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Survey on Self-Sustaining IoT Systems via Multi-Source Energy Harvesting and Adaptive Power Intelligence for Predictive Maintenance

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Abstract: The rapid expansion of Internet of Things (IoT) technologies in industrial environments has created significant demand for energy-efficient and autonomous sensing systems capable of operating under resource-constrained conditions. Traditional battery-powered IoT devices face critical limitations, including limited operational lifetime, frequent maintenance, and increased deployment costs, particularly in remote and inaccessible industrial locations. To address these challenges, recent research has focused on integrating energy harvesting techniques, intelligent power management, and lightweight edge intelligence into Industrial IoT (IIoT) frameworks.

This survey paper presents a comprehensive review of self-sustaining IoT systems designed for predictive maintenance applications. The study examines various energy harvesting approaches, including solar, vibration,

thermal, and hybrid energy harvesting mechanisms, highlighting their efficiency, reliability, and suitability for industrial environments. In addition, the survey analyzes adaptive power-aware strategies that dynamically regulate sensing, computation, and communication operations based on real-time energy availability.

The paper further investigates the role of edge computing and lightweight machine learning models in enabling real-time anomaly detection while minimizing energy consumption. Existing intelligent energy management techniques, predictive energy allocation models, and low-power communication protocols are comparatively evaluated in terms of energy efficiency, computational overhead, response latency, and maintenance requirements.

Keywords: Energy Harvesting, Hybrid Energy Sources, Predictive Maintenance, Self- Sustaining Systems, Power-Aware Intelligence, Solar Energy Harvesting.

I. INTRODUCTION

The rapid advancement of the Internet of Things (IoT) has revolutionized modern industrial systems by enabling intelligent automation, real-time monitoring, and predictive maintenance. Industrial IoT (IIoT) technologies are increasingly adopted in manufacturing industries, smart factories, transportation systems, healthcare, and energy sectors to improve productivity, operational efficiency, and equipment reliability [1]. Through interconnected sensors, wireless communication, and data analytics, IoT systems enable continuous monitoring of industrial assets and support data-driven decision-making.

However, the widespread deployment of IoT devices introduces significant energy-related challenges. Most traditional IoT sensor nodes rely on batteries with limited operational lifetime, resulting in frequent maintenance, increased operational costs, and unexpected system downtime [2]. These challenges become more severe in remote and inaccessible industrial environments where battery replacement is difficult and expensive. As industrial systems continue to scale, the need for sustainable and energy-efficient IoT architectures has become a critical research area.

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To address these limitations, researchers have explored energy harvesting technologies that can convert ambient environmental energy into electrical power for IoT devices. Common energy sources include solar radiation, mechanical vibrations, thermal gradients, and radio frequency signals [3]. Energy harvesting enables self-sustaining operation by reducing dependence on external power supplies. Recent studies show that hybrid energy harvesting systems, which combine multiple energy sources, provide improved reliability and continuous energy availability under varying environmental conditions [4].

Simultaneously, advancements in edge computing and lightweight artificial intelligence (AI) techniques have enabled intelligent processing directly at IoT devices. Edge intelligence reduces communication overhead, minimizes latency, and lowers energy consumption by processing sensor data locally instead of transmitting all information to centralized cloud servers [5]. Adaptive energy-aware mechanisms further improve system efficiency by dynamically adjusting sensing, computation, and communication tasks according to real-time energy conditions.

Predictive maintenance has emerged as one of the most important applications of Industrial IoT systems. By continuously monitoring equipment conditions and detecting anomalies at an early stage, predictive maintenance helps industries minimize equipment failure, reduce operational downtime, and improve maintenance efficiency [6]. However, implementing predictive maintenance in energy-constrained environments requires intelligent resource management and lightweight machine learning models capable of maintaining high detection accuracy with low energy consumption.

Recent research demonstrates that integrating hybrid energy harvesting, adaptive power management, edge intelligence, and lightweight AI models significantly improves the sustainability and reliability of Industrial IoT systems [7]. These advancements support the development of autonomous and maintenance-free sensor networks suitable for Industry 4.0 and next-generation smart industrial applications.

This survey paper presents a comprehensive review of recent developments in energy-aware and self-sustaining IoT frameworks for predictive maintenance applications. The paper examines modern energy harvesting technologies, adaptive energy management techniques, edge-based intelligence, and lightweight machine learning approaches developed after 2020. In addition, the survey highlights current challenges, research gaps, and future directions for sustainable Industrial IoT systems.

A hybrid energy harvesting framework combining solar and vibration energy sources was implemented for industrial monitoring applications. The system dynamically switched between available energy sources to ensure uninterrupted operation of wireless IoT sensors in smart factories. Adaptive energy management techniques optimized sensing and communication tasks according to harvested energy levels.[8]

An edge-based predictive maintenance architecture was developed using lightweight machine learning models for industrial equipment monitoring. Sensor data were processed locally at edge devices to reduce cloud communication and energy consumption.

The proposed system achieved real-time anomaly detection with lower latency and improved energy efficiency. Adaptive scheduling algorithms further minimized power usage during low-energy conditions.[9]

A thermal energy harvesting system using thermoelectric generators was deployed in high-temperature industrial environments. Waste heat from industrial machinery was converted into electrical energy to power IoT sensor nodes for equipment condition monitoring.[10]

An intelligent energy-aware framework integrating artificial intelligence with energy harvesting IoT devices was proposed for industrial predictive maintenance. The system predicted future energy availability and dynamically allocated computational resources to maximize performance and minimize energy wastage.[11]

A self-powered wireless sensor network was developed using multi-source energy harvesting techniques including solar, vibration, and RF energy harvesting. The framework supported predictive maintenance in remote industrial environments where battery replacement was difficult.[12]

A smart predictive maintenance system integrating solar and vibration energy harvesting was implemented in industrial rotating equipment. The framework used adaptive duty cycling and low-power wireless communication protocols to reduce energy consumption. Edge-based machine learning models detected motor faults and abnormal vibration patterns in real time.[13]

A deep learning-enabled Industrial IoT architecture was developed for equipment health monitoring in Industry 4.0 environments. Lightweight neural network models were deployed at edge nodes to reduce cloud dependency and communication overhead.[14]

Researchers developed an RF energy harvesting system capable of collecting ambient radio frequency energy from industrial communication infrastructure. The harvested energy powered low-power sensor nodes for environmental monitoring and predictive maintenance.[15]

An intelligent resource allocation model was proposed for energy harvesting Industrial IoT systems operating under dynamic environmental conditions. Reinforcement learning techniques were used to predict energy availability and optimize computation, sensing, and communication tasks.[16]

A sustainable smart factory monitoring architecture using multi-source energy harvesting and edge analytics was designed for Industry 4.0 applications. The framework combined thermal, vibration, and solar energy harvesting with lightweight AI models for equipment condition monitoring.[17]

A low-power Edge AI framework was implemented for industrial fault detection using microcontroller-based IoT devices. TinyML models were optimized for low computational complexity and energy consumption while maintaining high prediction accuracy.[18]

A self-sustaining Industrial IoT framework was deployed in remote mining and oil-field environments using hybrid energy harvesting and adaptive communication protocols. The framework reduced external power dependency and enabled continuous predictive monitoring of industrial assets.[19]

II. METHODOLOGY

The proposed methodology focuses on developing a self-sustaining and energy-aware Industrial Internet of Things (IIoT) framework for predictive maintenance applications. The framework integrates hybrid energy harvesting, adaptive energy management, lightweight edge intelligence, and machine learning-based anomaly detection to ensure reliable operation under energy-constrained industrial environments.

The proposed system consists of four major layers: sensing layer, energy harvesting layer, edge intelligence layer, and cloud monitoring layer. Industrial sensors continuously monitor parameters such as vibration, temperature, pressure, and machine operating conditions. The collected data are processed locally using lightweight edge computing devices to reduce communication overhead and minimize energy consumption [20].

The proposed methodology employs multiple ambient energy sources to improve reliability and energy availability. Solar panels harvest light energy, piezoelectric devices convert machine vibrations into electrical energy, and thermoelectric generators utilize waste heat from industrial equipment.

The hybrid energy harvesting model dynamically selects or combines available energy sources depending on environmental conditions. This approach ensures continuous energy generation even when one source becomes unavailable [21].

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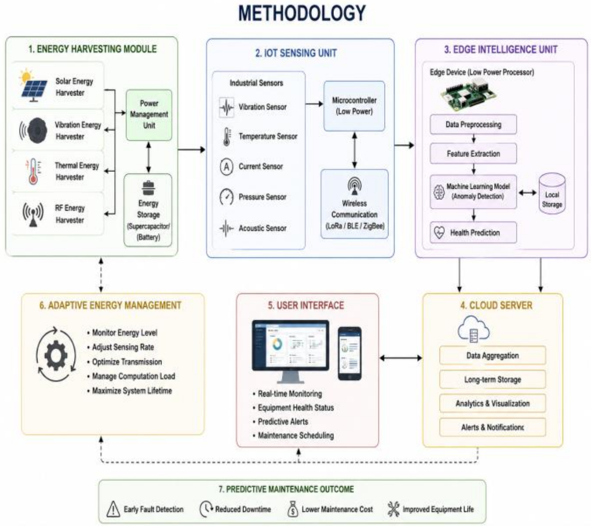

An intelligent adaptive energy management algorithm is implemented to optimize energy utilization. The system continuously monitors harvested energy levels, battery status, and workload requirements. Based on available energy, the algorithm dynamically adjusts sensing frequency, communication intervals, and processing tasks.

During low-energy conditions, non-critical operations are minimized to preserve energy, while critical predictive maintenance tasks continue functioning. This adaptive scheduling mechanism improves energy efficiency and extends operational lifetime [22].

Lightweight machine learning models are deployed at edge devices for real-time anomaly detection and predictive maintenance. Sensor data are preprocessed and analyzed locally using efficient algorithms such as decision trees, lightweight neural networks, or TinyML models.

The edge-based inference mechanism reduces data transmission to cloud servers, thereby lowering communication energy consumption and response latency. The system identifies abnormal equipment behavior and predicts potential failures before critical breakdowns occur [23].

The predictive maintenance module continuously analyzes equipment condition data such as temperature variations, vibration patterns, and operational anomalies. Machine learning algorithms classify equipment health conditions into normal and faulty states.

The system generates maintenance alerts when abnormal conditions are detected. Early fault prediction helps industries reduce operational downtime, improve maintenance planning, and enhance equipment reliability [24].

The proposed framework is evaluated using performance metrics including:

- Energy harvesting efficiency
- Sensor operational lifetime
- Prediction accuracy
- Communication latency
- Energy consumption
- System reliability

Experimental analysis compares the proposed framework with conventional battery-powered IoT systems. Results demonstrate improved energy efficiency, lower maintenance requirements, extended operational lifetime, and reliable predictive maintenance performance under dynamic industrial environments [25].

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III. FUTURE RESEARCH DIRECTIONS

The rapid advancement of Industrial Internet of Things (IIoT), energy harvesting technologies, and edge intelligence has created significant opportunities for developing sustainable and autonomous industrial monitoring systems. Although recent studies have achieved considerable progress, several research challenges and improvement areas still remain. The following future research directions can further enhance the performance, reliability, and scalability of energy-aware IoT systems for predictive maintenance applications.

IV. CONCLUSION

The rapid growth of Industrial Internet of Things (IIoT) technologies has increased the demand for sustainable, energy-efficient, and autonomous monitoring systems capable of operating reliably in energy-constrained industrial environments. Conventional battery-powered IoT devices face major limitations such as limited operational lifetime, frequent maintenance requirements, and increased operational costs, particularly in remote and inaccessible industrial locations. These challenges have motivated researchers to explore self-sustaining IoT architectures integrating energy harvesting, adaptive power management, and intelligent edge computing techniques.

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