sensors, and light detection and ranging (LiDAR) systems, enable robots to detect objects, interpret visual cues, and navigate complex environments. Applications in which precise visual perception is crucial, such as driverless cars, industrial automation, and medical devices, make extensive use of these cameras.

Inspired by the human sense of touch, tactile sensors enable robots to sense pressure, texture, and force when interacting with objects. These sensors are particularly beneficial in applications that require precision, such as robotic surgery, prosthetics, and advanced manufacturing. Tactile sensors improve dexterity and adaptability of robotic systems [1–3].

Proximity sensors, including ultrasonic, infrared, and capacitive sensors, help robots detect obstacles and measure distances without physical contact. These sensors enhance collision avoidance, improve navigation in dynamic environments, and enable safe human-robot interaction. Proximity sensors are widely used in mobile robotics, automated warehouses, and collaborative robotic systems to ensure efficiency and safety in various operational settings.

Despite the significant progress in sensor technology, several challenges remain. Sensor accuracy, response time, and environmental adaptability are the key areas of research. Factors such as lighting conditions, sensor noise, and interference can affect the performance of the vision and proximity sensors. Additionally, integrating multiple sensors into a cohesive robotic system presents computational and data processing challenges, necessitating advanced algorithms for sensor fusion and real-time decision-making.

This study provides an in-depth review of the latest advancements in vision, tactile, and proximity sensors, highlighting their role in modern robotics. It also examines emerging trends, such as neuromorphic sensing, bio-inspired sensor designs, and artificial intelligence-driven perception systems, which hold the potential to further enhance robotic autonomy and efficiency. By addressing the current limitations and exploring future research directions, this study underscores the importance of sensor technology in shaping the next generation of intelligent robotic systems.

VISION SENSORS

Vision sensors are fundamental to robotic perception, enabling machines to process visual data and interact with their environments. These sensors are vital for applications such as environmental mapping, navigation, and object identification. LiDAR systems, cameras, and depth sensors are common aesthetic sensors used in robotics. Each of these technologies makes a distinctive contribution to the improvement of robotic freedom and vision.

Computer-vision algorithms, such as RGB (Red, Green, Blue) and infrared devices, are used to assess pictures captured by cameras. They are extensively used in medical robotics, safety surveillance, and industrial automation. However, occlusion and light exposure can affect their operation [4].

Depth sensors, such as structured light and time-of-flight sensors, provide three-dimensional (3D) information about objects and environments. These sensors improve robotic navigation and object manipulation, particularly in cluttered environments.

LiDAR sensors generate high-resolution 3D maps by calculating the distances using laser beams. They are crucial for autonomous vehicles, precision agriculture, and robotic localization. Although highly accurate, LiDAR sensors are often more expensive than other vision technologies (Table 1).

Advancements in artificial intelligence (AI) and machine learning have significantly improved the efficiency of vision sensors, enabling real-time image processing and enhanced object recognition. As technology evolves, vision sensors will continue to drive innovation in robotics, expanding their capabilities across industries [5].

Table 1. Performance comparison of vision sensors.

Sensor type	Resolution	Depth perception	Response time	Cost	Applications
RGB Cameras	High	Low	Fast	Low	Industrial Automation, Security, Medical Robotics
Depth Sensors	Moderate	High	Moderate	Medium	Object Manipulation, Navigation
LiDAR	Very High	Very High	Fast	High	Autonomous Vehicles, Mapping, Precision Robotics

Table 2. Performance comparison of tactile sensors.

Sensor type	Sensitivity	Response time	Durability	Cost	Applications
Capacitive	High	Fast	Moderate	Medium	Prosthetics, Robotics Hands
Piezoelectric	Moderate	Fast	High	Medium	Industrial Robotics, Force Sensing
Optical	High	Moderate	High	High	Medical Robotics, Precision Grasping

TACTILE SENSORS

Because they allow machinery to detect pressure, texture, and contact with their surroundings in a manner akin to that of humans, tactile sensors are essential for chatbots. These sensors are fundamental to robotic grasping and object manipulation, making them indispensable in applications such as healthcare, industrial automation, and service robotics. By detecting forces and surface properties, tactile sensors enhance robotic dexterity, allowing safer and more precise interactions with objects and humans.

Various tactile sensing technologies are used in modern robotics, including capacitive-, piezoelectric-, and optical-based sensors. Owing to their high sensitivity and quick response speeds, capacitive tactile sensors are ideal for robotic hands and limbs because they detect changes in capacitance brought on by physical touch. When exposed to high temperatures or force, piezoelectric sensors produce an electrical charge, which allows them to measure force accurately but limits their capacity for detecting static pressure. Although they are sometimes more complicated and costly, optical tactile sensors provide high-resolution feedback using light-based detecting mechanisms [6].

Recent research has focused on integrating flexible and stretchable materials into tactile sensors to enable robots to achieve human-like adaptability. Soft robotics, electronic skin (e-skin), and bio-inspired designs have improved the ability of robotic systems to precisely handle delicate objects. Table 2 compares the key performance parameters of the different tactile sensors.

As advancements continue, future tactile sensors will become more flexible, durable, and capable of providing real-time haptic feedback, further improving robotic interactions with the physical world.

PROXIMITY SENSORS

Proximity sensors play a critical role in robotics by enabling machines to detect nearby objects without direct physical contact. These sensors are very helpful in autonomous devices and collaborative robots (cobots) because they are crucial for obstacle recognition, collision prevention, and safe routing. By providing real-time feedback, proximity sensors enable robots to operate efficiently in dynamic environments, ensuring safety during human-robot interactions.

In robotics, proximity sensors possess a variety of forms, each with unique properties and uses.

- *Ultrasonic Sensors:* These assess locations and identify obstructions using sound waves. Because they can operate in low-light conditions, they are frequently utilized in automated guided vehicles (AGVs), mobile robots, and manufacturing security systems. However, substances and ambient noise may affect their accuracy [7, 8].

- *Infrared (IR) Sensors:* These sensors detect objects based on infrared radiation. They are commonly used in short-range detection applications such as robotic vacuum cleaners and gesture recognition systems. Despite being affordable and energy-efficient, ambient light exposure can affect infrared sensors.
- *Capacitive Sensors:* By monitoring oscillations in capacitance caused by adjoining conductive or dielectric materials, these devices can identify things. They are appropriate for touch-based interfaces and factories because of their high sensitivity and ability to detect both metallic and non-metallic items. However, their detection ranges were limited (Table 3).

Recent developments in multiple-communication sensing and sensor fusion methods have significantly increased the accuracy and confidence of proximity sensors. By combining multiple sensing technologies, robots can achieve better environmental perception, reduce errors in obstacle detection, and enhance their operational efficiency. These improvements have expanded the use of proximity sensors in various fields including smart manufacturing, autonomous transportation, and assistive robotics [9–11].

CHALLENGES AND FUTURE DIRECTIONS

Despite the remarkable advancements in sensor technology, several challenges continue to hinder the full potential of robotic sensing systems. One of the primary concerns is sensor resolution and accuracy, particularly in dynamic environments, where robots must process vast amounts of real-time data. High-resolution sensors often generate large data volumes, increasing the computational burden and requiring advanced processing algorithms to efficiently extract relevant information.

Real-time integration of information and processing is another significant obstacle. To sense the surroundings, robots use a variety of sensors such as vision, touch, and proximity gauges. However, integrating data from different sensor types into a cohesive system remains a complex task. Sensor fusion techniques powered by AI aim to address this issue; however, achieving seamless synchronization while minimizing latency remains an ongoing research challenge.

The broad use of modern sensing technology is hindered by cost factors. High-performance sensors such as LiDAR and neuromorphic vision systems often incur significant manufacturing and operational costs, making them less accessible for budget-sensitive applications. Researchers are working on developing affordable alternatives without compromising performance.

Sensor miniaturization and energy efficiency are key areas of innovation. The development of compact, lightweight, and low-power sensors will enable their integration into smaller robotic platforms such as drones, medical robots, and wearable assistive devices. AI-driven sensor fusion techniques will further enhance robotic perception, allowing machines to interpret complex sensory data with greater accuracy.

In addition, bio-inspired sensing mechanisms are gaining traction. Technologies such as neuromorphic vision systems, which mimic human visual processing, and artificial skin, which replicates tactile feedback, hold great promise for next-generation robotic applications. These advancements will pave the way for more intuitive and human-like robotic interactions, thereby significantly improving automation in healthcare, industrial robotics, and service applications.

Table 3. Performance comparison of proximity sensors.

Sensor type	Detection range	Sensitivity	Response time	Cost	Applications
Ultrasonic	Medium-Long	Moderate	Moderate	Medium	AGVs, Mobile Robots, Industrial Safety
Infrared (IR)	Short	High	Fast	Low	Gesture Recognition, Consumer Electronics
Capacitive	Short-Medium	Very High	Fast	Medium	Industrial Automation, Touch Interfaces

RECOMMENDATIONS

The following solutions are put forth for bettering robotics sensor technological advances:

1. *Development of cost-effective and energy-efficient sensor solutions to improve accessibility and sustainability:* As sensor technologies become increasingly crucial to robotic systems, the development of cost-effective and energy-efficient solutions is essential for broadening accessibility. Lowering the cost of high-performance sensors will make advanced robotics more affordable for smaller companies and startups, thereby driving innovation across various sectors. In addition, the development of energy-efficient sensors will allow longer operation times, reducing the need for frequent recharging or battery replacement in autonomous robots, drones, and mobile platforms. By prioritizing sustainability, robots can operate more effectively in industries, such as healthcare, agriculture, and logistics, where long-term operational reliability is paramount. These innovations will also contribute to global efforts to reduce energy consumption in the manufacturing and automation sectors, aligning with environmental and economic goals.
2. *Integration of advanced AI algorithms to enhance real-time data processing and decision-making capabilities:* Enhancing robots' immediate analysis of data and decision-making demands the use of sophisticated computational intelligence (AI) systems. AI can significantly improve the decoding of sensor data, allowing robots to make rulings faster and more precisely. Deep learning techniques such as neural networks can improve object recognition, motion planning, and environmental mapping, even in dynamic and unstructured environments. Real-time AI-driven analysis can also optimize robot performance by dynamically adjusting parameters based on changing conditions, ensuring that the robot adapts to new challenges on the fly. In addition, the integration of AI with sensors allows for continuous learning, which enables robots to refine their sensory perception over time. This improvement is critical for autonomous vehicles, drones, and industrial robots, where reliable decision-making and adaptability are necessary to autonomously perform complex tasks in diverse environments.
3. *Adoption of multi-modal sensor fusion techniques to increase accuracy and reliability in complex environments:* The adoption of *multi-modal sensor fusion techniques* is a promising approach for increasing the accuracy and reliability of robotic systems, especially in complex environments. By integrating data from various sensors such as vision, tactile, and proximity sensors, robots can generate a more comprehensive understanding of their surroundings. By implementing the advantages of several sensors, multiple-communication fusion makes it practical to compensate for the disadvantages of each sensor. For example, vision sensors can provide detailed object recognition, whereas proximity sensors can ensure safe navigation by obstacle detection. By merging the outputs of multiple sensors, robots can obtain more reliable and accurate information, enabling them to make informed decisions and perform tasks with higher precision. This approach is particularly beneficial in applications such as autonomous driving, where safety is a priority, and in industrial environments, where high reliability and efficiency are crucial for success.
4. *Encouragement of interdisciplinary collaborations between engineers, material scientists, and AI researchers to drive innovation in sensor design and applications:* the future of robotics and sensor technologies will greatly benefit from interdisciplinary collaboration between engineers, material scientists, and AI researchers. Engineers provide practical knowledge of sensor integration and robotic systems, while material scientists can contribute to the development of novel materials that enhance sensor performance, such as flexible or stretchable materials. The establishment of algorithms that enable intelligent reception and decoding of sensory input by robots is primarily in the hands of AI researchers. By fostering collaboration across these fields, new sensor technologies that are both more efficient and cost-effective can be developed. For example, material scientists can develop new types of flexible, bio-inspired sensors, whereas AI algorithms can improve their data processing capabilities. This holistic approach will push the boundaries of what robots can achieve, particularly in sectors such as health care, manufacturing, and autonomous transportation.

5. *Implementation of standardized testing and benchmarking procedures to evaluate sensor performance across different robotic systems:* To ensure effective deployment and evaluation of sensor technologies in robotics, it is essential to implement standardized testing and benchmarking procedures. These standards provide a consistent framework for assessing sensor performance, including factors such as sensitivity, response time, accuracy, and environmental adaptability. By developing industry-wide benchmarks, manufacturers and researchers can objectively compare different sensor technologies, identify areas for improvement, and ensure that robotic systems satisfy specific performance requirements. This will lead to the optimization of sensor integration across various robotic platforms, from industrial robots to autonomous vehicles. Additionally, standardized testing procedures would provide more transparency for users and help accelerate the adoption of new technologies. Standardization is particularly important as robotics continues to expand into highly regulated industries such as healthcare and aviation, where safety and performance reliability are paramount.
6. *Exploration of bio-inspired sensing mechanisms to improve adaptability and robustness in robotic perception:* Exploration of *bio-inspired sensing mechanisms* presents an exciting opportunity to advance robotic perception systems. By studying how animals and humans interact with their environments, engineers can design sensors that mimic these natural processes, offering greater adaptability and robustness under various conditions. For example, *neuromorphic vision systems* inspired by the human visual cortex can improve the efficiency of image processing and object recognition. Similarly, artificial skin, modeled after the tactile feedback mechanisms found in human skin, could enable robots to better perceive pressure, texture, and temperature, making them more adept at delicate tasks, such as surgery or assembly. These bio-inspired systems also promise to improve the flexibility and resilience of robots, allowing them to adapt to different environments and handle unpredictable situations more easily. As research progresses in this area, bio-inspired sensors may become integral to the next generation of robots, particularly in fields requiring high precision and sensory feedback, such as medical and service robotics.

CONCLUSION

Sensor technologies are the backbone of modern robotic systems, enabling robots to perceive and interact with their environment in ways that mimic human capabilities. Vision, tactile, and proximity sensors are particularly critical, as they allow robots to gather essential data for tasks such as object recognition, navigation, manipulation, and safety. From manufacturing and healthcare to automobile autonomy and service robotics, the advancement of these technologies has significantly increased the accuracy and reliability of robots in various domains.

The capabilities of these sensors will change as technology improves, opening the door to more cognitive and flexible robotic systems. In one example, AI-enhanced processing of photos makes vision sensors more precise and effective, allowing robots to comprehend convoluted settings in an immediate response. Tactile sensors have advanced with the integration of flexible and stretchable materials, enabling robots to handle delicate tasks with greater dexterity and precision. Similarly, proximity sensors are refined to offer higher sensitivity and more reliable data in dynamic environments.

While these advancements have tremendous potential, several challenges remain, particularly in the areas of sensor integration, resolution, and real-time data processing. However, such challenges also offer fascinating potential for more creativity. As sensor technologies continue to evolve, they will play an even more crucial role in transforming robotics into an essential component of industries, such as healthcare, manufacturing, logistics, and beyond. Ongoing progress in these areas will pave the way for robots to interact more seamlessly and safely with humans, bringing us closer to a future where robots can work alongside us more effectively and autonomously.

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