IoT-Enabled Energy Harvesting Sensor Network for Smart Industries

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Abstract: Wireless Sensor Networks (WSNs) serve as an advanced industrial monitoring solution because they obtain real-time data for multiple industrial applications while optimizing these procedures. The networks include distributed sensors and actuators that permit simple measurements of critical parameters ranging from temperature to humidity along with vibration and pressure. Economical reliable continuous monitoring requirements for industries adopting smart automation systems causes WSNs to adopt renewable energy systems and energy-harvesting methods. Operating durations for these sensor networks become extended by employing renewable solar energy sources and harvesting energy from wind power and mechanical vibrations while reducing traditional power dependency. WSN devices enabled with environmental ambient energy can establish independent power systems that deliver continuous industrial monitoring operations. This paper investigates sustainable operation needs of wireless sensor networks with energy harvesting capabilities required for smart industrial monitoring and describes ongoing developments and obstacles in renewable power utilization for autonomous capability.The proposed Smart Self-Powered Wireless Sensor Network for Industrial Monitoring using Machine Learning establishes a self-charging industrial monitoring system that operates through a 12V battery powered by combinations of solar panel energy and piezoelectric sensor energy. The system operates continuously through automatic battery and AC mains power switching managed by relays. The central processing unit of this system operates on a Raspberry Pi while monitoring several sensors including DHT11 for environmental temperature detection and humidity measurements and DS18B20 for machine interior temperature evaluation along with harmful gas detection through an MQ-135 gas sensor.

1 INTRODUCTION

The accelerated industrial development rate makes it essential to have effective monitoring and management systems which modern industry demands. Industrial applications of today need monitoring solutions beyond traditional human-controlled methods because traditional systems lack adaptability features. A wireless self-powered smart sensor network introduced by the scientific project addresses monitoring obstacles through its autonomous operation system which draws power from renewable sources.

This system enables real-time data acquisition through machine learning algorithms by connecting Raspberry Pi with temperature, humidity and gas detectors which permits environmental condition analysis and prediction. The developed technical system achieved automated operations by producing rapid notifications to improve industrial safety standards. WSNs offer industrial monitoring improved attractiveness since they deliver continuous real-time data about temperature and humidity measurements and determine pressure and vibration values and analyze gas concentrations.

The steady execution of industrial operations along with operational efficiency needs precise parameters for optimal safety functions. Industrial WSNs decide through data analytics instead of exploratory methods to enhance operational performance while fulfilling predictive maintenance needs and environmental surveillance (Dahiya, R. S., & Shankar, P. 2020). Progressing reliable power supply with uninterrupted power delivery to every WSN node remains the major implementation

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challenge among other deployment obstacles (Zhang, L., & Zhang, Y. 2018).

Sensor nodes obtain operating power through energy harvesting techniques which extract power from surrounding environmental sources such as sunlight and wind variations as well as heat and vibrations sources (Zhang, J., & Wang, Q. 2017). Solar energy stands as one of the well-recognized renewable energy sources operating WSNs while simultaneously serving as their prime energy supply method.

Outer applications benefit from extensive research on WSNs powered by solar energy because solar radiation supplies necessary power to sensor nodes and other devices (Prabhu, R. S., & Kumar, K. 2019). The harvesting of vibration-based energy has shown promise for powering WSNs in industrial facilities because industrial machines produce usable electrical energy from their vibrations (Khan, R. A., & Hussain, S. 2020). These energy-efficient technologies function together to enable autonomous WSN settings with extended operational periods requiring minimal servicing thus being suitable for industrial monitoring framework needs (Bhattacharya, R., & Sharma, V. 2018).

Machines using power harvesting methods gain two major benefits by allowing cheaper monitoring systems and better environmental performance during operations with extended operational time (Zhu, Y., & Zhang, Z. 2019). The literature presents three essential methods to enhance energy efficiency of sensor nodes by balancing communication operations and hardware power usage levels when using supercapacitor-based recharge systems as demonstrated in (Xu, et al,2017, Lee, et al, 2020). The SWSN technology developed from combining data analytics with machine learning offers operational and predictive maintenance functions according to (Yang, H., & Zhou, W. 2021).

The study investigates how renewable energy systems together with energy harvesting influence industrial control operations through Wireless Sensor Networks implementations. The research observes current industrial research patterns to analyze critical integration issues prior to developing self-powered monitoring systems for sustainable industrial operations.

2 LITERATURE REVIEW

Zhang et al established an energy-efficient WSN for industrial use in 2022 by enabling nodes using solar energy harvesting for power supply. The authors discovered that industrial facilities can implement successful solar-powered WSNs which produce sustainable light energy collection to operate sensors autonomously from conventional utility sources. The authors emphasized the need to develop advanced energy storage systems because solar power generation performs unpredictably when lighting decreases.

In their work Lee et al provided vibration-based energy harvesting as an effective power method for Wireless Sensor Networks operating within industrial sites that exhibit regular machine-generated oscillations. The incorporated sensors operated by converting mechanical vibration into electric energy to power their sensor arrays. A continuous operation mode without battery changes helped reduce maintenance expenses for the proposed system. Vibrational power generation showed limited capacity according to the authors which restricted sensor operation at the same time.

In 2020 Patel and Bansal investigated the implementation of solar power integration with vibration energy for improved WSN system reliability. The practical implementation of this model showed significant worth in industrial environments getting steady solar illumination together with vibrations. Research findings established that hybrid energy systems provided extended reliable power supply but researchers faced difficulties when handling the combined energy flows.

During 2019 Sharma et al. conducted research on smart factory monitoring system energy harvesting solutions. This system contained solar panels along with heat energy harvesting elements that let it operate independently. Device temperature and humidity and pressure level detection necessitated power generation through heat from machines and solar energy systems. System power utilization decreased significantly according to the authors though they accepted the unit's thermal energy harvesting was less efficient than solar energy collection in regions with minimal temperature fluctuations.

In 2018 Singh and Gupta performed research on machine learning applications for self-powered WSNs in industrial monitoring. The researchers optimized power management and sensor data collection by using machine learning algorithms in their research work. The implementation of predictive models enabled forecasting of energy consumption and system failures to increase the operational duration of WSNs. The accurate operation of machine learning algorithms proved difficult because permanent training alongside specific adjustments were necessary to achieve precise predictions in continuously changing industrial environments.

3 EXISTING SYSTEM

The current industrial monitoring system requires connected traditional sensors for monitoring yet control units need manual and extensive support for maintenance. Diverse industries lack sufficient support from basic industrial monitoring systems for their operational requirements. Typical models operating today use only basic warning alarms and on-site data recording since predictive machine learning analytics techniques are not implemented. The main power grids experience standard power supply breakdowns that result in electricity interruption during utility outages. The dual power structure of batteries with AC mains triggers unnecessary double consumption of energy throughout the system operations. The complete environmental observation ends up degraded because several devices do not come equipped with integrated DHT11, DS18B20 and MQ-135 sensors. The present models demonstrate several limitations in real-time assessment while lacking intelligent response abilities which results in the need for better industrial safety system solutions.

4 PROPOSED SYSTEM

Modern sensor devices in combination with renewable energy systems through artificial intelligence achieve security enhancement of industrial monitoring features based on sustainable advanced designs within the Smart Self-Powered Wireless Sensor Network. An autonomous power supply results from integrating solar panels with piezoelectric sensors because the system relies on a 12V battery to work during periods without solar or electric power. The system develops higher reliability when automated battery power switching operates through relays. The Raspberry Pi collects machine and environmental data through its sensors which consist of combined DHT11 humidity and temperature equipment along with DS18B20 thermometers and MQ-135 gas detection tools. The system's motor driver facilitates precise control over machinery speed, with manual switches for fine-tuning. When SMS automation activates the buzzer produces notifications which play through the LCD display before connecting to working personnel via GSM. The system performs independent operational predictions through sensor input while using collected information to modify motor speed controls to reduce operational failures. Peak energy efficiency reaches its optimum through this integrated system since it enhances operational procedures while detecting impending system dangers for more effective maintenance scheduling that reduces operational risks. Machines under this system maintain autonomous operation until they achieve better specialized energy consumption levels while remaining reliable and safe.

4.1 Proposed System Block Diagram

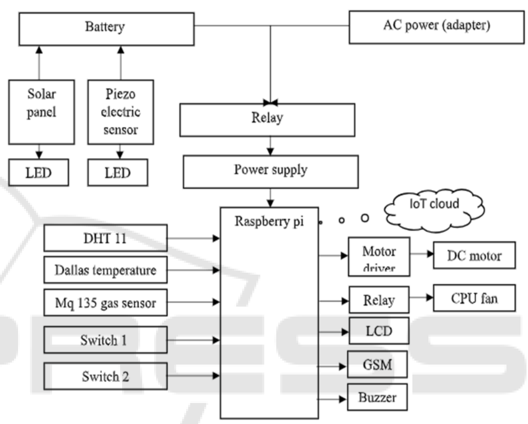

Figure 1: Proposed System Block Diagram.

The Smart Self-Powered Wireless Sensor Network solution (SSWSN) proves its capability to construct intelligent self-powered monitoring infrastructure for industrial applications through combination of renewable energy systems and next-generation sensor technology and machine learning methods. Detailed examination of system elements and functionalities follows next in the below paragraph. Figure 1 shows the Proposed System Block Diagram.

4.2 Energy Supply and Management

A solar panel supports energy operations through sustainable power resources which result in affordable and green solutions. The system utilizes piezoelectric sensors that turn mechanical energy into electricity which serves as an enhanced charging capability within vibration-driven industrial conditions.

A 12V battery deployed as the primary power source will be charged automatically through both solar energy from the panels and the piezoelectric sensors to support system functionality in all circumstances including dark conditions and power failures.

A switching mechanism based on relays enables the panel to switch power between the battery and AC mains delivery while improving both reliability and operational smoothness.

4.3 Data Acquisition and Sensor Network

The central CPU functions of the Raspberry Pi system gather and analyze sensor data for immediate real-time monitoring.

The DHT11 sensor operates as an environmental measurement device that evaluates both temperature and humidity levels.

The internal temperature of the machine is monitored by the DS18B20 Sensor for hot temperature protection against equipment destruction and burn damage.

The MQ-135 Sensor serves as a detection system for harmful gases which helps safety operations through its early identifying of hazardous situations in workplaces.

4.4 Real-Time Monitoring and Control

Motor Control: Allows precise motor speed control for optimal performance and energy efficiency.

The LCD touchscreen presents immediate sensor readings to show system operational status combined with temperature measurements along with humidity levels and gas detections and motor operating information.

4.5 Alerts and Notifications

Buzzer: Provides audible alerts for critical conditions, such as high temperature or gas levels.

A GSM Module can transmit SMS alert messages during emergencies or abnormal system conditions to take swift actions from any distance.

4.6 Machine Learning Integration

The performance attributes in sensor-based system designs enable users to merge defect detection systems with output functionality.
The system develops automatic motor speed control functionality because of its analysis capabilities.

By analyzing historical data predictive system equipment failure models calculate the perfect preventive maintenance periods needed to defend components from damage.

4.7 Enhanced Safety and Efficiency

Automated processing of predictive analytics systems enables organizations to achieve operational excellence along with minimal waste production through optimized energy system management.

Emergency response services achieve improved safety through their enhanced operation efficiency that permits gas level monitoring and incident data collection of temperature and humidity metrics.

5 HARDWARE & SOFTWARE COMPONENTS

5.1 12V Battery

- A rechargeable battery used for various applications, offering long-term cost savings and reducing waste.
- Types: Nickel-Cadmium, Nickel-Metal Hydride, Lithium-Ion, Lithium-Polymer; Voltage: 1.2V (Nickel-based), 3.7V-12V (Lithium-based)

5.2 Piezoelectric Sensor

- Operates based on piezoelectricity, where mechanical stress generates electricity, used for measuring physical quantities like pressure and acceleration.
- Measurement Range: Dependent on sensor design; Impedance: ≤500Ω

5.3 Solar Panel

- Absorbs sunlight to generate electricity through the photovoltaic effect, typically used for residential, commercial, and off-grid power generation.
- Efficiency: 15%-22% (silicon-based cells); Voltage: 12V-24V

5.4 Power Supply

- Converts different forms of energy (e.g., AC, solar, mechanical) into usable electrical power, essential for devices like computers and industrial machinery.

- Input Voltage: 110V/115V or 220V/240V; Output Voltage: 5V, 12V, depending on device.

5.5 LED

- A semiconductor device that emits light when current flows through it, known for being energy-efficient and durable.
- Material: GaAs, GaP, GaN, InGaAlP; Lifespan: Up to 50,000 hours.

5.6 Relay

- An electromagnetic switch used for controlling circuits with low-power signals, suitable for handling higher voltages or currents.
- Types: SPST, SPDT, DPST, DPDT; Applications: Logic functions, controlling high voltage/currents.

5.7 Raspberry Pi

- A compact computer designed for DIY projects and teaching computer science.
- Processor: Broadcom BCM2835 ARM1176JZF-S; Memory: 256 MB to 512 MB RAM.

5.8 DHT11 Sensor (Temperature/Humidity)

- A basic, low-cost digital sensor used to measure temperature and humidity.
- Humidity Range: 20% to 90% RH; Temperature Range: 0°C to 50°C.

5.9 DS18B20(Dallas) Temperature Sensor

- A digital temperature sensor with a wide range and high accuracy, using a single-wire protocol.
- Temperature Range: -55°C to +125°C; Accuracy: ±0.5°C.

5.10 MQ135 Gas Sensor Module

- Detects gases like ammonia, CO2, alcohol, and benzene.
- Detection Range: 10-10,000 ppm; Output Type: Digital and analog.

5.11 Switch (Push Button)

- A mechanical switch used to turn devices on or off, commonly found in industrial, medical, and consumer electronics.
- Power Rating: Max 50mA, 24V DC; Operating Temperature: -20°C to +70°C.

5.12 Motor Driver (L293D)

- Controls motors in robotics, commonly used for dual DC motor operation.
- Pins Description: Enable, Input, Output, Ground for motor control; Power: Vcc2 for motor power.

5.13 DC Motor

- Converts electrical energy (DC) into mechanical energy through rotation, used in various applications like toys, vehicles, and industrial machinery.
- Components: Stator, armature, commutator; Applications: Electric vehicles, conveyors, fans, power tools.

5.14 CPU Fan

- Ensures that the CPU remains cool by dissipating heat, preventing thermal throttling or failure.
- Components: Fan blades, motor, mounting points; Types: May include heatsinks, adaptive speed features.

5.15 LCD

- A thin, power-efficient display used in calculators, monitors, and other devices.
- Display Size: 16x2 characters; Voltage: 5V (4.7V – 5.3V).

5.16 GSM Module

- Enables wireless communication for voice calls, SMS, and data transmission via GSM/GPRS networks.
- Frequencies: 850MHz, 900MHz, 1800MHz, 1900MHz; Interfaces: RS-232

5.17 Buzzer

- A signaling device used in alarms and timers.
- Rated Voltage: 6V DC; Operating Voltage: 4-8V DC

5.18 Raspbian

- Official OS for Raspberry Pi, optimized with over 35,000 software packages.
- Base: Debian-based; Software: 35,000+ packages

5.19 Python

- A versatile programming language supporting multiple paradigms, used across platforms.
- Type: Interpreted, high-level; Cross-Platform: Windows, Linux, macOS

5.20 ThingSpeak

- IoT platform for aggregating and visualizing real-time sensor data.
- Type: IoT analytics platform; Features: Data aggregation, real-time visualization

5.21 VNC Viewer

- Remotely access and control computers over a network, supporting various platforms.
- Protocol: VNC; Security: Password protection, encryption

6 EXPERIMENTAL SETUPS

Install a solar panel and piezoelectric sensor to generate electrical power, connecting them to a 12V battery for energy storage. Use a relay module to switch between the battery and AC power as needed, and ensure a stable power supply for the system. Connect the Raspberry Pi to the power unit, and attach sensors like the DHT11, Dallas Temperature sensor, and MQ135 for real-time monitoring of temperature, humidity, and harmful gases. Install switches for manual control, and integrate a motor driver, relay, and CPU fan for cooling. Connect an LCD display for system updates. Figure 3 shows the Relay Shifts the Power Supply Between Ac Adapter and Battery.

Integrate a GSM module for mobile communication to send SMS alerts, and attach a buzzer for audible notifications. Configure the Raspberry Pi to connect to an IoT cloud platform for remote monitoring and data analysis. Power up the system and verify all components, ensuring that sensors, actuators, and communication modules are functioning properly. Figure 2 shows the Placement of hardware components and their connections. Figure 4 shows the Run the code. Figure 5 shows the Data is updating time to time on the python shell. Figure 6 shows the Think speak Will Represent the Parameters in Graphical Format. Figure 7 shows the Through GSM module received data messages sends to mobile phone frequently or time to time.

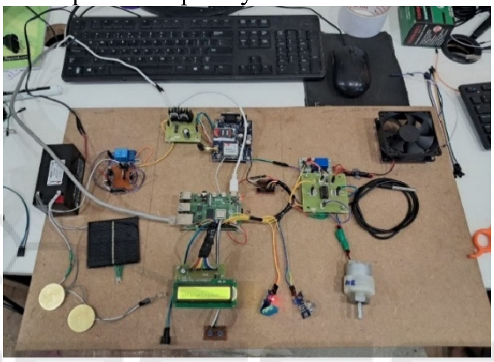

Figure 2: Placement of Hardware Components and Their Connections.

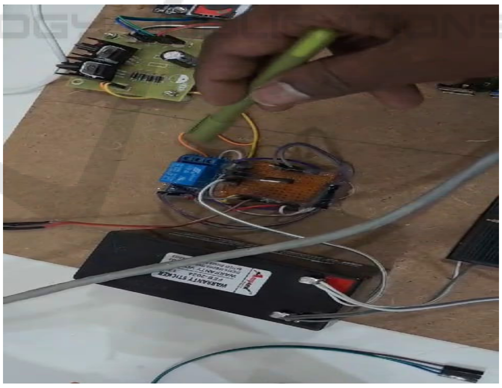

Figure 3: Relay Shifts the Power Supply Between AC Adapter and Battery.

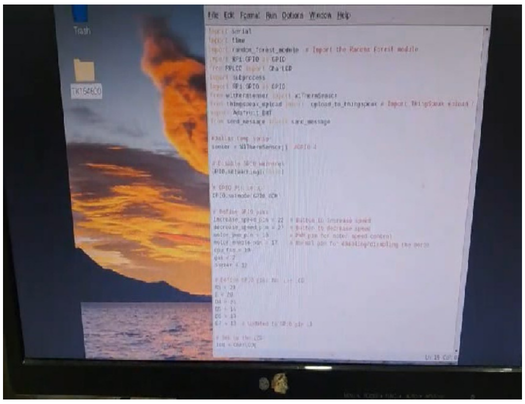

Figure 4: Run the Code.

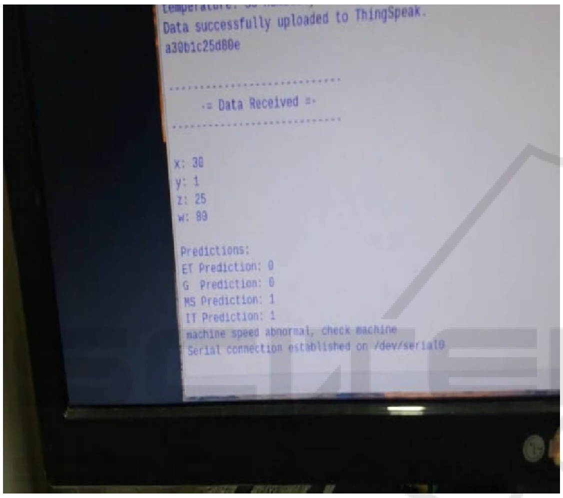

Figure 5: Data Is Updating Time to Time on the Python Shell.

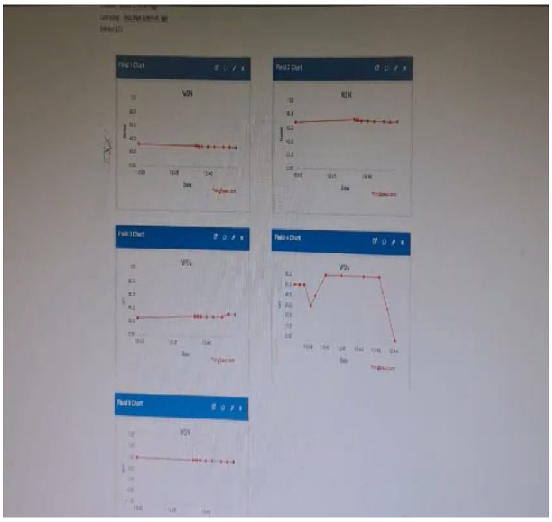

Figure 6: Think Speak Will Represent the Parameters in Graphical Format.

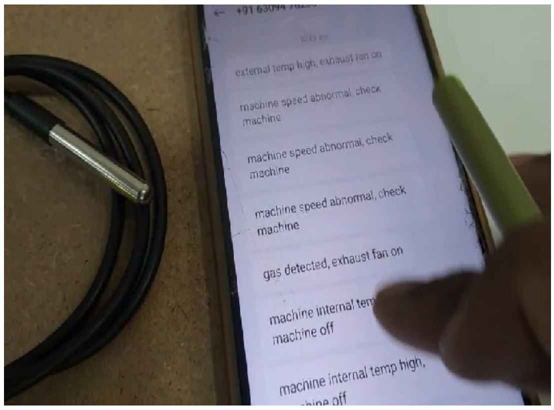

Figure 7: Through GSM Module Received Data Messages Sends to Mobile Phone Frequently or Time to Time.

6.1 Graphical Representation and Comparative Analysis

This project displays fluid numerical data which shows combined readings between temperature sensors DHT11 and DS18B20 and environmental gas sensory output of MQ-135 throughout time. The temperature data from sensor accuracy tests appears through both line graphs that show trends between points while the gas concentration bar or line graphs let workers identify critical periods. The analysis of safety risks depends on visual data and non-compliant environmental practices with simultaneous benefits for operational security during industrial operations. Figure 8(a),8(b) shows the Graphical Representation of The System Parameters.

Using comparative analysis as a research examination method allows professionals to study multiple objects by observing similarities and differences between them. Different social sciences and business sectors and technological fields employ the research method to create useful data that helps decision-makers make better choices. Social scientists use nation-to-nation political structures and educational methods and economic conditions to develop theoretical explanations of final results. The process of system comparison allows researchers to discover top-performing elements of different approaches which later results in improved current system strategies and better approaches. Research through scientific comparison yields connections between entities that become unobservable when entities are studied individually.

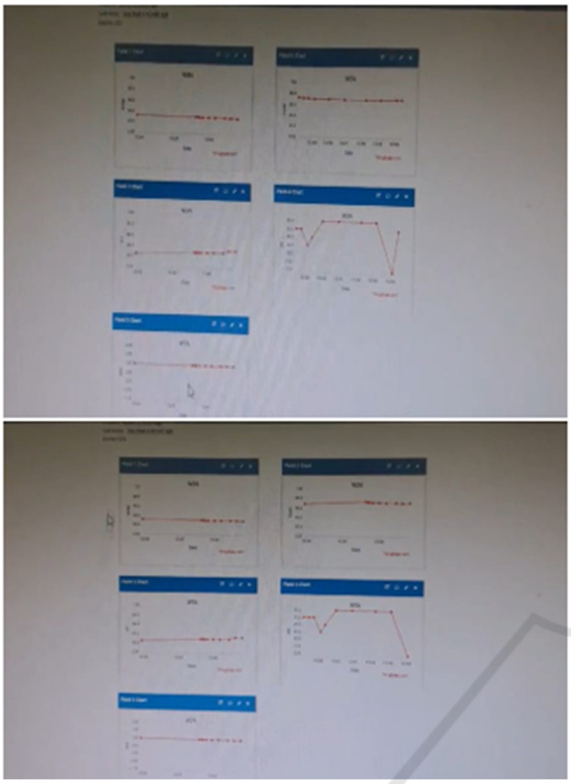

Figure 8: Graphical Representation of the System Parameters.

7 CONCLUSIONS

Through its implementation the Smart Self-Powered Wireless Sensor Network for Industrial Monitoring advanced industrial automation practice substantially. This system allows continuous oversight of parameters along with efficiency through the combination of renewable energy sources integrated to sensor frameworks that process data intelligence. The combination of operational safety and efficiency gains occurs because of machine learning integration. Modern smart industrial developments of sustainable automated systems gain practical possibilities through self-powered systems which combine sustainable tracking frameworks.

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