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# MEMS in Robotics: From Fundamental Design to Cutting-edge Innovation

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**Abstract:**

Applications from microelectromechanical systems (MEMS) technology to robotics are developing rapidly. Their unique miniaturization, high precision, and cost-effective features make them indispensable to modern robotics. This article examines the key applications of MEMS technology in robotics and thoroughly analyses how MEMS sensors and micro-actuators can revolutionize robotics by improving operational accuracy, reliability, and cost-effectiveness. Through a comprehensive review of the existing literature and a detailed analysis of multiple case studies, this study reveals innovative applications of MEMS technology in many fields, including medical robotics, exploratory robotics, and industrial automation. The paper also addresses several challenges in promoting MEMS applications, including the complexity of manufacturing technology, cost control, and equipment durability issues. A series of resolution strategies have been proposed to address these challenges, including adopting new materials, improved design, and adopting advanced manufacturing technologies, which are key factors in ensuring the reliable operation of MEMS equipment under strict conditions. In the future, MEMS technology is expected to play an even greater role in the field of intelligence and automation as the technology develops. MEMS technology can not only stimulate advances in robotics but should also stimulate technological innovation in broader fields such as medicine, environmental monitoring, and consumer electronics. Through continuous research and development, MEMS technology will continue to optimize its performance and range of applications, bringing revolutionary advances in robotics and other related fields.

**Keywords:** MEMS; Robotics; Sensors; Actuators; Technological innovation; Future development

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# 1. Introduction

This article examines in depth the impact and importance of MEMS technology in robotic applications. The article begins with a presentation of the context of research on MEMS technologies and the state of research, noting that current research focuses primarily on the development of sensors and actuators, while relatively little research has been conducted on the long-term reliability of MEMS devices and their performance in extreme environments. This highlights a critical gap in research, namely the limitations of MEMS components in terms of sustainability and environmental adaptability. In addition, although MEMS technology has been extensively researched due to its miniaturization and cost-effectiveness, it remains difficult to further reduce costs while maintaining performance [1].

The research aims to explore how MEMS technologies can significantly improve robot performance, accuracy, and reliability through innovative sensor and actuator solutions while exploring how these technologies can effectively reduce manufacturing and operating costs. The article presents in an exhaustive way the basic principles of MEMS technology and analyzes in detail its central applications in various robotic systems. It examines current research advances in MEMS technology and its future trends [2].

The study focused on the practice of MEMS technology in various fields of application of robotics, in particular medical robotics, shipping robotics, and industrial automation. Through a systematic compilation and analysis of the national and international literature, several key application cases have been selected for in-depth discussion, helping the reader to fully understand the different functions of MEMS technology and the many application perspectives. In terms of research methodology, this paper is not only to review the evolution and current state of MEMS technology but also to show, through concrete examples, the impact of technology in practice and the challenges it faces. Particular attention is paid to how technological advances solve the critical problems of robotics and to the specific contribution of these advances to improving robot performance.

Readers of this article should start with an introductory section that provides basic information about MEMS technology research and the motivations for this research. The following chapters examine in detail the specific applications of MEMS technology in robotics, as well as the performance and efficiency of these applications in practice. In the section “Application values and research advances in key technologies”, detailed application examples and the main technological challenges facing current technologies are presented, as well as corresponding resolution strategies. The article ends with projections of future trends, directions, and potential markets of MEMS technology.

# 2. Application Field and Principle

## 2.1 MEMS Sensor

### 2.1.1 Introduction to MEMS Technology

MEMS sensors use advanced miniaturized technologies that integrate mechanical components, sensors, actuators, and electronics on a microchip. Capable of detecting small changes in the environment and converting them into electrical signals, these sensors are widely used in the field of robotics to improve their performance and functionality. For example, MEMS accelerometers and MEMS pressure sensors. MEMS accelerometers contain a tiny block of vibratory mass capable of detecting changes in acceleration. As shown in Fig. 1, when the robot moves or changes direction, these changes are accurately detected and converted into electrical signals by changing the value of the capacity.

In addition, the MEMS pressure sensor contains a small deformable film capable of detecting pressure variations. When pressure is applied to the surface of the sensor, this film deforms, resulting in a change in volume in the miniature cavity below it and, in turn, a change in the value of the capacity inside the cavity. As shown in Fig. 2, this pressure-induced capacitance variation is then converted into electrical signals allowing the system to accurately monitor and control the robot’s contact force and pressure in a complex environment, optimizing operational performance and robot response efficiency.

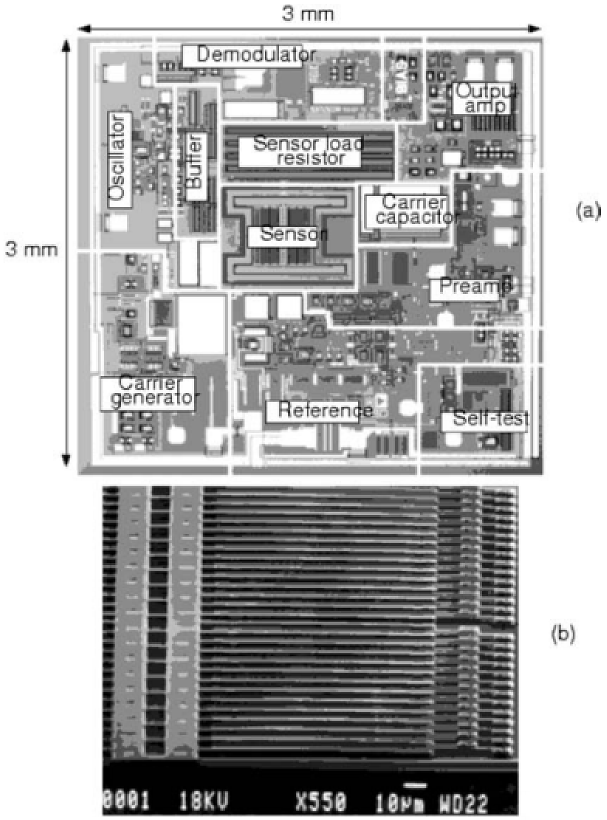

**Fig. 1 Surfaced micromachined MEMS accelerometer. (a) Overall chip structure showing sensor and electronics; (b) Micrograph of sensing element (Analog Devices, Inc.) [1]**

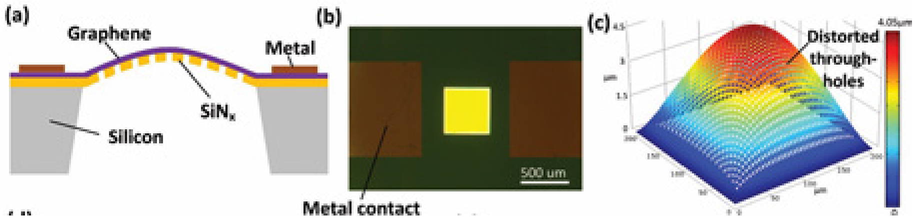

**Fig. 2 MEMS pressure sensors in different forms (a) Schematic of the proposed MEMS pressure sensor using a graphene membrane on a perforated SiNx thin membrane formed on a micromachined silicon base. (b) Optical image of the fabricated pressure sensor. (c) Simulated deformation of the membrane and shape distortion of the through-holes [3].**

### 2.1.2 Application Examples

MEMS sensors play a key role in robot navigation and positioning systems. The autonomous mobile robot (AMR) performs precise inertial navigation thanks to the integration of a MEMS accelerometer and a gyroscope. This allows the robot to accurately identify its position and state of movement in three-dimensional space in real-time. For example, MEMS accelerometers detect changes in speed, while gyroscopes provide information on angular speed, which improves the accuracy and reliability of position estimates. In underwater robotic applications, MEMS pressure sensors play a crucial role. These sensors accurately measure water pressure and thus help the robot regulate its buoyancy, ensuring a stable horizontal position or performing precise descent and ascent operations in a complex and variable underwater environment. For example, when underwater robots are required to detect or repair the seabed, accurate depth control is essential to prevent collisions and optimize work efficiency. These highly integrated MEMS sensors are not only compact and lightweight, they also have the advantages of low power consumption and fast response, which greatly improves the adaptability and operational performance of the robot in a variety of environments.

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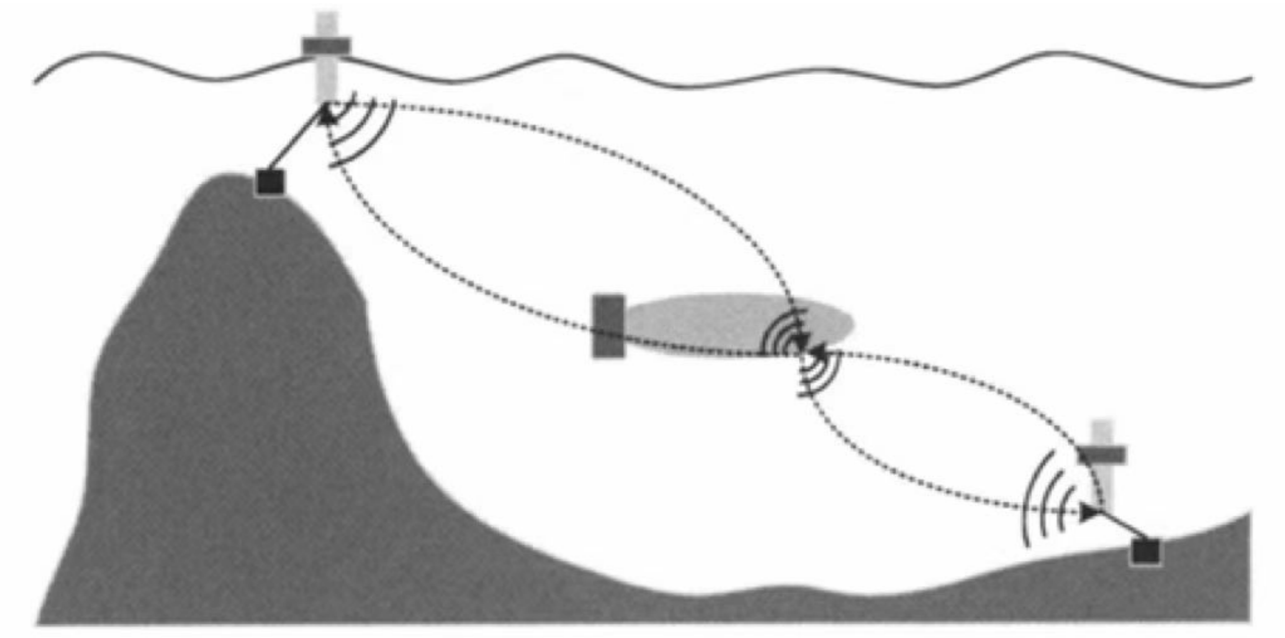

Fig. 3 Illustration of the movement of the AUV [4]

As shown in Fig. 3, in robotics, the application of MEMS pressure sensors demonstrates their functionality and importance in many environments. For example, MEMS pressure sensors are essential components in the design of underwater robots. They accurately measure water depth and feedback data to adjust the robot's buoyancy, ensuring stable and accurate underwater operation. This pressure sensor helps underwater robots perform delicate seabed detection tasks, such as inspecting underwater pipelines or collecting biological samples, by monitoring changes in water pressure.

In addition, in the development of interactive intelligent dog-type robots, the application of MEMS pressure sensors offers an innovative way to improve the interactive experience with the user. As shown in Figs. 4 and 5, the integration of MEMS pressure sensors on the surface of the robotic dog makes it possible to accurately detect the user's tactile strength and position, allowing for richer interactive feedback. This pressure-sensing technology not only allows the robotic dog to detect the user's interactive movements but also to respond differently depending on the strength and frequency of contact, simulating the behavior of a real pet, such as shaking the tail to indicate joy or withdrawal to indicate alert. In addition, in combination with voice feedback and dynamic expression changes, this interactive design can significantly improve the user's emotional experience, especially in educational activities such as assisted reading for children. Robotic dogs can encourage children to participate more actively in reading through feedback mechanisms.

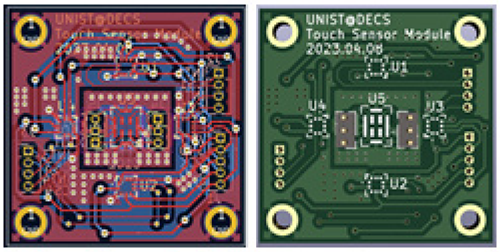

Fig. 4 Touch sensor module circuit design; left: PCB layout, right: 3D model view [5]

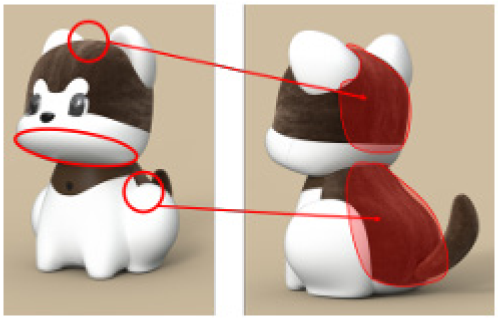

Fig. 5 Touch sensor module operating area (colored in red) [5]

### 2.1.3 Performance Advantages

In terms of performance advantages, MEMS sensors offer several significant advantages over conventional sensors, making them indispensable components in robotics. First, the miniaturization of MEMS sensors allows their easy integration into various robotic systems without additional overload. For example, in UAV applications, the integration of MEMS gyroscopes allows for more accurate flight control, while having little impact on the overall weight and design complexity of the UAV.

In addition, the low power consumption of MEMS sensors means they can operate with less power consumption, which is especially important for robots requiring long periods of remote operations. The low power consumption not only extends the robot's operating time but also reduces the need for frequent recharge or battery changes, improving the efficiency and reliability of the robotic system.

Most importantly, MEMS sensors offer fast response and high-precision feedback, which is essential for the performance of the robotic system. These sensors detect and process complex environmental data in real-time, allowing the robot to react more quickly, whether for automatic obstacle avoidance, accurate positioning, or sensitive operational tasks. In industrial automation, for example, MEMS pressure sensors can accurately control the force exerted by the robotic arm and prevent damage to sensitive components, thus ensuring the quality and safety of the production process.

In short, the advantages of MEMS sensors in terms of volume, energy consumption, and speed of response make them an irreplaceable role in modern robotics. These sensors are expected to reveal greater potential in a greater number of robotic applications as technology develops.

## 2.2 MEMS Microactuators

### 2.2.1 Technical details

As shown in Figs. 6 and 7, MEMS micro-actuators use the technology of micro-electromechanical systems for precise control of various complex robot movements through sophisticated design and a highly integrated manufacturing process. These actuators are usually made from silicon-based materials, taking advantage of their excellent mechanical properties and compatibility. There is also the need to use metallic and polymer materials for specific applications. Silicon-based actuators are widely used due to their compatibility with existing semiconductor manufacturing processes, while metal materials such as aluminum and titanium have been chosen to withstand higher mechanical loads for their structural strength and durability. Polymer materials such as PDMS (polydimethylsiloxane) are suitable for medical and biological applications due to their unique flexibility and biocompatibility [6].

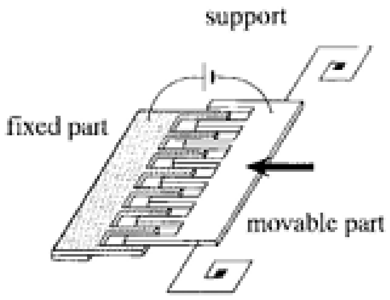

**Fig. 6 Comb-drive microactuator [7]**

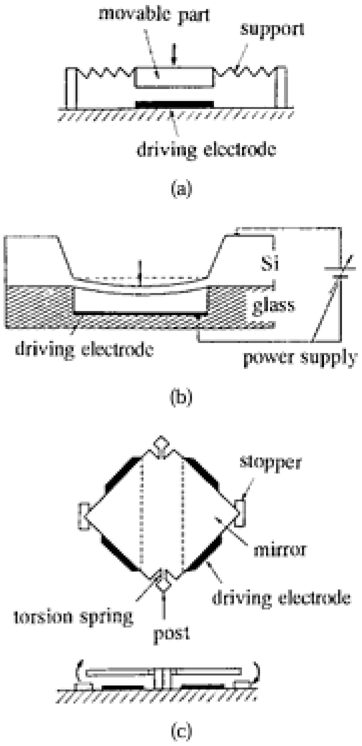

**Fig. 7 Microactuators with flexible support. (a) Parallel plate type; (b) Membrane deformation type [8]; (c) Torsion mirror [9].**

### 2.2.2 Control of movement

In terms of motion control, MEMS microactuators allow precise movements from micron to nanometer [10], making them extremely important in robotic applications requiring precise handling. For example, in precision assembly and micromanipulation robots, these actuators can accurately control the position of the robotic arm or tool head for tasks such as assembling chips or inserting miniature components. In addition, the quick response properties of MEMS actuators enable excellent performance in dynamic adjustment and real-time feedback mechanisms, such as stable walking by quickly adjusting joint or foot position during robotic walking or balance adjustment.

### 2.2.3 Application of technology

As shown in Figs. 8 and 9, for innovative applications, the miniaturization characteristics of MEMS microactuators make them particularly useful in the field of microrobotics. In the medical field, for example, micro-robots can use MEMS actuators to perform in vivo surgical operations, such as precision cutting or spot drug release.

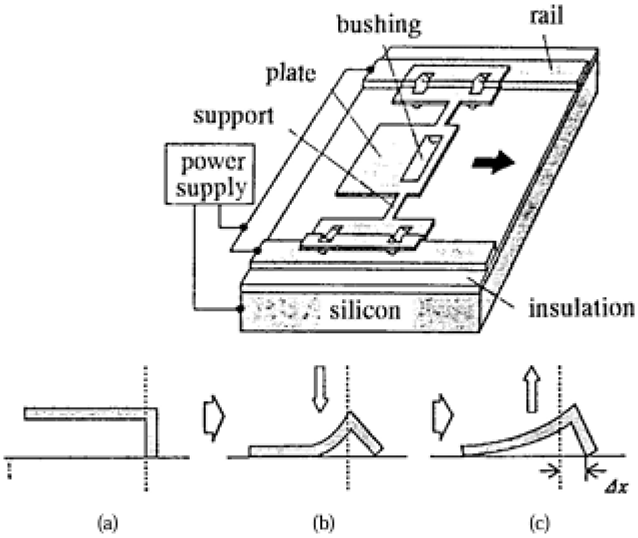

**Fig. 8 Scratch-drive actuator. (a) Initial; (b) Voltage applied; (c) Move forward by x upon voltage removal [11]**

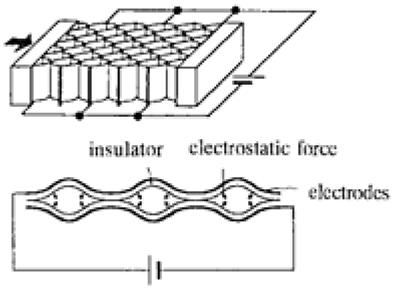

**Fig. 9 Microactuator composed of distributed force elements [12]**

These in vivo robots allow very precise handling thanks to miniature actuators, significantly reducing surgical invasions and improving treatment efficiency. Another innovative application is the use of micro-detection robots in environmental monitoring or search and rescue missions. These robots equipped with MEMS actuators can operate and collect data in tight or hazardous environments demonstrating the enormous potential of MEMS technology in specific environments [13].

# 3. Progress and Exposure of Typical Applications of MEMS Technology in Robotics

## 3.1 Value of MEMS Application in Key Technologies and Research Advances

MEMS technology has advanced considerably and is largely influenced by its miniaturization, low cost, and high performance in many industries. This technology has been particularly successful in creating high-precision sensors for physical, gas, and chemical detection, with applications ranging from automotive systems to medical devices, etc [1].

### 3.1.1 Typical Areas

(1) Medical robotics
The use of MEMS sensors in medical robotics improves the accuracy and responsiveness of surgical tools. For example, MEMS pressure sensors help maintain the effort required in robotic surgery, improving safety and surgical results.
Explore the robot
In exploration applications such as drones or underwater vehicles, MEMS accelerometers, and gyroscopes provide critical data that help these robots navigate complex environments by detecting direction, movement, and acceleration.
(2) Automation of the industry
MEMS sensors simplify operations in automated production lines. Pressure sensors and accelerometers are used to accurately monitor and control mechanical movements, improve efficiency, and reduce downtime.

### 3.1.2 Technological Challenges and Parties to the Resolution

(1) Complexity of manufacturing
One of the main challenges is the complexity of manufacturing processes for small sensors. Advanced microsining and lithography techniques have been developed to address these complexities, allowing the production of highly detailed and reliable MEMS sensors.
Question of cost
Although MEMS equipment is generally profitable, the initial investment in dedicated manufacturing facilities can be high. Economies of scale and process optimization are key strategies to reduce costs.
(2) Question of sustainability
The small size and complexity of MEMS components can affect their durability. Solutions include the use of robust materials such as silicon carbides and protective coatings to improve the service life and reliability of MEMS sen-

sors under various environmental conditions.

## 3.2 Forecasting Future Trends

### 3.2.1 Technological Innovations

MEMS technology has made significant advances in physical induction applications, producing a range of small, robust, and cost-effective devices, such as accelerometers, gyroscopes, and pressure sensors. Increasingly, these devices incorporate digital output and on-chip signal processing functions, enhancing their capabilities and range of applications. Innovations have also focused on the development of sophisticated MEMS sensors, such as yaw sensors for mass production with a complex microstructure.

Technologies of the future:

As MEMS technology evolves, its scope of application expands rapidly and is no longer limited to traditional physical detection. With regard to gas detection in particular, metal oxide gas sensors manufactured using micro-machining techniques, commonly referred to as “micro-hot plates “, have been commercially successful on the market, although the effects have previously been less important than physical detection. This marks the growing potential of MEMS technology for gas detection applications. In addition, research on MEMS technology is extending to more sophisticated analysis devices. Now, not only simple detectors but also more sophisticated devices such as microspectrometers and laboratory chip systems are beginning to adopt MEMS technology. These advanced testing devices are expected to have a profound impact in several areas, including advanced diagnostics and environmental monitoring in healthcare, illustrating the shift from MEMS technology to the integration of more advanced testing systems. In the biomedical field, biomems are an emerging technology that combines biological processes with MEMS technology to develop applications such as miniaturised PCR systems. This new technology is expected to revolutionize areas such as genomics and drug testing, offering unprecedented biodetection capabilities. As technology advances, biomems are expected to play an even greater role in biomedical research, pushing scientific exploration and clinical diagnosis toward greater efficiency and accuracy.

### 3.2.2 Market Forecasts

Market dynamics:

The market for MEMS sensors is expected to grow, fueled by their integration into consumer electronics and automotive applications. It is likely that the demand for MEMS equipment in these sectors will increase due to their ability to improve product functionality and performance in a cost-effective manner. Future legislation on environmental monitoring and public safety could further stimulate demand for MEMS sensors, particularly for vehicle exhaust monitoring and IAQ applications [2]. In addition, according to the latest market research from BlueWeave Consulting, MEMS is showing strong growth worldwide. From $14.26 billion in 2022, the market is expected to grow to $23.5 billion in 2029, representing a compound annual growth rate of 7.52%. This growth is mainly due to the increased demand for high precision and miniaturised MEMS sensors in fields such as medical, consumer electronics, and automotive. Especially in the field of medical and consumer electronics, the demand for MEMS sensors for smart devices and medical devices continues to grow. In portable devices, for example, the application of MEMS sensors for heart rate and blood pressure monitoring functions has become a key factor that has led to the rapid expansion of the MEMS market. In addition, the development of MEMS technology is strongly supported by the growth of the automotive sector, particularly in the areas of safety and security, navigation, and automated vehicles. However, the high production and testing costs associated with MEMS are expected to be a potential constraint to market growth [14].

Factors of influence:

The future development of MEMS technology is influenced by a number of key factors that together shape the expansion of the MEMS market and the trajectory of technological progress. First, the global economic environment has a direct impact on R&D investment and consumer purchasing power in MEMS technologies. A thriving economy could increase the ability of businesses and consumers to invest in advanced technologies, thereby fostering innovation and the diffusion of MEMS applications.

Second, technology standardization is an important factor in the commercialization of MEMS technology. By establishing common industry standards, the production costs of MEMS products can be significantly reduced, while facilitating rapid deployment and market acceptance of the technology. The standardization process simplifies integration issues in multi-vendor environments and facilitates the adoption of MEMS devices.

Policy and regulatory support are also essential for MEMS technology to be widely used. Policy measures such as financial subsidies and the protection of intellectual property rights can encourage firms to invest in technological R&D in the long term while protecting their innovations from intrusion, thus fostering a healthy environment for technological innovation.

Since its launch in the 1960s, MEMS technology has successfully developed high-performance sensors for the

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detection of various physical variables, at an extremely low unit cost, allowing it to be applied on a large scale in price-sensitive markets. These applications range from automotive to consumer electronics and are expected to expand further with the continued progress of MEMS technology. In the field of gas detection, although no major gas sensor is entirely based on MEMS technology, new large-scale applications are expected to stimulate the wider use of MEMS technology.

In conclusion, future market forecasts for MEMS technologies are influenced by several factors that interact in terms of technological development, market demand, and policy support which, together, stimulate the development and application of MEMS technologies.

## 4. Conclusion

This paper reviews the key applications of MEMS technology in robotics and analyses in depth how MEMS sensors and micro-actuators can revolutionize robotics, particularly concerning their contribution to improving accuracy, reliability, and cost-effectiveness. By exploring MEMS technology, this study not only shows its central place in modern robotic applications but also highlights its high efficiency and adaptability to complex tasks.

The results show that MEMS technology can significantly improve robots' ability to operate in extreme environments. From medical surgery to environmental exploration, precision control and miniaturized design of MEMS devices opens up new possibilities for robotics. These advances have not only improved the functionality of robots but also reduced production and operating and maintenance costs, demonstrating the crucial role of MEMS technology in future developments.

The interest of this study is to highlight the potential of MEMS technology to advance robotics and automation, to improve the operational accuracy and intelligence of equipment. As technology evolves, MEMS should continue to find applications in wider areas, such as industry, medicine, and consumer electronics.

In the future, with the continued emergence of new materials and advanced manufacturing technologies, the application prospects of MEMS technology will be wider. Research should focus on ways to overcome current manufacturing complexity and cost issues, as well as on ways to improve the durability and reliability of MEMS devices under extreme conditions. In addition, through the combination of artificial intelligence and machine learning technologies, future MEMS devices will be more intelligent and adaptive and will be better able to meet the complex requirements of environments and applications. This requires not only interdisciplinary cooperation but also concerted efforts by policymakers and industry leaders to ensure the sustainable development and correct application of technologies.

In summary, MEMS technology not only supports current robotics but also opens new paths for innovation and future applications of robotics. As research progresses, it is reasonable to believe that MEMS technology will play an increasingly important role in global technological progress.

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