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A Review of MEMS Technology: Classification, Applications, and Industrialization Challenges

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Abstract. In recent years, with continuous innovation in industrial upgrading and related technologies, the micro-electromechanical systems (MEMS) field has become increasingly critical in engineering and academic research, providing important support for technological development. However, the relevant research remains relatively fragmented, and the field lacks a systematic summary. To clarify the research and development trajectory of MEMS technology, this paper uses MEMS research progress as its core theme to systematically organize the current state of MEMS technology classification, performance benchmarks, and multi-scenario applications. The study found engineering problems such as power consumption and synchronization errors in inertial measurement unit (IMU) arrays. The industry lacks unified wafer-level testing standards and specialized vehicle-grade verification standards. Long-term service degradation models and device reliability data remain limited. As application fields evolve rapidly, these standardization and reliability shortcomings hinder high-end MEMS applications.

Keywords: micro-electromechanical systems (MEMS), inertial measurement unit (IMU) array, consumer electronics and wearable devices, vehicle-grade and industrial applications, biomedical and optics

1. Introduction

As a cutting-edge, and cross-disciplinary field, micro-electromechanical systems (MEMS) technology has attracted sustained attention in academia and industry. With the popularisation of the Internet of Things, artificial intelligence, and intelligent terminal devices, MEMS technology's impact on social production modes and technological innovation patterns will deepen further. Based on current trends, MEMS technology has gradually shifted from early academic exploration to industrial application, showing strong prospects in consumer electronics, vehicle-grade systems, biomedical, and other fields.

However, existing studies point out that problems such as insufficient standardisation of the MEMS classification system, non-unified wafer-level test standards, and a lack of long-term service drift models are gradually emerging, which to a certain extent restricts the in-depth development of the technology toward higher-reliability scenarios. This article adopts the sensing-and-actuation framework as the classification baseline and integrates consumer-grade, navigation-grade, and

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vehicle-grade performance benchmarks into a unified comparison framework. It systematically reviews the current discussions on MEMS technology classification, performance benchmarks, and application status, and compares the differences across use scenarios. It further analyzes the common bottlenecks faced by industrialization, aiming to provide a reference for classification system standardization and performance evaluation standards. In addition, by analysing key bottlenecks in emerging directions such as flexible MEMS, inertial measurement unit (IMU) arrays, and drug delivery chips, it also provides a reference for formulating relevant industry standards, the strategic layout of enterprise products, and the planning of scientific research directions.

2. Basic principles

2.1. Classification of MEMS technology

MEMS is a micro-integrated system composed of microstructures, microsensors, micro-actuators, and control and processing circuits. These functional elements together constitute the technical core of MEMS devices [1]. Currently, the academic community mainly divides MEMS devices into two functional categories: sensing and actuation [2]. Sensing devices mainly include inertial sensors (accelerometers, gyroscopes), pressure sensors, and acoustic sensors (microphones), etc.; actuators include micro-mirrors, inkjet heads, micro-flow control chips, and other micro-actuators [2, 3].

2.2. Performance benchmarks

Among the various technical paths to improve inertial measurement unit (IMU) performance, the IMU array scheme has attracted attention for its balance of cost and accuracy. The existing literature on IMU performance benchmarks can be summarised into two modules: static grading benchmarks and dynamic optimisation paths. The static reference line defines the performance benchmarks for consumer-grade and navigation-grade products, with bias instability as the core. The dynamic implementation path bridges the gap from low-precision devices to high-precision indicators through multi-sensor data fusion of IMU arrays and system integration. Consumer-grade devices usually exhibit bias instability ranging from several degrees to dozens of degrees per hour, while navigation-grade devices must reach less than 0.01 degrees per hour [4]. Vehicle-grade IMUs fall between these two and require higher environmental adaptability. Some studies have shown that offsetting random noise through redundant configurations and data fusion of multiple low-precision IMUs can approach higher-grade inertial measurement units at equivalent accuracy [4]. This approach bypasses the physical limitations and process bottlenecks of single-chip high-performance IMUs and relies on system integration to meet performance requirements. However, the path still needs to solve key problems such as power consumption, system volume, and multi-sensor synchronisation accuracy for engineering promotion.

2.3. Testing methods and technical paradigms

In testing MEMS devices, Zhang focused on non-contact optical testing methods reflects the field's ongoing pursuit of high spatial resolution and high-speed imaging capabilities in precision measurement [5]. Optical methods such as laser Doppler vibration measurement and digital holographic interference occupy a unique position in wafer-level testing and device failure analysis because they offer accuracy advantages for measuring small displacements and deformations. However, this method faces deployment flexibility challenges in large-scale industrial production:

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the optical path's sensitivity to environmental vibration, temperature gradients, and even air disturbances requires additional vibration isolation and environmental compensation, increasing costs when applied in noisy, dusty, or space-limited production workshops. The electrical test method is usually inferior to the optical method in micro-displacement measurement resolution, but it offers greater robustness in test speed, automatic integration, and anti-interference performance. The trade-off between the two test paradigms largely depends on whether accuracy or efficiency takes priority in specific application scenarios, and it also reflects, to some extent, the broader problem of wafer-level test standards not conforming to a single standard [4, 5].

3. Typical application scenarios: technical requirements and status analysis

3.1. Consumer electronics and wearable devices

MEMS technology is deeply integrated into intelligent terminal products in consumer electronics. This includes multi-axis inertial measurement units in smartphones, bone conduction and voice pickup microphone arrays in true wireless stereo (TWS) headphones, and motion tracking and posture perception modules in wearable devices. These applications no longer focus solely on basic functions; they are gradually evolving toward higher levels of user-experience optimisation.

Cao pointed out that the contradiction between packaging reliability and acoustic performance stability is particularly prominent in the current pursuit of lighter, highly protective consumer electronic products [6]. Proposed improvement directions, such as using new polymer materials to replace traditional silicon-based packaging and introducing a digital signal-processing front end for dynamic compensation, show potential at the principle level. However, the effectiveness of these technical schemes also depends heavily on precise control of the packaging process and verification of the material's long-term reliability.

The technical challenges in wearable devices are more complex and multidimensional. Leng and other scholars believe that innovative structural design is necessary at the fabric-sensor system integration level [7]. The signal conversion relationship model proposed by Bi et al. is a theoretical exploration in this direction. However, the model is still in the concept verification stage, and its decoupling ability and generalisation performance for complex human movement postures need further revision and improvement [8].

At present, the development focus of consumer-grade MEMS technology is shifting. Song et al. summarised the development of MEMS microphones as three application waves: analogue substitution, digital interface, and the evolutionary path of AI embedding [9]. The realisation of voice wake-up word recognition, environmental sound scene classification, on-device audio event detection, and other functions introduces new requirements for the microphone array's power-consumption budget and computing-power allocation. Collaborative optimisation between dynamic power-consumption management strategies and continuous perception algorithms may, to some extent, affect the final user experience more than simple improvements in hardware performance indicators. This trend indicates that as algorithm- and system-level optimisation plays a greater role in user experience, MEMS device suppliers and system algorithm developers need to move beyond a traditional upstream-downstream supply relationship toward deeper joint definition and customized development.

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3.2. Vehicle-grade and industrial high-reliability systems

Automotive and industrial applications represent the fastest-growing segment of the MEMS market. MEMS pressure sensors and inertial measurement units play an increasingly important role in advanced driver assistance systems (ADAS) and autonomous driving scenarios such as tyre pressure monitoring, oil pressure sensing, collision detection, rollover warning, and high-precision positioning [4, 10]. This field has stricter requirements for device reliability and functional safety standards.

The reliability requirements of vehicle-grade MEMS in extreme environments such as strong vibration, high impact, and a wide temperature range have certain similarities with some national defence application scenarios. Wen et al. systematically analyzed the application prospects of MEMS technology in target detection, navigation positioning, flight control, telemetry communication, security and fuse, health monitoring, etc. [10]. Although the study focuses on the missile-borne application scenario, it overlaps significantly with application requirements analysis for MEMS devices in extreme environments and with vehicle-grade application scenarios, both of which emphasise the device's environmental adaptability and long-term stability. In terms of device technology, Chen et al. noted that array technology is an effective way to achieve low-cost, high-precision inertial measurement [4]. However, at the system-verification level, systematic assessment reports on vehicle-grade MEMS remain insufficient. Zhang et al. that MEMS dynamic test technology faces unprecedented challenges, and that comprehensive test technology combining multiple methods has become the main development direction [5].

3.3. Biomedical, optical MEMS, and other emerging fields

The MEMS applications in biomedicine mainly include precise drug delivery and intraoperative intelligent sensing. Yao introduced MEMS applications in drug delivery chips, focusing on the principles and manufacturing processes of drug-controlled release chips, all-plastic component hydrodynamic micro drug release systems, and implanted intelligent drug release systems based on artificial muscle principles. He pointed out that drug delivery chips have good application prospects in pulsed or continuous release of single or multiple substances [11]. Zhao et al. focused on applying MEMS intelligent sensors in total knee replacement. Through microsensors, the position of the lower-limb force line and the intra-articular stress of the knee joint are converted into visual information, providing an objective basis for force-line adjustment and soft-tissue loosening [12]. Although it shows strong promise, it still faces significant challenges in developing biocompatible materials and verifying long-term implant reliability [7].

Optical MEMS research is still in its infancy, and research on optical phased arrays (OPAs) remains relatively limited. Only some reviews mention that optical communication is an important future direction for MEMS [13]. Based on the above analysis, the current application pattern of MEMS technology can be roughly summarised as follows: consumer-grade applications face intense competition, vehicle-grade applications are growing rapidly, and biomedical and optical phased-array applications are still emerging. The competitive focus in the field of consumer electronics has shifted from performance to cost and power consumption; the market growth in the in-vehicle and industrial fields is relatively significant, but the reliability verification system is not yet perfect; the technology penetration rate of emerging technologies such as biomedical and optical phased arrays is still low, and the industrialisation process faces multiple barriers.

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4. Discussion

4.1. Findings

4.1.1. Engineering challenges of IMU array technology

While improving accuracy, the array scheme also increases overall power consumption and system volume, and creates practical challenges for multi-sensor synchronized acquisition and data alignment. Whether the model accounts for coupling effects from complex factors such as temperature drift and mechanical stress in practical applications needs verification through more in-depth experiments. Whether the system can maintain and stabilise the array scheme's performance gain across different dynamic scenarios still needs evaluation.

4.1.2. Lack of unified testing standards

There is a wide variety of MEMS devices, from inertial sensors to microphones, pressure sensors, optical MEMS, with different structural designs, material systems, and failure modes, which leads different manufacturers to customise test schemes based on their own process characteristics. This lack of unified benchmarking increases the risk and cost of device selection for system integrators and, to some extent, delays the cross-manufacturer promotion of new technology solutions. In addition, systematic assessment reports on vehicle-grade MEMS are still insufficient: only a small number of studies mention the device verification requirements under the AEC-Q100 standard, and most of them provide overview descriptions rather than specific reliability data for MEMS-specific failure modes (such as adhesion, fatigue, and temperature drift) [4, 10]. Implementation evaluations of the functional safety standard ISO 26262 at the MEMS device level are rarely reported in depth. Given these factors, the constraining effect of standard unification on MEMS industrialisation is less visible than the technical bottleneck, but more lasting.

4.1.3. Lack of long-term performance verification

Currently, most studies remain limited to short-term laboratory tests. Systematic modelling of the performance degradation law of MEMS devices over several years to decades under real working conditions is lacking. This shortcoming is especially prominent in vehicle-grade and biomedical applications [4, 10, 14]. Wen and Yan both pointed out the urgent need for long-term reliability research on MEMS devices [15, 16]. The commercialisation process of flexible MEMS still faces multiple obstacles: the compatibility of its preparation process with the traditional IC process, the mechanism of electrical property degradation in the flexible substrate under repeated deformation, and the long-term environmental stability of the flexible packaging scheme all constitute technical barriers that limit large-scale application. Yao pointed out that MEMS inertial sensors face problems such as insufficient data accuracy, questionable safety, and poor comfort and water resistance in smart clothing [17]. These problems reflect the conflict between the rigid characteristics of sensing elements and the flexible structure of textiles [14].

4.2. Future directions

In general, MEMS technology has gradually moved from academic exploration to industrial application. However, standardizing the classification system, unifying performance benchmarks, and establishing a verification system for high-reliability scenarios remain key factors in whether the

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technology can achieve deeper penetration across a wider field. Future research should focus on unifying wafer-level test standards and establishing a mutually recognizable performance evaluation system. In addition, system modelling and accelerated life tests of the long-term service behaviour of MEMS devices are needed to fill gaps in reliability data. Future research should also focus on key scientific issues in emerging directions such as flexible MEMS, IMU arrays, drug delivery chips and other related devices and build the necessary foundation for industrial breakthroughs. Advancing these research directions will require closer collaboration between academic institutions, industry, and standards organizations, particularly in data sharing and test validation.

5. Conclusion

Based on the existing literature, this article explores the classification system, performance benchmarks, and typical application scenarios of MEMS technology. The research focuses on analyzing common industrialization challenges, such as IMU arrays, non-conformity of test standards, and lack of long-term reliability. The study notes that MEMS has moved from academic laboratory exploration to industrial application. However, issues such as insufficient classification standardization and an imperfect verification system still limit its development to a higher, deeper level.

This research relies only on existing literature and secondary data and does not include a systematic literature review or quantitative comparative analysis. The application of emerging manufacturing technologies and directions (flexible MEMS, biomedical, optical MEMS) is still in the early stage, and industrialisation promotion remains difficult. Future research should focus on promoting the unification of wafer-level test standards, establishing long-term service drift models of devices, and overcoming engineering-related problems of IMU array technology; at the same time, it should strengthen the experimental verification of key scientific problems such as flexible substrate reliability and multi-sensor synchronization error, and promote industry-academia-research collaboration to fill the reliability data gap.

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