Applications of MEMS sensors in industrial equipment condition sensing and the Internet of Things

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Abstract: This paper systematically studies the integrated application of microelectromechanical systems (MEMS) sensors in industrial equipment condition sensing and the Internet of Things (IoT). The research shows that MEMS sensors, with their advantages of miniaturization, low cost, and low power consumption, effectively overcome the limitations of traditional monitoring technologies in terms of deployment density and economy, laying a solid foundation for building large-scale equipment condition sensing networks. By analyzing multi-dimensional parameters such as vibration, attitude, and pressure, and combining edge computing and data fusion technologies, accurate diagnosis and early warning of the operating status of industrial equipment are achieved. Further research indicates that when MEMS sensors are deeply integrated into the industrial IoT architecture, not only is real-time monitoring of equipment status realized, but the operation and maintenance model is also promoted from reactive maintenance to predictive maintenance, significantly improving equipment reliability, production efficiency, and safety management levels. Although challenges remain in measurement accuracy, environmental adaptability, and standardization, with the deep integration of new materials, new processes, and artificial intelligence technologies, MEMS sensors will play an increasingly important role in building intelligent and adaptive industrial ecosystems, providing key technological support for industrial digital transformation.

Keywords: MEMS; MEMS sensors; Condition monitoring; Predictive maintenance; Industrial Internet of Things (IIoT)

1 INTRODUCTION

With the advent of Industry 4.0 and the deepening of the concept of intelligent manufacturing, global industry is undergoing a digital and intelligent transformation centered on data. Against this backdrop, the health status of industrial equipment no longer relies solely on periodic maintenance and post-event repairs but urgently requires a new operation and maintenance paradigm capable of real-time perception, accurate prediction, and intelligent decision-making [1]. Traditional monitoring methods, due to their large size, high cost, and inconvenient deployment, are insufficient to meet the widespread demands of modern industry for equipment lifecycle management. Meanwhile, the booming development of IoT technology provides a solid foundation for the collection and exchange of massive amounts of data, but the most crucial "perception" link still requires breakthroughs through cutting-edge sensing technologies [2]. This convergence of industrial demands and technological development has propelled MEMS sensors to the forefront of industrial applications, and their unique technological advantages provide a highly promising path to solving the challenges.

MEMS sensors are a product of the deep integration of microelectronics technology and precision machining technology. They achieve the function of sensing the physical world by constructing miniature mechanical structures and circuit systems on silicon wafers. Since its inception in the latter half of the last century, MEMS technology has experienced rapid development from laboratory research to commercial applications. Its most significant feature is the successful reduction of sensor size, cost, and power consumption to levels unattainable by traditional technologies, while ensuring sufficient measurement, accuracy and reliability [3]. From initial triggering of automotive airbags to smartphones and wearable devices in the consumer electronics field, MEMS sensors have proven their maturity and stability in large-scale applications. Today, continuous technological iteration is driving its evolution towards higher performance, greater intelligence, and richer functions, paving the way for entry into more demanding industrial fields.

The development of industrial equipment condition sensing and the IoT together constitute the two major engines driving this transformation. On the one hand, the goal of industrial equipment condition sensing has evolved from simple fault alarms to early identification of equipment degradation processes, accurate diagnosis of fault modes, and prediction of remaining lifespan. This forms the cornerstone of predictive maintenance and is key to ensuring production safety, improving operational efficiency, and reducing maintenance costs [4]. On the other hand, the IIoT aims to build a vast network ecosystem connecting physical devices and the digital world, realizing a closed-loop process of data acquisition, transmission, analysis, and execution. However, the value of this ecosystem is highly dependent on the coverage density, data quality, and economic feasibility of its peripheral nerves-the sensors deployed on various devices. Therefore, the industry urgently needs a smart sensing solution that can be deployed on a large scale and at low cost.

Looking at research and practice both domestically and internationally, academia and industry have long recognized the enormous potential of MEMS sensors in the industrial field. Early research mainly focused on verifying the feasibility of devices such as MEMS accelerometers in vibration monitoring and comparing them with traditional piezoelectric sensors. In recent years, research has shifted its focus to how to compensate for the shortcomings of MEMS sensors in some performance respects through advanced signal processing algorithms, and how to utilize their multi-parameter sensing capabilities (such as simultaneous monitoring of vibration, temperature, and tilt) for multi-dimensional fault diagnosis [5]. At the application level, leading international industrial enterprises and technology companies have launched wireless monitoring nodes and solutions integrating MEMS sensors, which have been successfully applied in various scenarios such as wind power, mining, and factories. Domestic research and applications are also catching up rapidly, achieving significant results in pilot projects in specific fields. However, there is still room for improvement and catching up in terms of the extreme environmental adaptability of sensor chips, the accuracy of data analysis models, and the maturity of overall solutions.

Based on the above background and analysis, this paper will systematically explore how MEMS sensors can empower industrial equipment's state perception and deeply integrate with IoT technology. The full text will first analyze the core technical principles of MEMS sensors and their unique properties in industrial environments; then, it will elaborate on the key technical implementation paths of MEMS sensors in equipment state perception, including multi-parameter perception and intelligent edge algorithms; next, by constructing its integrated architecture in the industrial IoT and combining typical application cases, it will specifically analyze the practical benefits it brings; finally, it will summarize the current technical and application challenges and look forward to future development trends [6]. The research in this paper aims to provide theoretical reference and practical guidance for the deeper and wider application of MEMS sensors in the industrial field.

2 TECHNICAL PRINCIPLES AND CHARACTERISTICS OF SENSORS IN MICROELECTROMECHANICAL SYSTEMS

The technological foundation of MEMS sensors originates from silicon micromachining, a precision manufacturing technology for constructing micro-mechanical structures and electronic components on silicon-based materials. Its core lies in borrowing from and surpassing the planar processes of integrated circuits. Through steps such as photolithography, thin film deposition, ion implantation, and etching, complex three-dimensional microstructures such as movable mechanical parts, cantilever beams, mass blocks, and cavities can be precisely "carved" onto chips [7]. These processes not only achieve miniaturization of the structure but also enable the sensor core unit and signal conditioning and processing circuits to be integrated onto the same chip, forming a so-called "system-on-a-chip." This manufacturing paradigm has brought about a revolutionary change, transforming sensors from independent discrete components into fully functional micro-systems, laying the physical foundation for subsequent mass production, performance consistency, and cost control.

In the broad spectrum of industrial applications, several key MEMS sensor types play an indispensable role. MEMS accelerometers sense acceleration by detecting the displacement of a mass block under inertial force. This principle makes them the cornerstone of equipment vibration monitoring and shock analysis, enabling them to sensitively capture early fault characteristics such as bearing wear and rotor imbalance in rotating machinery. Complementing this is the MEMS gyroscope, which uses Coriolis force to measure angular velocity. This is crucial for monitoring subtle tilts in large structures, tracking the precise posture of robotic arms, and even assessing torsional vibrations in turbines [8]. MEMS pressure sensors, typically based on piezoresistive or capacitive effects, sense the deformation of a microdiaphragm caused by medium pressure and are widely used in monitoring the status of hydraulic systems, fluid pipeline pressure, and fan pressure. Furthermore, MEMS magnetometers determine orientation by detecting changes in the magnetic field. Combined with accelerometer and gyroscope data, they can achieve a more accurate attitude reference system. Other sensors, such as MEMS microphones for noise analysis and MEMS temperature sensors for thermal management, together form a multi-parameter, comprehensive industrial sensing network.

Undeniably, the rapid penetration of MEMS sensors into the industrial field is due to their three inherent advantages: miniaturization, low cost, and low power consumption. It's extremely small physical size allows it to be embedded in critical parts of equipment or even moving parts, achieving previously unattainable deployment density and monitoring flexibility. The mass production characteristics based on semiconductor technology have significantly reduced its unit cost, making large-scale, full-coverage sensor deployment economically feasible. At the same time, its microwatt-level ultra-low power consumption characteristics perfectly match the industrial Internet of Things' requirements for long-term, wireless, and battery-powered deployments, greatly reducing the complexity of installation and maintenance [9]. However, while embracing these advantages, we must also be aware of the challenges it faces in harsh industrial environments. Despite continuous technological advancements, some MEMS sensors still lag traditional high-precision sensors that have been optimized over decades in terms of absolute measurement accuracy, long-term stability, and noise levels. In addition, the extreme temperatures, severe shocks, strong electromagnetic interference, and corrosive environments commonly found in industrial settings pose severe challenges to the packaging reliability, material stability, and signal integrity of MEMS sensors with silicon as the main material. These remain key areas that current research and engineering applications need to continuously optimize and overcome.

3 KEY TECHNOLOGIES OF MEMS SENSORS IN INDUSTRIAL EQUIPMENT STATUS SENSING

The successful application of MEMS sensors to industrial equipment status perception is far more than simple data acquisition. Its core lies in a complete set of technologies that transform physical signals into operable insights. This process begins with the accurate capture of key status parameters of the equipment. Among the many parameters, the analysis of vibration signals is of the core. MEMS accelerometers can continuously capture the vibration spectrum of the equipment in three-dimensional space. By analyzing the amplitude and trend of specific frequency components (such as rotational frequency, harmonic frequency, and bearing passing frequency) in the spectrum, typical mechanical faults such as rotor imbalance, misalignment, bearing fatigue spalling, and gear tooth breakage can be accurately diagnosed [10]. At the same time, the monitoring of tilt angle and attitude provides a key basis for the safety assessment of large structures (such as wind turbine towers and large gantry cranes). The collaborative work of MEMS gyroscopes and accelerometers can calculate the tilt angle of the equipment in static conditions and the attitude change in dynamic conditions, effectively warning of the risks caused by foundation settlement or structural deformation. Furthermore, MEMS pressure sensors provide direct evidence of fluid system blockage, leakage, or pump efficiency reduction by sensing pressure fluctuations and average values in hydraulic systems, pneumatic pipelines, or sealed containers; while integrated temperature and humidity sensing units together constitute a microscopic portrait of the equipment's operating environment, which is crucial for assessing electrical connection status, preventing condensation hazards, and optimizing cooling efficiency.

Monitoring a single parameter often only reveals one aspect of the equipment's health status, while the failure modes of modern industrial equipment are usually the result of multiple coupled factors. Therefore, MEMS-based multi-sensor data fusion technology has become key to improving the reliability and depth of diagnostics. This technology can perform collaborative and correlation analysis on heterogeneous data collected from different types and locations of MEMS sensors (such as accelerometers, gyroscopes, pressure sensors) [11]. Such as correlating abnormal vibration signals with simultaneous temperature surges or slight attitude drifts can more accurately locate the source of the fault and distinguish between internal mechanical damage and secondary phenomena caused by external loads or foundation deformation. This cross-validation of multi-source information not only significantly reduces

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the false alarm rate, but also constructs a three-dimensional, mutually corroborating panoramic view of the equipment's health status, thereby enabling early and accurate identification of complex faults.

However, the direct transmission of massive amounts of raw data places a huge burden on industrial IoT networks, and the latency of cloud processing is insufficient to meet the demands of real-time response. This has spurred the deep involvement of edge computing and intelligent sensing algorithms. At the source of data generation—the device side where MEMS sensors are deployed-online feature extraction and signal processing are first performed on the raw signals through embedded edge computing nodes. This includes extracting key feature indicators (such as RMS value, peak factor, kurtosis, and spectral envelope) that can characterize the equipment status from the time domain, frequency domain, and time-frequency domain, thereby achieving "slimming down" and "purification" of the raw data. Furthermore, advanced intelligent algorithm models can be deployed at the edge to utilize these extracted features for real-time pattern recognition [12]. By establishing an early fault warning model based on machine learning or deep learning, the system can autonomously learn the degradation trajectory of equipment from normal to abnormal state, and issue warnings in the nascent stage before a fault occurs, realizing a fundamental transformation from passive response to proactive prediction in operation and maintenance mode, and ultimately completing the intelligent leap from "perception" to "cognition".

4 INTEGRATION AND APPLICATION OF MEMS SENSORS AND INDUSTRIAL INTERNET OF THINGS

The true stage for the revolutionary impact of MEMS sensors lies in their deep integration with the IIoT system. In this grand technological architecture, MEMS sensors play a crucial role as the system's peripheral nerves, forming the foundation for perceiving the physical world. As data acquisition tools, they are densely deployed throughout factories, converting the physical states of equipment, such as vibration, posture, and pressure, into initial digital signals, achieving monitoring coverage from key points to the entire system. These signals are efficiently converged to the network layer through wireless transmission protocols optimized for low-power, wide-area scenarios (such as LoRa, NB-IoT, and Wi-Fi), solving the cabling challenges of traditional wired deployments. Ultimately, the data is integrated, analyzed, and visualized in cloud platforms or edge computing nodes, supporting advanced applications such as predictive maintenance and asset performance management, completing a full closed loop from raw data to decision-making value, transforming cold machine data into a core production factor driving operational optimization.

This integrated model has demonstrated powerful vitality in multiple industrial scenarios. In the field of predictive maintenance for rotating machinery, MEMS vibration sensors attached to the bearing housings of motors, pumps, and fans can continuously capture subtle changes in the health status of equipment. Through long-term tracking and analysis of vibration spectra, the system can accurately identify early signs of failure such as bearing wear and rotor imbalance, thereby transforming maintenance activities from fixed periodic inspections to precise interventions based on the actual condition of the equipment, effectively avoiding unplanned downtime. In the health monitoring of large structures, MEMS tilt and acceleration sensor networks deployed on bridges, tower cranes, or high-voltage towers constitute a system for real-time perception of structural safety. They can monitor the deformation and vibration response of structures under wind loads, temperature differences, and long-term loads,

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providing indispensable data support for assessing structural integrity and providing early warnings of excessive displacement or damage accumulation, greatly ensuring the safe operation of public infrastructure. Within smart factories, the efficient collaborative operation of automated guided vehicles (AGVs) and industrial robots relies on the accurate perception of their own status. MEMS inertial sensors integrated into robot joints provide real-time feedback on motion posture and vibration, ensuring precise and smooth movements. Simultaneously, this data is used to assess the wear condition of mechanical components, providing a basis for preventative maintenance of the robot and ensuring the continuity and stability of the flexible production line.

Through the above application practices, the benefits of integrating MEMS sensors with the IIoT are comprehensive and far-reaching. The most direct demonstration is a significant improvement in equipment operational reliability and overall production efficiency, as the reduction in unplanned downtime directly translates into an increase in effective operating time. In terms of economic benefits, it drives the shift in operation and maintenance models from reactive repair and scheduled maintenance to predictive maintenance, significantly reducing spare parts inventory costs, unnecessary preventative maintenance expenses, and huge production losses caused by sudden failures. Furthermore, by eliminating potential hazards in advance, it fundamentally reduces the risk of safety accidents that may arise from equipment failures. Ultimately, the profound significance of this technological combination lies in enabling enterprise management decisions to move away from relying on experience or lagging indicators and instead be based on a deep, real-time, data-driven understanding of the operational status of their physical assets, thus moving towards a smarter and more precise new paradigm of industrial operation.

5 CHALLENGES AND DEVELOPMENT TRENDS

While MEMS sensors have demonstrated immense potential in the IIoT field, their path to widespread adoption still faces numerous practical challenges. At the technical level, the core challenge lies in balancing performance and cost. Although MEMS sensors generally meet the requirements for most scenarios in terms of general specifications, their measurement accuracy, long-term stability, and overload resistance still lag traditional specialized sensors in extreme operating conditions involving precise diagnostics and high reliability. Harsh industrial environments, such as continuous high temperatures, strong electromagnetic interference, and chemical corrosion, pose severe challenges to sensor packaging technology and material durability. Simultaneously, there remains ongoing engineering optimization pressure in pursuing lower power consumption to extend battery life and in achieving greater functional integration within miniaturized spaces.

Beyond the technology itself, the construction of the application ecosystem also faces bottlenecks. Currently, the industry lacks unified interfaces, data formats, and performance evaluation standards, leading to difficulties in interoperability between sensors and platforms from different manufacturers, increasing the complexity and cost of system integration. With the surge in monitoring data volume, information security and privacy protection issues during transmission, storage, and processing are becoming increasingly prominent. Preventing data leaks and ensuring system resilience against attacks are crucial issues that must be addressed. Furthermore, seamlessly integrating the new MEMS monitoring system with existing heterogeneous control systems and management software in the factory to achieve smooth data flow and collaborative business logic is crucial to its successful implementation and value creation.

Looking ahead, a series of technological breakthroughs are guiding the development direction. The most significant trend is the intelligentization of sensing terminals. By integrating more powerful processing capabilities and artificial intelligence algorithms locally on sensor nodes, on-orbit data processing and feature extraction can be achieved, uploading only valuable results or alarms, thereby greatly reducing network load and improving real-time response. To completely solve power supply constraints, self-powered technologies that collect energy from the environment, such as mechanical vibration, temperature difference, and light energy, and convert it into electricity are expected to create "permanently online" maintenance-free sensing nodes. In terms of new materials and processes, the application of wide-bandgap semiconductor materials such as silicon carbide and aluminum nitride, as well as advanced manufacturing technologies such as 3D integration, will significantly improve the performance boundaries of sensors under high-temperature and high-frequency response conditions. Ultimately, all these advancements will converge on a common goal: to fully integrate MEMS sensing technology with the cyber-physical systems advocated by Industry 4.0 and the human-centered and resilient goals focused on by Industry 5.0, making it an indispensable sensing foundation for building future intelligent, sustainable, and adaptive industrial systems.

6 CONCLUSION AND OUTLOOK

This study systematically explores the integrated application of MEMS sensors in industrial equipment condition sensing and IoT. In-depth analysis confirms that MEMS sensors, with their unique advantages of miniaturization, low cost, and low power consumption, successfully overcome the bottlenecks of traditional monitoring technologies in terms of deployment density and economy, providing a physical foundation for building large-scale, fine-grained equipment condition sensing networks. Their comprehensive monitoring capabilities across multiple parameters such as vibration, attitude, and pressure, combined with edge computing and data fusion technologies, enable accurate diagnosis and early warning of complex industrial equipment. Practice shows that when MEMS sensors are deeply embedded in the architecture of the Industrial IoT, they are no longer merely data acquisition terminals, but key enablers for predictive maintenance and driving operational decision-making changes, significantly improving equipment reliability, production efficiency, and safety management.

Looking to the future, this field still holds vast innovation potential and development opportunities. Future research should focus on the following directions: at the sensing level, there is an urgent need to develop novel sensitive materials and smart structures for extreme operating conditions, and to improve the intrinsic performance and environmental robustness of sensors through micro-nano process innovation. At the system level, efforts should be focused on building an intelligent processing paradigm that integrates edge, cloud, and endpoint technologies. Research should be conducted on how to implement more accurate and lightweight fault diagnosis algorithms at resource-constrained edge nodes, while simultaneously strengthening the development of cross-platform data interaction standards and secure transmission mechanisms. From an application ecosystem perspective, it is necessary to explore the deep coupling of MEMS sensing data and digital twin models to achieve dynamic mapping and prediction of the entire lifecycle status of equipment and further explore its value in emerging paradigms such as the industrial metaverse. Ultimately, with the continuous evolution of technology and the expansion of application scenarios, MEMS sensors will inevitably integrate more closely with cutting-edge technologies such as artificial intelligence and energy harvesting, becoming an indispensable nerve ending in building a

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future intelligent and adaptive industrial system, injecting continuous momentum into the digital transformation and upgrading of industry.

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