Prototype of a Wireless MEMS-Based Sensor Node within a Wireless Sensor Network Concept

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Abstract: *The aim of this work is to implement a wireless communication system for MEMS-based sensors within the framework of Internet of Things (IoT) applications, specifically in the context of Predictive Maintenance (PdM). The focus is placed on developing a functional prototype of a wireless sensor node that enables efficient data acquisition and transmission from commercially available MEMS vibration sensors. The solution leverages an ESP32 microcontroller for data handling and Wi-Fi communication, forming the basis of a scalable wireless sensor network (WSN). The project emphasizes their integration into a wireless system architecture suitable for industrial monitoring scenarios. This approach aims to demonstrate how low-cost MEMS sensors, when combined with IoT technologies, can contribute to accessible and modular condition monitoring solutions aligned with Industry 4.0.*
Keywords*: MEMS, WIRELESS SENSOR NETWORK, PREDICTOVE MAINTENANCE, INDUSTRY 4.0, IOT*

1. Introduction

The ongoing transformation of industrial systems towards the principles of Industry 4.0 has increased the demand for intelligent, interconnected, and self-monitoring infrastructure [1]. Although many existing predictive maintenance solutions are technically capable, they remain financially out of reach or overly complex for small and medium-sized enterprises (SMEs). This concept paper aims to bridge this gap by proposing a scalable, cost-effective, and easy-to-integrate wireless sensor network (WSN) architecture. At the heart of this system are low-cost microelectromechanical systems (MEMS) accelerometers paired with widely available microcontrollers [2]. MEMS sensors offer a compact and affordable alternative to traditional solutions, making the technology suitable for a wider range of industrial applications [3]. Effective PdM practices not only reduce unplanned maintenance costs, but also enhance equipment reliability, directly impacting production continuity and quality [4]. This is particularly relevant in industries where machinery failure can lead to costly production halts or even safety hazards.

By integrating MEMS accelerometers with the ESP32 [5] microcontroller, this wireless sensor node prototype achieves a balance between cost efficiency and technical performance. The proposed nodes are compact, energy efficient, and capable of collecting high-resolution vibration and temperature data. Designed with modularity in mind, the system can scale seamlessly by adding synchronized nodes to maintain a precise time correlation between measurements.

To enhance accessibility, the system uses Wi-Fi for data transmission, enabling rapid deployment without the need for extensive cabling. The data collected are transmitted to a centralized database for processing, anomaly detection, and visualization. The use of a time series database ensures efficient handling of high-frequency data streams. In addition, the modular design of the system allows it to adapt to a wide range of industrial scenarios [6].

By democratizing access to PdM technologies, this concept offers SMEs an affordable path to implement intelligent maintenance practices. The following sections discuss related research, system architecture, potential use cases, and the anticipated impact on industrial maintenance strategies.

2. System Architecture

The proposed architecture is designed to be both modular and scalable, enabling easy integration and future expansion. Ensures that it can evolve alongside technological advancements and accommodate growing industrial demands.

2.1. Sensor Node

The WSN is built around a custom-designed sensor node that integrates the IIS3DWB MEMS accelerometer with the ESP32 NodeMCU microcontroller. A prototype of the sensor node is presented in Fig. 1.

Each sensor node has [7]:

- three-axis acceleration measurement,
- temperature measurement,
- data at sampling rates of up to 6 kHz,
- wide selectable bandwidth of up to 2.67 kHz,
- low noise density,
- full-scale acceleration ranges from ±2g to ±16g.

These characteristics make the IIS3DWB a highly suitable choice for PdM use cases where accurate temporal resolution and low-latency data handling are essential.

Each node operates autonomously and is powered by a 3.7V rechargeable lithium-ion battery. To support energy autonomy and operational safety, a dedicated power management circuit is integrated into the PCB, enabling efficient power regulation and secure battery charging.

Fig. 1 *Prototype of MEMS-based sensor which could be use in WSN architecture.*

2.2. Wireless Communication Architecture and Data Infrastructure

The proposed system architecture relies on Wi-Fi for data transmission, eliminating the need for physical cabling. This simplifies deployment, particularly in environments with limited accessibility or complex machine layouts. In this concept, the wireless connection is a fundamental design choice that supports scalability, modularity, and ease of integration.

Each sensor node is built around an ESP32-based platform, which includes an integrated Wi-Fi module. This component, sourced from the ESP32 development ecosystem, offers a cost-effective solution for wireless communication in IoT systems. As the network may consist of numerous sensor nodes deployed throughout a facility, one of the primary design considerations is the temporal synchronization of data acquisition. To achieve this, the Network Time Protocol (NTP) is implemented on all nodes. Synchronization through NTP ensures that all sensor measurements are time correlated, which is essential when assessing vibration patterns from multiple angles or comparing data across different machines on the same production line.

Data communication between the sensor nodes and the central server is carried out using the HTTP protocol. Basic diagram is shown in Fig. 2. This choice is motivated by the need to handle relatively large volumes of high-frequency data continuously generated by multiple nodes. HTTP provides a scalable framework for transmitting these data efficiently and securely. Each node sends structured measurement packets to a back-end server, where the data is parsed and stored in an InfluxDB time-series database. This database is optimized for handling large-scale sensor data streams with high write throughput and time-based query performance.

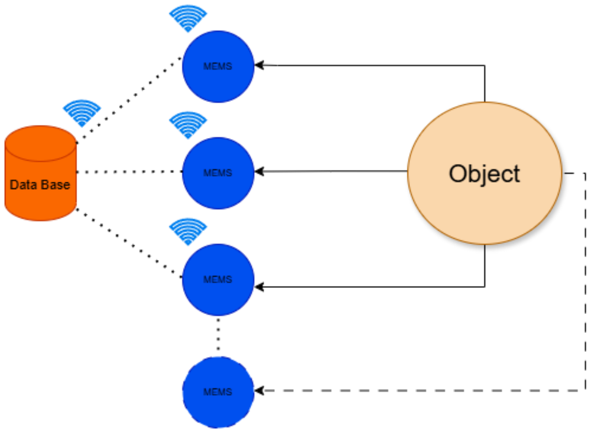

Fig. 2 *Basic diagram for multi-node PdM architecture.*

Data synchronization across multiple nodes is achieved using the Network Time Protocol (NTP), ensuring accurate time correlation among the distributed sensor nodes. This synchronization is crucial for multi-point vibration analysis and comparative diagnostics, as it guarantees that data collected from various locations remains temporally aligned. Without proper synchronization, phase shifts between measurements could lead to inaccurate assessments, particularly in applications involving vibration pattern analysis or machine condition monitoring. By integrating NTP synchronization directly into the startup procedure, the system minimizes human error and ensures that each measurement cycle begins with accurately synchronized nodes.

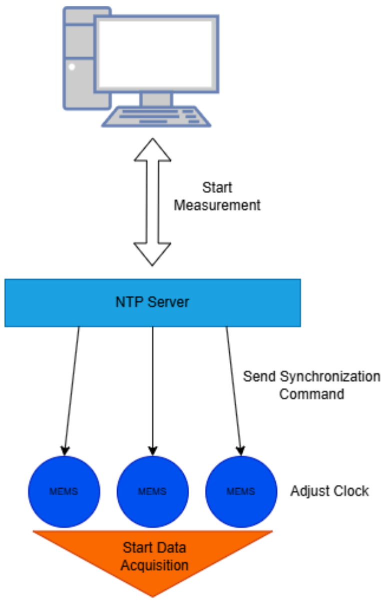

Fig. 3 *Schematic for nodes synchronization.*

To initiate the measurement process, an application is provided that allows operators to start, stop and manage data acquisition from a PC or mobile device. When the measurement is triggered, the application sends a synchronization signal to all sensor nodes, which in turn requests the current time from an NTP server. The nodes then adjust their internal clocks to match the received timestamp, achieving precise temporal alignment before data collection begins (Fig. 3). Once synchronized, the sensor nodes begin data acquisition, packaging the collected data into structured packets. These packets include a timestamp, sensor ID, and measurement data, ensuring that each data point can be accurately linked to a specific moment in time and a particular sensor location.

The proposed architecture envisions broader applications for the collected data. Beyond standard monitoring, the infrastructure supports integration with advanced systems such as virtual reality environments, real-time diagnostics, and AI-based predictive maintenance platforms.

3. Use Case and Applications

The proposed wireless sensor network system is designed to be flexible and adaptable, catering to diverse industrial environments ranging from traditional machine workshops to modern smart factories. One of its key advantages is the ease of scalability and customization, which allows it to be tailored to various machine setups without significant adjustments. This makes it particularly valuable for small and medium enterprises that often face financial constraints when adopting proprietary condition monitoring systems.

Using MEMS technology, sensor nodes offer a compact and cost-effective alternative to piezoelectric-based solutions [8]. MEMS sensors are approximately ten times cheaper while providing sufficient accuracy and sensitivity for PdM applications. This cost advantage allows SMEs to deploy comprehensive monitoring systems without incurring prohibitive expenses.

The WSN architecture is modular. Sensor nodes can be easily mounted on industrial assets such as motors, compressors, CNC machines, or other rotating equipment. Each node collects high-resolution acceleration data across the XYZ axes and temperature readings, which are important to identify early-stage mechanical problems such as imbalance, misalignment, or bearing faults.

A fundamental feature of this system is its ability to scale without requiring complex configurations. New sensor nodes can be added seamlessly, with automatic synchronization. The plug-and-play nature of the ESP32 firmware further enhances usability, allowing rapid expansion or reconfiguration to accommodate different machine layouts.

Furthermore, the wireless nature of the WSN eliminates the need for extensive cabling, making it particularly advantageous in facilities where machinery configurations frequently change or where mobility is required. This allows for quick deployment in both permanent and temporary monitoring setups.

Real-time data can be integrated with digital twins of the factory floor, developed using platforms like Unity or Unreal Engine. These virtual environments enable operators and engineers to view the health status of machines through color-coded overlays or animated vibration patterns. Such interactive visualizations promote an intuitive understanding of the conditions of the equipment, facilitating routine inspections.

In addition, maintenance personnel can receive proactive notifications and detailed status reports through mobile apps or smart devices, such as augmented reality glasses. These alerts are based on anomaly detection algorithms running on historical data stored in a time series database. By identifying deviations from normal operational patterns, the system can prompt timely maintenance actions, reducing downtime and prolonging the useful life of the machine.

Integration of the system with real-time diagnostic platforms and AI-based PdM algorithms also supports predictive maintenance. Operators can remotely analyze machine performance, receive early warnings of possible failures, and even simulate fault conditions within a Virtual Reality training module [9]. This approach to machine health management not only improves operational efficiency, but also enhances workforce training, allowing a deeper understanding of mechanical behaviors and maintenance strategies.

4. Discussion

The MEMS-based wireless sensor node presented within a WSN concept demonstrates significant potential for scalable, cost-effective predictive maintenance applications, especially in small and medium-sized enterprises. Using MEMS accelerometers, the system achieves a substantial reduction in cost compared to traditional piezoelectric sensors, making high-frequency vibration monitoring more accessible to a broader range of industrial settings.

One of the primary advantages of this architecture is its modularity and ease of integration. The use of the ESP32 microcontroller with built-in Wi-Fi enables seamless data transmission without the need for physical cabling, significantly reducing installation time and costs. Additionally, NTP-based time synchronization ensures that multinode data collection remains coherent, which is important when analysing vibration data from multiple measurement points.

However, some challenges remain to ensure data integrity and consistency as the system scales up. Network congestion and potential delays in NTP responses could affect the accuracy of synchronization, particularly in environments with fluctuating connectivity. To address this, it might be necessary to implement local time correction algorithms or to use alternative synchronization protocols in critical cases.

Moreover, reliance on Wi-Fi for data transmission could pose limitations in industrial environments with high electromagnetic interference or large physical obstructions. Future work could explore the incorporation of alternative wireless technologies to improve communication robustness and extend the operational range of the system.

Despite these challenges, the proposed system demonstrates a promising pathway for integrating PdM techniques into industrial processes cost-effectively. Its flexible architecture supports real-time monitoring, visualization, and scalable deployment, providing a foundation for the next generation of intelligent maintenance solutions.

5. Conclusion and Future Work

This paper posits a novel conceptual framework for a modular and scalable wireless sensor network based on accelerometer nodes based on MEMS, designed to facilitate predictive maintenance in a variety of industrial environments. By addressing key impediments to adoption, namely cost, architectural complexity, and proprietary systems, this concept aims to enable Small and Medium Enterprises to initiate their transition towards Industry 4.0 through a pragmatic and extensible instrumentation paradigm.

The proposed framework exhibits significant theoretical potential to transform conventional machinery condition monitoring practices via the provision of comprehensive data analytics and visualization modalities. The integrated aggregation of data streams from heterogeneous machinery within a unified monitoring architecture is theorized to enhance industrial process operational efficiency and underpin proactive maintenance strategies, thereby mitigating unscheduled downtime and associated maintenance expenditures.

Future work will involve empirical validation through physical instantiation and testing within operational environments to ascertain system performance characteristics and reliability metrics. Planned enhancements include the theoretical exploration and potential implementation of energy optimization strategies, such as adaptive sampling rates and duty cycling, alongside the investigation of alternative network connectivity protocols. The conceptual development of the Virtual Reality interface will be extended to incorporate real-time interactive capabilities and guided maintenance protocols, further augmenting the theoretical utility of the framework.

Subsequent efforts will aim to conceptualize a user-centric interface for on-site configuration and data retrieval, potentially incorporating mobile application interfaces and augmented reality overlays for real-time maintenance assistance. By synergistically combining sensor-derived data with Artificial Intelligence-driven PdM models, the framework has the potential to evolve into a holistic platform for intelligent maintenance, supporting decision-making processes with actionable analytical insights.

In parallel, the conceptual development of a cloud-based management portal \cite{Wang2017} enabling remote monitoring and configuration of distributed deployments, thereby theoretically paving the way towards fully integrated digital twins and intelligent factory ecosystems.

FUNDING

This research was funded by the AGH University of Krakow – Excellence Initiative – Research University, Action. 12 – Integration of educational process with scientific research – Support for student research clubs – Rector's grants, 5rd edition of the competition (ID 12443).

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