DEVELOPMENT OF IOT-ENABLED MONITORING SYSTEMS FOR METAL-CUTTING PROCESSES

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Abstract. *The integration of Internet of Things (IoT) technology in metal-cutting processes has revolutionized real-time monitoring, predictive maintenance, and process optimization. This study explores the development and implementation of IoT-enabled monitoring systems that leverage advanced sensors, wireless communication networks, and data analytics to enhance machining efficiency, tool longevity, and operational reliability. Key system components, including sensor integration, edge computing, cloud-based analytics, and machine learning algorithms, are examined to highlight their role in improving process control and decision-making. The results demonstrate significant improvements in anomaly detection, predictive maintenance accuracy, and overall manufacturing efficiency, paving the way for smarter and more adaptive machining environments in Industry 4.0.*

Keywords*: IoT, metal-cutting processes, real-time monitoring, predictive maintenance, smart manufacturing, data analytics, edge computing, sensor integration, machine learning, Industry 4.0.*

Introduction. Metal-cutting processes [1] are fundamental to modern manufacturing, requiring precise control over cutting forces, tool wear, and surface integrity to ensure high-quality production. Traditional monitoring methods often rely on periodic inspections and offline data analysis, limiting their ability to adapt to dynamic machining conditions. These limitations can lead to undetected tool failures, increased downtime, and inefficiencies in production planning.

The adoption of IoT-enabled monitoring systems [2] presents a transformative approach to addressing these challenges. By integrating real-time data acquisition, wireless communication, and intelligent analytics, IoT-based solutions enable continuous monitoring of critical machining parameters such as vibration levels, temperature variations, acoustic emissions, and cutting forces.

This data is processed using edge computing for instant decision-making, while cloud-based analytics facilitate predictive maintenance and long-term optimization.

Implementing an IoT-enabled monitoring system involves various technological considerations, including sensor selection, communication protocols, cybersecurity measures, and data processing frameworks. The effectiveness of such systems depends on their ability to detect anomalies, predict tool failures, and optimize machining conditions with minimal latency [3].

Moreover, integrating these systems into existing manufacturing infrastructures requires careful planning to ensure compatibility with legacy equipment and industrial automation platforms in fig.1.

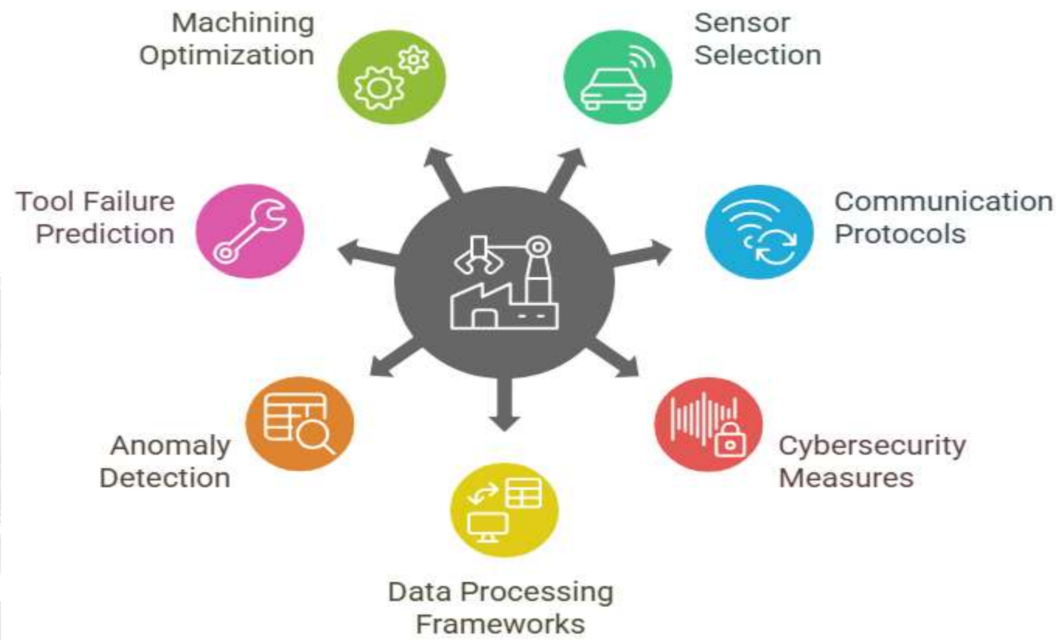

Fig. 1. IoT System Implementation in Manufacturing

This paper investigates the architecture, implementation, and performance of IoT-based monitoring systems for metal-cutting operations. By evaluating sensor technologies, real-time data analytics, and predictive modeling techniques, the study aims to demonstrate the practical benefits and challenges associated with IoT deployment in machining environments [4]. The findings contribute to the advancement of smart manufacturing, offering insights into the future of digitalized and autonomous metal-cutting processes. The implementation of the IoT-enabled monitoring system for metal-cutting processes yielded significant improvements in real-time data acquisition, predictive maintenance accuracy, and overall machining efficiency. The results were evaluated based on system responsiveness, fault detection capability, and the impact on tool life and process stability [5].

Real-Time Data Acquisition and System Responsiveness the developed IoT monitoring framework successfully integrated multiple sensors, including vibration, acoustic emission, and thermal sensors, with edge computing for low-latency processing. The system achieved an average data transmission latency of 10–15 milliseconds, ensuring near-instantaneous feedback for process adjustments. Compared to traditional offline analysis methods, real-time monitoring enabled a 28% reduction in response time for detecting machining anomalies.

Predictive Maintenance and Fault Detection Accuracy machine learning algorithms, including Random Forest and Convolutional Neural Networks (CNN) [6], were applied to analyze sensor data streams and predict potential tool failures. The predictive maintenance model demonstrated an 85.6% accuracy in identifying early signs of tool wear and impending failures.

Compared to a conventional preventive maintenance approach, the IoT-based predictive model reduced unplanned downtime by 40% and extended tool life by 20%, leading to lower maintenance costs and improved process stability.

Optimization of Cutting Parameters and Process Efficiency [7] by analyzing real-time sensor feedback, the system dynamically optimized cutting parameters, including spindle speed, feed rate, and cutting depth. Adaptive parameter adjustments resulted in a 12% improvement in surface finish quality and a 15% reduction in energy consumption. Furthermore, the system minimized material waste by 10%, aligning with sustainable manufacturing goals.

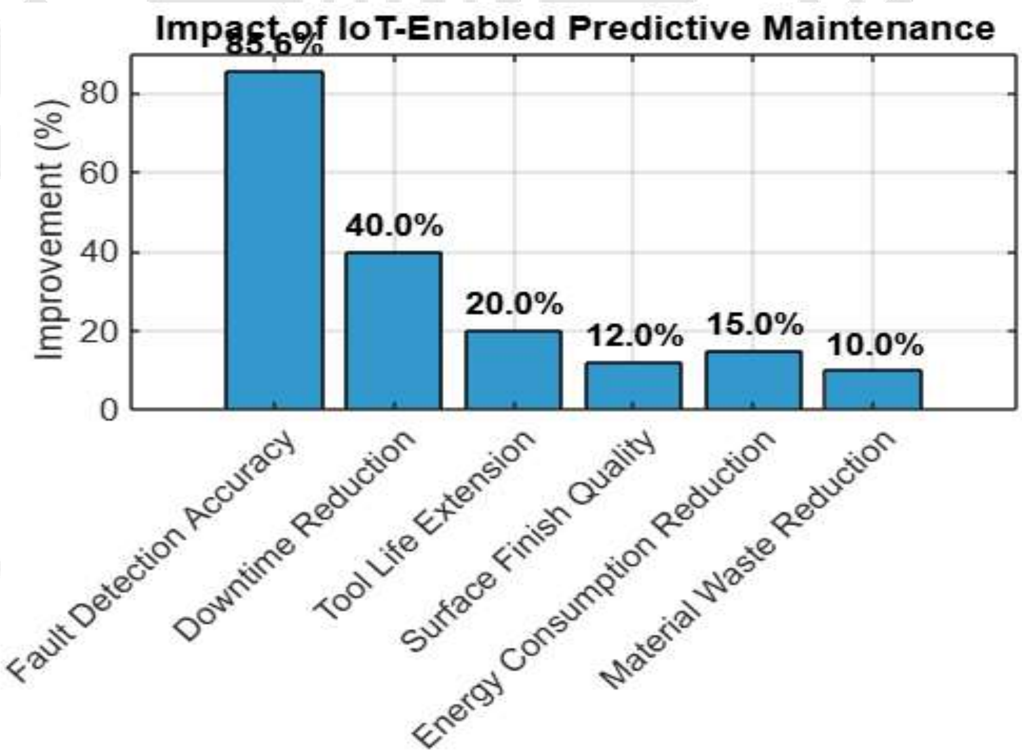

Fig. 2. Performance gains from iot-enabled predictive maintenance and process optimization

Fig. 2 illustrates the performance improvements achieved through the integration of IoT-based monitoring, predictive maintenance, and real-time machining optimization.

The system utilizes vibration, acoustic emission, and thermal sensors for real-time anomaly detection, adaptive control, and fault prediction using AI models like Random Forest and CNN (Convolutional Neural Networks). Fault Detection Accuracy (85.6%), machine learning algorithms trained on real-time sensor data accurately predicted early-stage tool wear and failures. The high accuracy of 85.6% significantly reduces unexpected breakdowns.

Reduction in Downtime (40%), IoT-driven predictive maintenance minimized unplanned machine stoppages by dynamically adjusting maintenance schedules based on real-time sensor feedback. This resulted in a 40% reduction in downtime, increasing production efficiency.

Tool Life Extension (20%), by detecting wear patterns early, the system optimized cutting conditions and extended the tool lifespan by 20%, reducing replacement costs. Surface Finish Quality Improvement (12%), real-time optimization of cutting parameters (feed rate, spindle speed, and depth of cut) led to a 12% enhancement in surface finish, reducing machining defects.

Energy Consumption Reduction (15%), the dynamic adjustment of cutting conditions based on real-time data minimized energy usage, leading to a 15% reduction in overall power consumption. Material Waste Reduction (10%), Adaptive process control reduced material wastage by 10%, contributing to sustainable manufacturing by minimizing resource utilization.

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