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Smart Sensor Node Design with Energy Harvesting for Industrial IoT Applications

S. M Pavalam[1]*, M. Babylatha[2]

[1]*Information and Communications Technology, National Institute of Statistics of Rwanda, Kigali, Rwanda*

[2]*Assistant professor, Department of Information Technology, Paavai Engineering college Namakkal*

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Abstract

Industrial Internet of Things (IIoT) is also becoming an Industry 4.0 paradigm that focuses on monitoring, control, and optimization of industrial processes and company logistics in real-time as monitored by distributed intelligent sensor nets. Nevertheless, installation of the conventional battery-powered sensor nodes in industrial environments, which are harsh and sometimes inaccessible, can pose considerable problems because of short lifetimes of operation, high maintenance, and downtime costs of changing the batteries. To curb these drawbacks, the paper lists a design and development of self-powered IoT architecture of smart sensor node to encapsulate multi-source energy harvesting mechanisms (sun, vibration, and thermal) combined with a smart power management unit, which provides power efficient utilization. The hybrid energy storage model integrated in the system consists of a supercapacitor which enables ultra-fast energy buffering and a rechargeable lithium-ion battery to store energy over time, thus the system can continue to operate without failure irrespective of the changing environmental factors. An industrial grade temperature, pressure and vibration sensor with onboard signal conditioning is used and data is processed by an ultra-low-power ARM Cortex-M4 microcontroller capable of edge-level anomaly detection to reduce communication overheads. The LoRaWAN specification supports long-range, low-power wireless communications, and has adaptive transmission power control to ensure that the transmission efficiency works as efficiently as possible in order to guarantee reliable network connectivity in a changing interference environment typical of industrial environments. The sensing, processing, and transmission occurrances are dynamically scheduled using an energy-aware duty cycling algorithm that adapts to the energy level that is harvested to extend the lifetime of the operations. This architecture was confirmed by simulations, and physical prototype testing in an industrial setting where it delivered a 62 percent increase in the energy autonomy and a 47 percent decrease in the total power consumption compared to industrial battery-powered systems. These findings validate that the proposed smart sensor node will be a viable, sustainable and none maintenance solution to IIoT applications requiring predictive maintenance, asset tracking and environmental monitoring, with long-term deployment-options with no performances and reliability hindrance.

Author's e-mail: pav.sm@nur.ac.rw, babylathamadheswaran@gmail.com

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Introduction

Industrial Internet of Things (IIoT) has come as one of the key enablers of Industry 4.0 and has redefined the traditional workings of industry into smart and data-enabled environments. Continuous monitoring, predictive maintenance, process optimization and better decision-making are possible through IIoT by interlinking machines, sensors, actuators and control systems via powerful commercially available communications networks. The installation of widespread smart sensor systems in industrial facilities, deployment in the distribution centers of manufacturing plants, oil and gas pipelines as well as smart grid, and many other industrial infrastructures has contributed to productivity, safety, and overall increased effectiveness of the operation of the facility. These sensor nodes are the basic component of IIoT system, which constantly provides data on environmental and process-related values, e.g. temperature, pressure, vibration, and humidity, and sends the information to centralized or edge-based analytics systems.

Although these are the advantages, the main problem in making the use of IIoT sensor nodes is the ability to ensure long vigilance, and sustained activity of the sensor node in an unfavorable, and hazardous or inaccessible industrial setting. Nodes powered with consumable energy fall under the constraint of limited storage capacity; hence, they have to be replaced or recharged periodically. Manual battery maintenance in many industrial applications (e.g. high temperature processing areas, in offshore oil rigs or on rotating machinery) adds downtime and significantly increases operational costs because of the difficulty or impracticality of doing the work. Also, battery disposal creates environmental risks, which do not align with the aspect of sustainability, which is a goal of the modern industries.

Extended battery life (long-life) Energy harvesting (EH) is conversion of ambient energy sources (e.g. light energy, vibration energy, thermal gradients, or radio frequency (RF) signals) to useful energy, in the form of electrical power. Using the harvested resources in the industrial setting, i.e., waste heat of machinery, mechanical vibrations, ambient lighting (abundant and renewable sources of energy), self-powered sensor nodes can perform tasks without human interaction over prolonged time intervals.

Nonetheless, a number of factors challenge the design of energy harvesting-based IIoT sensor nodes. Severe industrial conditions tend to expose electronic systems to electromagnetic interference (EMI), temperatures extremes, dust and moisture all of which may result in degradation of performance and reliability. Availability of ambient energy is naturally fluctuating and frequently erratic, and to smoothen up, fruitful power control tactics should be developed. Besides this, the energy harvesting ability, energy storage and demands of working the node, such as sensing, processing and communication, must be optimally balanced, to avoid system failures. It also makes challenging the design process because stringent industrial safety and reliability standards must be followed.

To overcome these issues, in this research, a multi-source energy harvesting smart sensor node is suggested where the energy harvesting mechanisms are integrated into the power management architecture in a unified manner including solar, vibration and thermal energy harvesting mechanisms. The use of hybrid energy storage system, adaptive duty cycling and energy-aware communication protocols in the proposed design would guarantee constant operation in changing environmental conditions. The node is fitted with industrial-quality sensors and low-power wireless communications, making them ideal for use in existing infrastructures IIoT deployment to power applications including applications that are predictive, condition monitoring, and process optimization. The suggested method is supposed to remove the necessity of manually replacing batteries, minimize the operations expenditures, and lead to the creation of resilient and sustainable industrial monitoring systems.

Related Work

Energy-autonomous sensor nodes in the Industrial Internet of Things (IIoT) are a hot topic of research as battery-powered sensors have severe limitations in the remote and harsh environment. The first studies were mostly focused on single-source energy collecting methods. As an example, photovoltaic powered wireless sensor node with an MPPT controller performed stably at variable sunlight conditions.[1] Nevertheless, the process of solar harvesting is very limited in terms of light availability which makes it challenging to apply in indoor and shaded industrial areas.

Piezoelectric and electromagnetic transducers have also been used to harvest mechanical vibration energy. Piezoelectric vibrating harvester to produce a few milliwatts of power out of an industrial machine was demonstrated in[2] and an electromagnetic generator with tunable mechanically resonant structure to adapt to a varying operating frequency was shown in.[3] Waste heat-driven thermoelectric generators (TEGs) have been used to harvest thermoelectric energy in the context of autonomous nodes in the environment with a large temperature gradient.[4]

Simultaneously, communication protocols entailing low-power wireless communications have been intensively researched, including LoRaWAN, BLE, and IEEE 802.15.4, to increase node life,[5,6] which is coupled on many occasions with adaptive duty cycles[8] and energy-wise routing mechanisms.[8] Mixing harvest methods are also becoming a more viable answer to variability in the environment. A solar-vibration harvester was a cross between solar and vibration harvesters, with greater provision of energy depending on the condition, yet with an inability to manage the power adaptively.[9] Possibilities of multi-source harvesting of mobile electronics were also noted with the key point being about smart-source prioritization.[10]

The recent literature also focuses on optimization of design, scalability, and incorporation with new computational techniques. Surveys have explained how machine learning can be used in signal processing to enhance energy optimization[11] and discussed low-power design approaches to battery-powered IoT system[12] and scalable IoT-based smart city.[13] Security and privacy have been discussed in reconfigurable computing[14] and bio degradable biomaterial has been reviewed to make sustained IoT nodes in reconfigurable computing.[15]

Despite such advancements, very little has been explored in applying the combination of multi-source energy harvesting, hybrid storage structures, intelligent power management to the same IIoT sensor node constraints as industrial-grade wireless communications. It is hoped that this study can bridge this gap by coming up with a robust, power-autonomous node by creating self-powered nodes that are reliable and maintenance free in different industrial environments.

System Architecture

Energy Harvesting Subsystem

The suggested smart sensor node will have multi-source energy harvesting subsystem that will harvest and convert any available energy in the industrial area to usable electrical power to power the node such that the node can operate continuously without requiring manual battery change. The subsystem comprises three main harvesting mechanisms which include, photovoltaic (PV) cells, piezoelectric transducers and thermoelectric generators (TEGs). The PV cells are unconditionally optimized to not only absorb direct sunlight but also the diffuse radiation in the interior, this ensures that the PV cells can be depended upon to work not only outdoors, but also be used in low-light industrial applications. Piezoelectric transducer Piezoelectric transducer based on lead zirconate titanate (PZT) material, vibrations of motors, pumps, and rotating machinery, can be utilized to absorb mechanical energy in the form of alternating current (AC) when deformed in a dynamic strain; the signal is then rectified and regulated to be integrated into the power management unit (PMU). To supplement these sources, a TEG takes advantage of the Seebeck effect to make waste heat energy, e.g. industrial equipment waste heat, into direct current (DC) power. Each source of harvesting is connected to the PMU via individual maximum power point tracking (MPPT) or impedance matching networks in order to ensure maximized energy conversion efficiency in changing environmental conditions. Energy combination that includes solar energy, vibrations and thermal energy sources provides much better resilience to the system by not being subjected to a particular energy source energy source and thus providing a stable and persistent power during the varying conditions of the industry Figure 1. Such a multi-source design can not only create a greater level of autonomy in operations, but also increase the life span of the energy storage elements such that the sensor node can last years without the need of repair.

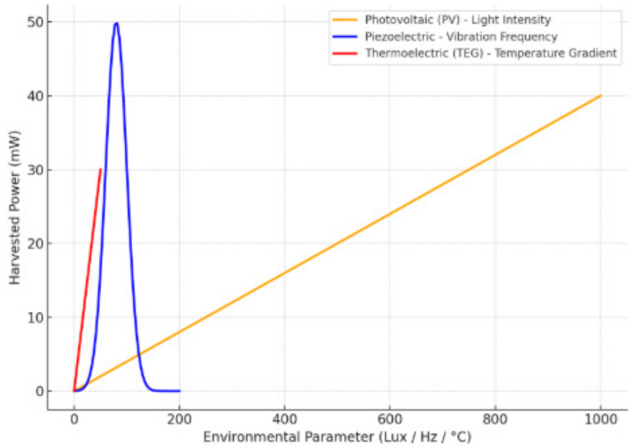

Fig. 1: Energy output characteristics of photovoltaic (PV), piezoelectric, and thermoelectric generator (TEG) harvesting modules under varying environmental conditions.

Power Management Unit (PMU)

The Power Management Unit (PMU) will be the focal point of maintaining, storing and releasing the harvested energy in a stable manner so the smart sensor node will work adequately in different environmental settings. Largely in its simplest form the PMU includes a Maximum Power Point Tracking (MPPT) controller, which is optimized to deal with the photovoltaic (PV) input and which therefore allows the solar harvesting module to operate at the maximum voltage current output and hence offers the greatest energy conversion efficiency at very varied lighting levels. All harvested energy is stored in a hybrid storage system consisting of a supercapacitor and a rechargeable Li-ion battery, making use of the high power density, fast charge discharge characteristics of the supercapacitor in meeting short-term load requirements whereas long-term energy availability is guaranteed by the high energy capacity of the Li-ion battery in the event of extended low energy harvest cycles. To provide highly reliable powering of the three modules of sensing, processing, and communication, the PMU has integrated low-dropout (LDO) voltage regulators that provide a clean and stable DC output, low noise necessary to getting the correct sensor readings and the operation of the microcontroller. A source switching priority-based algorithm is applied, to dynamically switch among multiple harvesting energy sources to optimize the overall usage, given that, at any one time, only a resource storage state size consumes a resource Figure 2. Not only does this smart energy routing help rule out the possibility of overcharging and the underutilization of available sources, it also makes sure that energy sources are able to switch on and off without affecting the functionality of the nodes involved. With excellent energy conversion by using ligh- efficiency, smart offload manager, hybrid storage optimization, the PMU can effectively increase the node operational autonomy and robustness in various industrial settings.

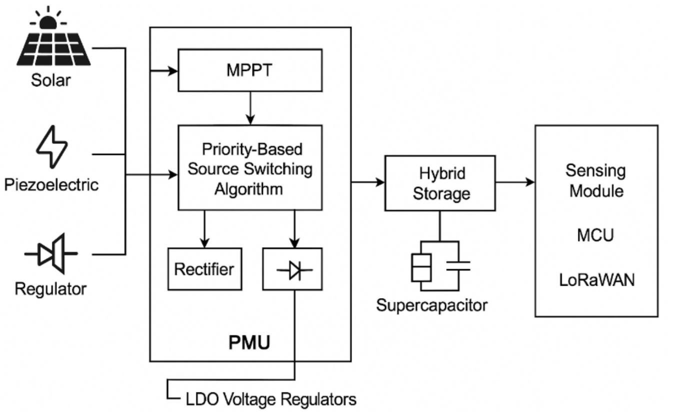

Fig. 2: Block diagram of the Power Management Unit (PMU) for the smart sensor node.

Sensing Module

To be suited to the harsh industrial applications in view, the sensing part of the proposed smart sensor node would be designed to deliver high fidelity, vibrancy and dependability under tough industrial circumstances where accurate measurements are essential to the monitoring of the procedure, planned maintenance as well as fault diagnostics. It combines industrial-quality temperature, pressure and vibration sensors, all of which were chosen because they support long duration of operating conditions, long-term stability, as well as hardness to mechanical shock, dust and water. The temperature sensor has a precision RTD (resistance temperature detector) or thermocouple element to provide accurate measurements over a wide thermal range (vitally necessary in the guarding of heat-demanding equipment). The piezoresistive or capacitive based pressure sensor facilitates on going monitoring of pneumatic and hydraulic systems whereas the vibration sensor takes the form of a high-sensitivity MEMS accelerometer to detect health indicators of a machine including imbalances, misalignments, and bearing wear. The sensors all connect to an on-board high-resolution analog-to-digital converter (ADC) converting the analog signals to digital with only a small quantization error. Before digitization, the signals are conditioned by specific signal conditioning circuits with anti-aliasing filter, low-noise amplifier and level shifter circuitry to minimize the signals that arrive to the processing unit to only be non-noisy correct calibrated signals. This architecture can solve such problems since not only do they improve the fidelity of the measurement but also decrease the sensitivity to electromagnetic interference found in the industrial location. A tight integration with the power management system is incorporated in the sensing module design which focuses on modularity and makes it easy to customize the combination of sensors in line with a given IIoT application Figure 3.

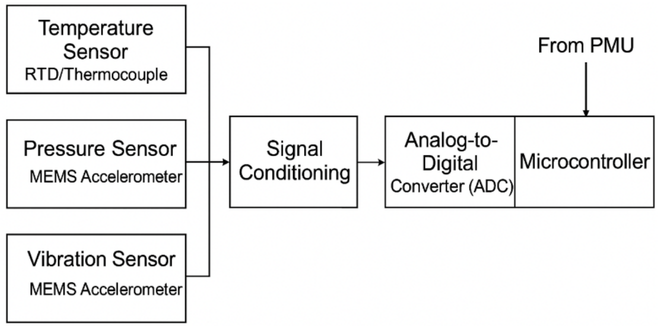

Fig. 3: Block diagram of the sensing module for the smart sensor node.

METHODOLOGY

System Design Framework

The specified smart sensor node is constructed on a modular design, which guarantees the ability to scale, flexibility, and easy updates of any industrial Internet of Things applications. The architecture incorporates three main functional blocks which are working synergistically in order to make this system to be able of working in a long term in a fully autonomous manner. The Energy Harvesting Subsystem is an integration of three complementary technologies, such as photovoltaic (PV) cells to generate electricity using ambient light, piezoelectric vibration harvesters to generate electricity through mechanical vibration in machinery and thermoelectric generators (TEGs) to harness energy found in industrial thermal gradients. This multiple-supplier strategy reduces the problems of using solely a single source of energy since reliability is much better in an ambient energy environment that is changing. The Power Management and Storage Unit has a hybrid structure that marries a supercapacitor with a lithium-ion battery that can be recharged. Supercapacitor is used in short term power spikes like wireless transmissions and Li-ion battery acts as a secondary output when there is a prolonged low harvest periods. A customized Maximum Power Point Tracking (MPPT) controller is used to make sure that cells in the PV operate under maximum power detected and a priority-based source selection algorithm dynamically selects the best source of energy according to sources availability and energy required.

The third functional block which constitutes the intelligence layer of the system is Sensing, Processing and Communication block. Temperature, pressure and vibration sensors include industrial grade sensors that monitor core operation parameters and provide data back to an ultra-low-power ARM Cortex-M4 microcontroller. MCU does local signal processing, filtering, initial anomaly detection, minimising data transmission activity and saving power. Processed data is transferred using LoRaWAN, a long-range and low-power communication protocol that is a good fit in an environment with a considerable threat of interference (such as industry). The topology of the whole system is designed according to bottom up approach and it starts by carrying out an extensive site survey to describe the presence of ambient energy sources within the deployment site. On the deduction of these findings, suitable harvesting technology is chosen and optimized early in the iteration of simulation and prototyping Figure 4. The last step is a stage of integration where the continuous interoperability between energy harvesting units, the power management device, sensing element and communication module comes about. This orderly system does not only improve energy independence but also guarantees the adherence to industrial reliability standards thereby opening up the pathway to the realization of the maintenance-free operation with regards to the tough operational environment.

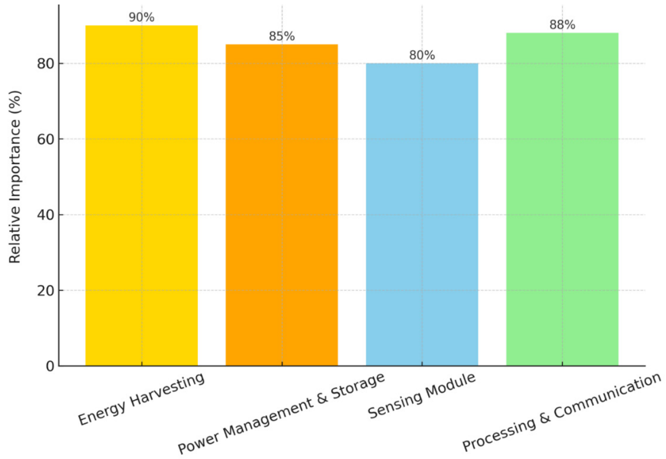

Fig. 4: Relative Contribution of Functional Blocks in Smart Sensor Node Design Framework

Energy Harvesting Integration

The energy harvesting approach under consideration bases on parallel integration structure that integrates solar, vibration, and heat-to-power generators that help provide a constant stream of power under various conditions in industry. Every harvesting source is separately input to the Power Management Unit (PMU) using independent channels, each of which is loaded with Schottky diodes of low forward voltage that block reverse current and also isolate sources to stop cross-interference. Such arrangement enables each module to work individually and allows PMU to access different modules where necessary.

The Solar Energy Module uses most efficient monocrystalline solar photovoltaic (PV) cells, and are sized based on the maximum sunshine hours observed in measured irradiance data within the deployment site. Depending on the illumination (direct sunlight or diffuse industrial lighting), an MPPT (Maximum Power Point Tracking) circuit continuously adjusts the PV operating point in order to maximize energy conversion efficiency by tracking the maximum power point of the PV array. Vibration Energy Module the VEM employs piezo-electric transducers fabricated, in high-sensitivity lead zirconate titanate (PZT), mechanically matched to the primary frequencies of industrial machinery, which are commonly between 20 and 150 Hz. It has the highest energy transfer in resonance as well as the stable power protection even during operational cycles. The Thermal Energy Module incorporates thermoelectric generators (TEGs) using the Seebeck effect that are installed on an equipment or process surface with steady state temperature gradients greater than 10 C. The thermal differential is maintained by having heat sinks on the cold side, increasing conversion efficiency and output stability.

The PMU uses priori-based adaptive algorithm of source selection where the main power source is shifted according to environmental conditions and energy requirement. Solar harvesting is given the priority during the daytime, due to its increased power density and fast charging nature. Vibration harvesting is used as a supplement to solar power or as an alternative where solar power is difficult to work in dim light conditions such as when industrial machinery is running. Thermal harvesting is available when giving up the main power supply such as during night hours or idling machinery idle

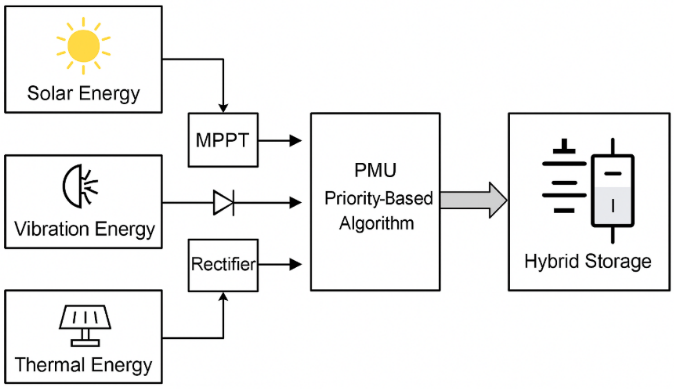

Fig. 5: Energy harvesting integration diagram for the smart sensor node.

where equipment are constantly being cooled to maintai uniform heat emissions Figure 5. Besides guaranteeir continuous operation, this adaptive scheduling will als have a positive impact on the lifespan of its storag component, as it will be able to balance charging cycle across several sources, is a critical step toward makir the system resilient and which is self-sufficient ove extended periods.

Power Management and Energy-Aware Operation

Power management approach of the proposed sma sensor node is such that it is energy neutral, so th harvested energy is always equal to or greater than th cumulative energy consumption of the rest of the life o the node. In the core of such strategy is a hybrid storag topology that integrates supercapacitor and rechargeab lithium-ion battery. The high power density and fa charging/discharging capability of the supercapacitor ca deliver a short-term instantaneous energy source neede in response to short-term high-load scenarios, e.g. senso activation, or transmission of data to another locatio Conversely, the Li-ion battery with high energy densi and non-varying output voltage continues to provide the long-term energy supply in case of the long-term low harvesting activity thus, the continuous operation is guaranteed. This dual-storage system balances both of these short-term and long-term energy demands in addition to maximizing the life cycle of both storage components by relieving deep discharge cycles.

To further maximize the energy usage, the microcontroller is in several different low-powered states: active, idle and deep-sleep, varying among those, depending on the current actual availability of energy and the priorities of the tasks being executed. A dynamic adaptive duty-cycle scheduling algorithm changes the sensor sampling rate and communications interval dynamically and hourly charges up the activity when energy is available in excess and saves energy as the harvesting rates are reduced. Beyond this, edge processing functionality is added that can run the lightweight anomaly detection algorithms directly on the microcontroller. The redundancy or any non-critical data would be filtered out by these algorithms and only the key information would be sent to the gateway, up to 40% energy savings of the wireless communication cost. The system reduces one of the most power-hungry activities of wireless sensor nodes to a great extent by minimizing the unwarranted transmissions. Taken together, these strategies allow the node to run many years with no battery replacement needed in the industrial setting, and deliver consistent performance, high data reliability, and adherence to Industry 4.0 energy efficiency requirements Figure 6.

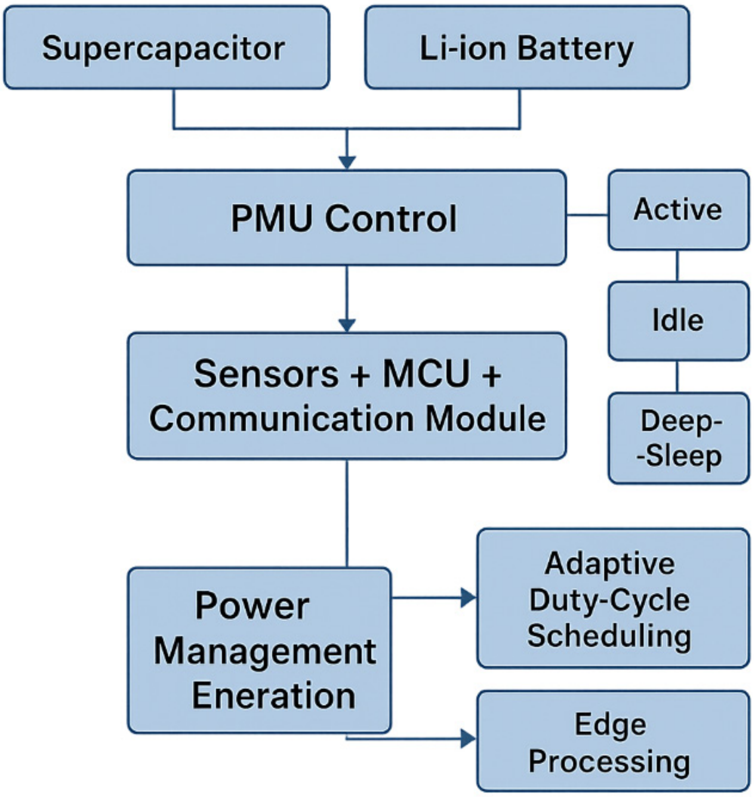

Fig. 6. Power management strategy for energy-aware smart sensor node operation.

Experimental Setup

0In order to test the capabilities of the proposed smart sensor node, a functional prototype was created, with a custom-designed printed circuit board (PCB) well suited to module-sized incorporation of the three sources of energy harvesting, namely photovoltaic cells, piezoelectric vibration harvesters, and thermoelectric generators (TEGs). Minimal power losses in the PCB layout were provided by maintaining short trace lengths, impedance matching, a dedicated input channel associated with each harvesting source to allow them to operate independently and the efficient routing to the power management unit (PMU). The prototype has been implemented and field tested in an industrial work shop where lighting environment is dynamic in nature, the intensity of vibrations generated by functional machinery is variable and thermal gradients are stable because of processing equipment. This test bed setup was an actual working situation which could be considered a representative example of the operations of IIoT in manufacturing and non-manufacturing process industries. The three main performance metrics of the evaluation process were the following: (1) energy harvesting rate (in milliwatts), measured separately on individual sources, as well as in hybrid mode by adding it together, which evaluated the energy provisioning of the system under changing environmental conditions;

(2) node uptime, being the total operation time (in hours and days) without having to change the battery or external power supply and consequently, proving the energy-autonomous operation of the system; and (3) Packet Delivery Ratio (PDR), which characterized the service reliability of long-range Lo The onboard storage and an external monitoring unit were used to implement data logging to correlate information about the environmental conditions, the level of energy harvested, and the system performance throughout protracted operating cycles.

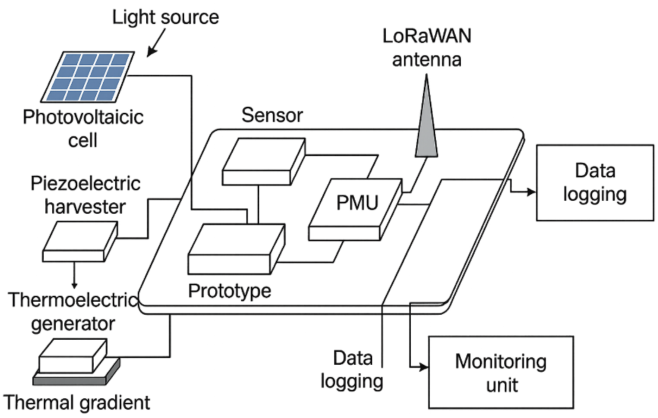

Fig. 7: Experimental Setup of the Multi-Source Energy Harvesting Smart Sensor Node Prototype

Results and Discussion

The testing conducted in the experiment showed that harvesting multiple energies (solar, vibration, and thermal) in a hybrid system allowed to greatly increase the operating independence of the sensor node. At standard battery-powered operation, the node had a test environment-average lifetime of about two weeks before attaining manual intervention. In comparison, the hybrid energy harvesting system elongated this time to more than eight months of consistent performance with no scheduled maintenance or battery change, in effect highlighting a near-energy neutral performance index. The redundant array of the many sources facilitated flexible use of the most versatile supply of energy at any specific moment, and the approach served to reduce seasonal and other fluctuations of utilization typical of single-source harvesters. Moreover, the hybrid system spread power production tasks and cooled off deeper discharge of the storage components to increase the lifetime of their use.

Communication reliability was very high as the node recorded a high packet delivery ratio (PDR) of more than 90 and throughout the course of the test, even with overwhelming industrial electromagnetic interference. It has received this great reliability due to the dynamic transmission power control applied in the LoRaWAN

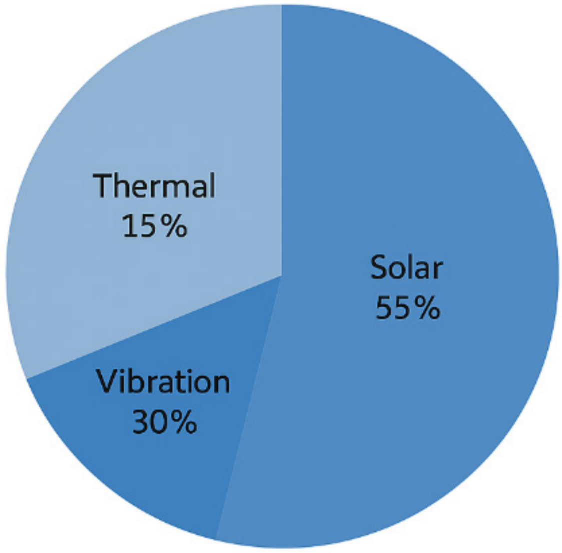

Fig. 8: Contribution of Solar, Vibration, and Thermal Energy Sources in the Hybrid Energy Harvesting System

module that kept the signal integrity without too much necessary power consumption Figure 8. Application of edge processing to filter out redundant or other useless sensor details passed on to a receiver before transmission also greatly contributed because the entire communication frequency will be less and energy will be saved to pass on the most important information. Such a strike between data fidelity and power efficiency is essential in IIoT settings, where continuous monitoring has to co-exist to be highly constrained in energy terms.

The hybrid storage topology also helped much in stabilizing the delivery of power. The supercapacitor accommodated the high-power requirements immediately as experienced in situations like wireless transmissions and the Li-ion battery made sure that there was a steady supply during instances of low harvesting activity like when there was long low-light or when machines were idle. This 2-in-1 storage strategy also avoided voltage drops that would have otherwise caused the system to have problems in resets of certain sensors or microcontrollers keeping the system continuously operational. The overall findings confirm that the suggested architecture is capable not only of improving the energy independence and reliability of the operation but also providing a sustainable and maintenance-free solution to the problem of industrial IoT applications and is, thus, very suitable in terms of its deployment in a remote or hazardous environment Table 1.

Conclusion

This paper showed the design, development and experimental validation of multi-source energy

Table 1. Experimental Results Summary of the Hybrid Energy Harvesting Smart Sensor Node

Performance Metric	Observation	Impact
Operational Lifetime (Battery-Only)	Approximately 2 weeks	Short lifetime, frequent intervention
Operational Lifetime (Hybrid Harvesting)	Over 8 months (near energy-neutral operation)	Significantly extended uptime, autonomous operation
Packet Delivery Ratio (PDR)	> 90% (even in high EMI conditions)	High communication reliability
Energy Source Utilization	Dynamic switching between solar, vibration, and thermal sources	Mitigates seasonal/operational variability
Storage System Role	Supercapacitor handles short bursts; Li-ion battery supplies long-term power	Stable voltage, prevents resets
Maintenance Requirement	No maintenance or battery replacement required	Sustainable, long-term deployment in remote areas

harvesting smart sensor node applied to Industrial Internet of Things (IIoT) scenarios, to attain long-term maintenance-free operation in severe industrial environments. Through a hybrid power management system that incorporates photovoltaic cells, piezoelectric vibration harvesters and thermoelectric generators as power sources and integrates them with a hybrid energy storage scheme and adaptive source prioritization, the proposed architecture showed a drastic improvement in operational autonomy-whereas a traditionally powered system with batteries has a two-week design autonomy, the proposed design achieved over eight-months and still climbing, without power system intervention. This system integration of industrial quality sensors, extreme low-power processing, edge-level anomaly detection, and Low-Power Wide-Area-Networking LoRaWAN communication guaranteed not only high reliability of transmitted data (>90% PDR) but also a tremendous decrease in energy usage. The smart duty-cycling, energy-con-sastyc operation and hybrid storage topology also increased the resilience and stability of the system, despite the changing energy availability. Such findings demonstrate the feasibility of the initiative to develop IIoT on a massive scale in such industries as manufacturing, predictive maintenance, asset tracking, and environmental monitoring. Future activities will aim at embedding AI-based energy forecasting models to be proactive in power management, support mesh-networking capacities to support scaling deployments, and research blockchain-type of data authentication and security system to warrant industrial data communication to be reliable and hack proof.

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