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Energy-Efficient Sensor System for Structural Wear Detection in Building Envelopes for Digital Twin and Predictive Analytics

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Summary: This paper presents the development of an energy-efficient sensor node designed for predictive maintenance in building infrastructure. By continuously monitoring temperature, humidity, pressure, and acceleration, the system detects mechanical wear in doors and windows. The intelligent combination of sensor data and low-power operation enables real-time maintenance recommendations, reducing costs and optimizing energy efficiency.

Keywords: Predictive maintenance, Sensor nodes, Energy efficiency, Building monitoring, Digital twin

Maintenance of windows and doors in buildings is often resource-intensive and time-consuming, especially when relying on fixed inspection intervals [1]. Such routines can overlook early wear, while reactive maintenance may lead to unexpected failures and increased energy loss [2].

This work introduces an energy-efficient sensor node for predictive maintenance. By continuously monitoring environmental and structural parameters, the system enables early detection of wear, reducing manual inspections and enabling targeted, data-driven interventions [3]. This approach enhances operational efficiency and supports long-term sustainability goals.

Method

Sensor Selection and Microstructure Design

The selection of sensors was guided by the need to capture high-resolution physical changes linked to structural wear while minimizing energy consumption and hardware complexity. The sensor node integrates analog-output components to monitor ambient pressure, humidity, temperature, and motion along three spatial axes. To enable meaningful interpretation, the sensors are combined with a microcontroller that performs local preprocessing, including offset correction and noise filtering. This ensures that only high-fidelity data contributes to downstream analytics. By embedding this preprocessed data into a predictive maintenance workflow, it becomes possible to replace manual inspection routines with real-time, sensor-driven diagnostics. This transformation not only lowers the frequency of physical maintenance but also enables early intervention before irreversible damage occurs.

Hardware Implementation

Two main circuit configurations were developed: a baseline model and an optimized energy-efficient variant. The baseline model provided the initial system architecture, facilitating comparative analysis. The optimized variant included enhancements such as the selective activation of sensors through an enable-pin on the voltage regulator and improved sensor layout to minimize power consumption and size. Energy consumption was significantly reduced from an initial 69.6mW to 16.6mW during active operation, and further minimized to 0.9 mW in sleep mode.

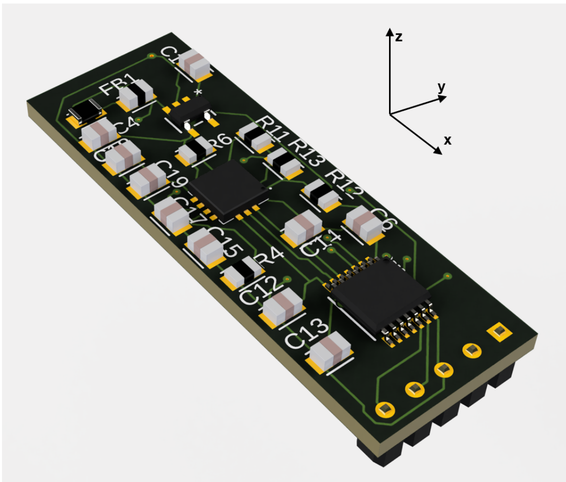

Fig. 1: 3D-Rendering of the sensor system

Figure 1 provides a 3D rendering of the final miniaturized sensor node. With dimensions of 14 mm × 40 mm, the compact form factor supports integration into space-constrained environments such as window or door frames. The layout includes a low-power microcontroller, dual voltage regulation with enable-pin control, and analog-output sensors. Components are densely placed to optimize PCB footprint while ensuring signal integrity through proximity-based placement of passive filtering elements. The design supports

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dynamic sensor activation to minimize energy usage. Additionally, the figure indicates the sensor's orientation axes for motion detection, aiding interpretation of measured accelerations in real-world applications.

Embedded Firmware, Signal Preprocessing, and Data Handling

The firmware manages sensor operation, data acquisition, and adaptive power control. Measurement intervals are dynamically triggered based on detected motion using a tri-axial accelerometer, reducing energy consumption during inactive periods.

Signal preprocessing includes offset correction, smoothing, and low-pass filtering to suppress noise and transient effects. Implausible values are filtered through statistical outlier detection without compromising trend fidelity. Time-synchronized and normalized sensor data ensures robust feature extraction.

Processed data is evaluated via a hybrid system: edge-level analytics detect immediate anomalies, while cloud-based analysis supports long-term trend evaluation.

Validation and Performance Analysis

The sensor node was validated by mounting it onto window frames and monitoring both environmental and mechanical influences under real-world conditions. Distinct acceleration peaks were consistently recorded during closure events, indicating structural impacts relevant for early-stage wear detection.

Beyond dynamic events, the system captured sustained shifts in Z-axis acceleration when the window was left in a tilted-open position. These deviations allowed differentiation between closed, open, and ventilated states. A tilt-angle estimation algorithm, based on gravitational offset, indicated a deviation of approximately 5.7° along the Z-axis—consistent with the physical tilt geometry of the test window.

To evaluate long-term performance, over 19 million raw sensor samples were recorded across multiple days. The data shown in Figure 2 represents unfiltered raw data and illustrates the correlation between acceleration events and window usage. These findings confirm that the sensor node reliably detects both transient mechanical shocks and static positional changes, supporting predictive maintenance strategies in building applications.

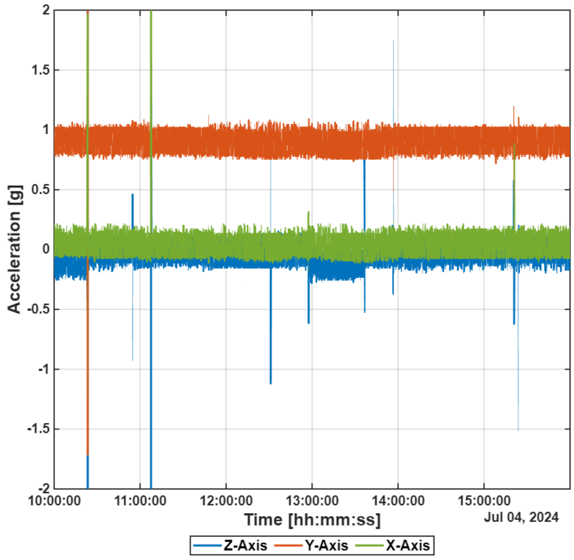

Fig. 2: Measured acceleration over time

Outlook: Digital Twin Expansion and Predictive Intelligence

Future work will focus on deepening integration with digital twin platforms to model wear progression and environmental effects over time. High-resolution sensor data will support real-time monitoring and long-term simulations within Building Information Modeling (BIM) environments. The predictive framework will be enhanced by AI-based analytics for fault detection and lifetime estimation. Wireless communication (e.g., Zigbee, BLE) and energy harvesting (e.g., photovoltaic, thermoelectric) will be added to support autonomous, maintenance-free operation. In future developments, MEMS-based sensors will be increasingly investigated for applications in jointed or flexibly mounted structures. [4]

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