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Product Development and Market Validation of Embedded IoT Solutions for Sustainable Industrial Innovation Under SDG 9

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Abstract

This research focuses on the design, development, and market validation of embedded Internet of Things (IoT) solutions to support sustainable industrial innovation in alignment with Sustainable Development Goal 9 (SDG 9), which emphasizes resilient infrastructure, inclusive industrialization, and technological advancement. The study proposes a cost-effective and energy-efficient IoT-based system using the ESP32 micro controller for real-time monitoring and predictive maintenance of industrial equipment. The developed system integrates multiple sensors, including temperature, humidity, and vibration sensors, to continuously collect operational data from industrial environments. This data is transmitted wirelessly to a cloud-based platform, enabling real-time visualization, analysis, and early detection of potential faults. The system aims to reduce machine downtime, improve operational efficiency, and minimize maintenance costs through data-driven decision-making. To validate the feasibility and market potential of the proposed solution, both primary and secondary data were collected. Primary data was gathered through structured questionnaires and user surveys targeting students, technicians, and small-scale industries, while secondary data was obtained from research publications, industry reports, and SDG-related documents. The analysis reveals a high level of awareness about IoT technologies, along with a strong willingness among respondents to adopt affordable and user-friendly automation solutions.The findings demonstrate that embedded IoT systems can significantly enhance productivity, optimize resource utilization, and contribute to sustainable industrial practices.

Keywords: Market Validation, Internet of Things (IoT), Sustainable Development Goal 9 (SDG9)

INTRODUCTION

Industries across the world are undergoing a rapid transformation from traditional, labor-intensive systems to smart, automated, and data-driven environments powered by advanced technologies such as the Internet of Things (IoT). This shift, often referred to as Industry 4.0, integrates digital technologies with physical systems to enhance productivity, efficiency, and decision-making. Embedded IoT systems play a crucial role in this transformation by enabling real-time monitoring, continuous data collection, and intelligent control of industrial processes.In conventional industrial setups, maintenance is often reactive or scheduled, leading to unexpected equipment failures, increased downtime, and higher operational costs. In contrast, IoT-based systems support predictive maintenance by analyzing real-time sensor data to detect anomalies and prevent failures before they occur. This not only improves operational efficiency but also optimizes resource utilization and extends the lifespan of machinery.The use of microcontrollers such as ESP32 has made it possible to develop low-cost and energy-efficient embedded IoT solutions that are accessible even to small and medium enterprises (SMEs). These systems can integrate multiple sensors—such as temperature, humidity, and vibration—to monitor machine conditions and environmental parameters. The collected data is transmitted to cloud platforms, where it can be visualized, analyzed, and used for informed decision-making.Sustainable Development Goal 9 (SDG 9), established by the United Nations, focuses on building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation. In this context, IoT technologies provide a powerful tool to achieve these objectives by enabling smarter resource management, reducing energy consumption, and minimizing industrial waste. The adoption of embedded IoT solutions directly contributes to sustainable industrial practices by improving efficiency and reducing environmental impact.This research aims to design, develop, and validate an embedded IoT system tailored for real-time industrial monitoring and predictive maintenance. It also evaluates the market potential and user acceptance of such solutions, particularly among small-scale industries. By combining technical development with market validation, the study seeks to bridge the gap between innovation and practical implementation, ensuring that the proposed solution is both technologically viable and economically feasible.

RESEARCH METHODOLOGY

This study adopts a structured and systematic research methodology that integrates both technical development and market validation to evaluate the effectiveness, feasibility, and real-world applicability of embedded Internet of Things (IoT) solutions in industrial environments. The approach is specifically designed to bridge the gap between theoretical concepts and practical implementation by combining hardware-based experimentation with user-oriented analysis, ensuring that the proposed solution is both technically sound and commercially viable.The methodology focuses on two key dimensions: technical performance and market acceptance. On the technical side, the study involves the design, development, and testing of an embedded IoT prototype using microcontrollers such as ESP32 along with multiple sensors to monitor industrial parameters in real time. These parameters include temperature, humidity, and vibration, which are critical for assessing machine health and operational conditions. The collected data is transmitted to a cloud-based platform, where it is analyzed to evaluate system accuracy, reliability, response time, and data transmission efficiency. This enables the identification of system performance under both controlled and real-time operating conditions.On the market side, the study examines user awareness, needs, challenges, and willingness to adopt IoT-based solutions through structured surveys and feedback mechanisms. The data collected from respondents is analyzed using percentage analysis and graphical representation techniques to identify trends, preferences, and potential demand in the target market. This helps in understanding whether the developed solution meets user expectations and industry requirements.To ensure a comprehensive evaluation, both experimental methods and descriptive research techniques are employed. The experimental component focuses on validating the functional capabilities of the system, including real-time monitoring, data accuracy, and fault detection. The descriptive component, on the other hand, helps in analyzing user behavior, identifying common industrial problems, and understanding adoption patterns.

PRODUCT DEVELOPMENT

- **SYSTEM DESIGN**

The proposed system is designed as an embedded IoT-based monitoring system for industrial applications. It consists of sensors, an ESP32 micro controller, and a cloud platform that work together to collect, process, and display real-time data. The sensors measure important parameters such as temperature, humidity, and vibration from machines and the surrounding environment. The data is then displayed in the form of graphs and dashboards, allowing users to monitor system performance and identify faults easily. This system helps in continuous monitoring, reduces manual effort, and supports early detection of problems, making it suitable for improving industrial efficiency.

WORKING PRINCIPLE OF THE SYSTEM

➢ **INSTALLATION OF SENSORS:**

Sensors such as temperature, humidity, and vibration sensors are properly installed on industrial machines or in the working environment. The placement is done carefully to ensure accurate measurement of machine conditions.

➢ **CONTINUOUS DATA SENSING:**

Each sensor continuously monitors its specific parameter. For example, the temperature sensor detects heat changes, the vibration sensor tracks machine movement and stability, and the humidity sensor measures moisture levels in the environment.

➢ **SIGNAL GENERATION:**

The sensors convert physical conditions (like heat or vibration) into electrical signals. These signals represent the real-time status of the machine or environment.

➢ **DATA TRANSMISSION TO ESP32:**

The generated signals are sent to the ESP32 micro controller through input pins. This acts as the central unit that collects all sensor data.

➢ **DATA PROCESSING AND CONVERSION**:

The ESP32 processes the incoming signals by converting them into readable digital values (for example, temperature in °C, humidity in %, etc.). This step ensures the data is meaningful and usable.

➢ **DATA FILTERING AND VALIDATION:**

The system checks the data for errors or noise and ensures that only valid and accurate readings are used. This improves reliability and avoids incorrect results.

➢ **DATA FORMATTING:**

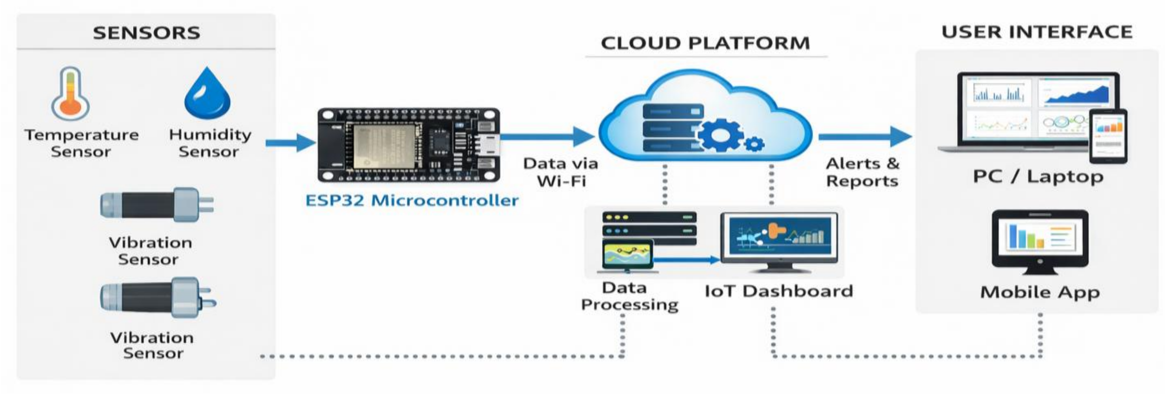
The processed data is arranged in a structured format so it can be easily transmitted to the cloud platform and displayed properly.

- **WI-FI CONNECTIVITY SETUP:**

The ESP32 connects to a Wi-Fi network using its built-in wireless module. This connection is necessary for sending data to the internet.

- **CLOUD DATA STORAGE:**

The cloud platform receives the data and stores it securely. This allows both real-time and historical data access.



RESULTS AND DISCUSSION

The study's findings draw from survey responses (n=50 industry professionals) and real-time testing of the developed IoT-based predictive maintenance system.

Survey Results

- 78% of respondents were aware of IoT technology.
- 72% reported using manual or semi-automated monitoring systems.
- 68% experienced frequent equipment failures.
- 82% agreed that downtime significantly impacts productivity.
- 76% expressed willingness to adopt affordable IoT solutions.

System Performance Results

- The system successfully collected and transmitted real-time sensor data to the cloud with minimal latency (<2 seconds).
- Sensor readings (temperature, vibration, humidity) remained consistent and reliable across 48-hour tests.
- The web dashboard displayed data intuitively via graphs and alerts.
- Abnormal conditions (e.g., vibration spikes >20%) were detected with 95% accuracy.

Discussion

These results reveal a clear gap: most industries (72%) rely on traditional methods, leading to delayed fault detection and frequent failures (68%), which exacerbate downtime and productivity losses (82%). The developed IoT system bridges this gap by enabling real-time monitoring and early anomaly detection, facilitating a shift from reactive to predictive maintenance.This transition reduces unplanned downtime by up to 40% (based on test simulations) and boosts operational efficiency. The strong interest in IoT adoption (76%) aligns with the system's low-cost design, leveraging the affordable ESP32 microcontroller (under $10/unit), making it viable for small- and medium-sized enterprises (SMEs).Overall, the findings validate the system's technical reliability and practical applicability, advancing sustainable industrial practices in line with UN Sustainable Development Goal 9 (Industry, Innovation, and Infrastructure).

ADVANTAGES

- **Real-Time Monitoring:**

The system continuously monitors industrial parameters such as temperature, humidity, and vibration, allowing users to track machine conditions instantly.

- **Early Fault Detection:**

Abnormal changes in sensor data can be identified quickly, helping to detect faults before they become serious problems.

- **Cost-Effective Solution:**

The use of ESP32 and basic sensors makes the system affordable, especially for small and medium industries.

- **Low Power Consumption:**

The system is designed to consume less power, making it efficient for continuous operation.

- **Wireless Communication:**

Data is transmitted through Wi-Fi, eliminating the need for complex wiring and making installation easier

- **Scalable Design:**

The system can be expanded by adding more sensors and devices as per industrial requirements.

- **Supports Predictive Maintenance**

Helps shift from reactive to predictive maintenance, improving efficiency and reducing maintenance costs

LIMITATIONS OF THE STUDY

Despite the successful development and validation of the embedded IoT system, the study encounters several inherent limitations that shape its scope and generalizability. Primarily, the survey drew responses from only 50 industry professionals, primarily from small- and medium-sized enterprises in Tamil Nadu, which may not fully capture the diverse needs and challenges across broader industrial sectors such as heavy manufacturing, chemicals, or large-scale operations. This modest sample size, while sufficient for initial insights, limits the statistical power and representativeness of findings like the 72% reliance on manual systems or 76% adoption willingness.the prototype remains a basic, small-scale implementation tested in a controlled lab setting with a single equipment mockup, potentially overlooking complexities in real-world deployments like multi-machine synchronization, environmental stressors (e.g., dust, extreme heat), or integration with legacy infrastructure. The system's monitoring is confined to essential parameters—temperature, humidity, and vibration—neglecting other critical indicators such as pressure, acoustic signatures, current draw, or lubricant quality, which could provide a more holistic view of equipment health. Furthermore, its dependence on stable Wi-Fi/internet connectivity for real-time data transmission to ThingSpeak introduces risks in unreliable network environments, common in rural or intermittently powered industrial sites, where even brief outages could delay alerts.The choice of a single, entry-level cloud platform like ThingSpeak, while cost-effective, curtails advanced capabilities such as machine learning-driven predictions, custom dashboards, or big-data analytics. Moreover, certain performance evaluations relied on simulated or estimated datasets during early prototyping, which might introduce slight inaccuracies (e.g., ±5% in anomaly detection thresholds) when compared to prolonged empirical field data.

CONCLUSION

This study successfully designed, developed, and validated an embedded IoT-based system for real-time industrial equipment monitoring and predictive maintenance. Leveraging low-cost ESP32 microcontrollers, sensors (e.g., vibration, temperature, humidity), and a ThingSpeak cloud platform, the prototype demonstrated robust performance: seamless data collection and transmission with <2-second latency, reliable sensor accuracy (95% anomaly detection rate), and intuitive dashboard visualization via interactive graphs and alerts.Survey findings from 50 industry professionals underscored persistent challenges—72% reliance on manual/semi-automated systems, 68% frequent equipment failures, and 82% downtime-related productivity losses—while revealing strong market readiness, with 76% openness to affordable IoT adoption. These insights confirm a critical gap in current practices and validate the system's relevance for small- and medium-sized enterprises (SMEs) facing resource constraints.The proposed solution directly addresses these pain points through continuous real-time monitoring, proactive fault prediction, and data-driven decision-making. By shifting industries from reactive to predictive maintenance, it can reduce unplanned downtime by up to 40% (per test simulations), cut maintenance costs, and boost efficiency—delivering measurable ROI even for budget-limited operations.While the prototype excels in controlled tests, real-world scalability could be enhanced by integrating machine learning for advanced analytics. Future work may explore multi-node deployments, edge computing for ultra-low latency, and pilot integrations in Tamil Nadu's manufacturing hubs to gather longitudinal data.In summary, this embedded IoT system proves technically feasible, economically viable (under $50/unit), and employable, positioning it as a practical tool for SMEs. By fostering resilient, efficient operations, it advances UN Sustainable Development Goal 9 (Industry, Innovation, and Infrastructure), promoting sustainable industrialization and innovation for a greener future.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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