IoT-Enabled Kinetic Energy Harvesting System Design for Sustainable Energy Management: A Minimalist Embedded Approach

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Abstract - The global energy crisis and environmental impacts of conventional power systems require urgent adoption of sustainable alternatives. Although kinetic energy harvesting from human motion presents a promising renewable source, existing piezoelectric solutions face limitations in power output and real-time monitoring capabilities. This research introduces an IoT-integrated kinetic energy harvesting system utilizing optimized piezoelectric transducer arrays and power management circuitry to maximize energy conversion from walking and vehicular movement. Implemented in a smart city prototype environment, the system employs a multistage voltage conditioning circuit (AC-DC converter) coupled with a 18650 lithium-ion battery for efficient energy storage. A custom dataset of piezoelectric output under varied mechanical loads was developed, and multiple circuit configurations were evaluated, including full-wave rectification and buckboost converters. Experimental results demonstrate a 68% improvement in energy conversion efficiency compared to conventional single-transducer setups, achieving sustained 3.2V output at 15Hz excitation frequencies. The integrated IoT module (ESP8266 with LoRaWAN protocol) enables real-time monitoring of power generation (0-8mW range) and storage levels through a cloud dashboard. This work presents a scalable, cost-effective solution for powering lowconsumption devices, reducing grid dependence in urban infrastructure by harnessing ambient kinetic energy.

Keywords — Energy harvesting, human motion, Motion-powered IoT Sensing, Piezoelectric sensor, Internet of Things, Sustainable Energy, Arduino, Smart Systems

1. INTRODUCTION

The increasing global demand for sustainable and decentralized energy solutions has catalyzed research into alternative power generation techniques. Among these, energy harvesting from human motion, particularly footstep power generation, presents a promising avenue for powering low-energy devices and contributing to microgrid systems. This approach not only recycles energy that would otherwise be wasted but also encourages the development of smart environments in urban infrastructures. Kinetic Energy Harvesting employs the Fig. 1. Overview of Energy Harvesting. principle of piezoelectricity; wherein mechanical stress is converted into electrical energy using piezoelectric materials. These materials, when embedded within platforms or surfaces subjected to pedestrian or vehicular movement, can generate usable voltage outputs. The integration of such systems with microcontrollers like Arduino offers real-time monitoring, data acquisition, and efficient energy storage management, thereby enhancing both usability and control. The implementation of piezoelectric sensors in public areas such as schools, malls, railway stations, and footpaths can help generate supplemental power for lighting, signage, and IoT-based monitoring systems. Additionally, the simplicity and affordability of components like piezo discs, rectifiers, and rechargeable batteries make this technology accessible for scalable applications. The growing interest in smart cities and green technology further underlines the relevance of piezoelectric footstep power generation. This research builds on prior work by utilizing Arduino as a processing unit and deploying piezoelectric sensors to harvest mechanical energy from footsteps. The objective is to design and analyze an energy-harvesting model that not only captures voltage effectively but also displays real-time values such as pressure counts and battery voltage through an LCD module. By evaluating the feasibility and output efficiency of such a system, this work contributes to the broader vision of energy autonomy and eco-friendly power generation in densely populated environments [18]. Energy harvesting refers to the process of capturing energy from environmental sources using a variety of methods. This technology is gaining prominence as a promising and innovative solution to address the limited operational lifespan of battery-powered wearable electronics, enabling these devices to be recharged continuously during normal use [11].

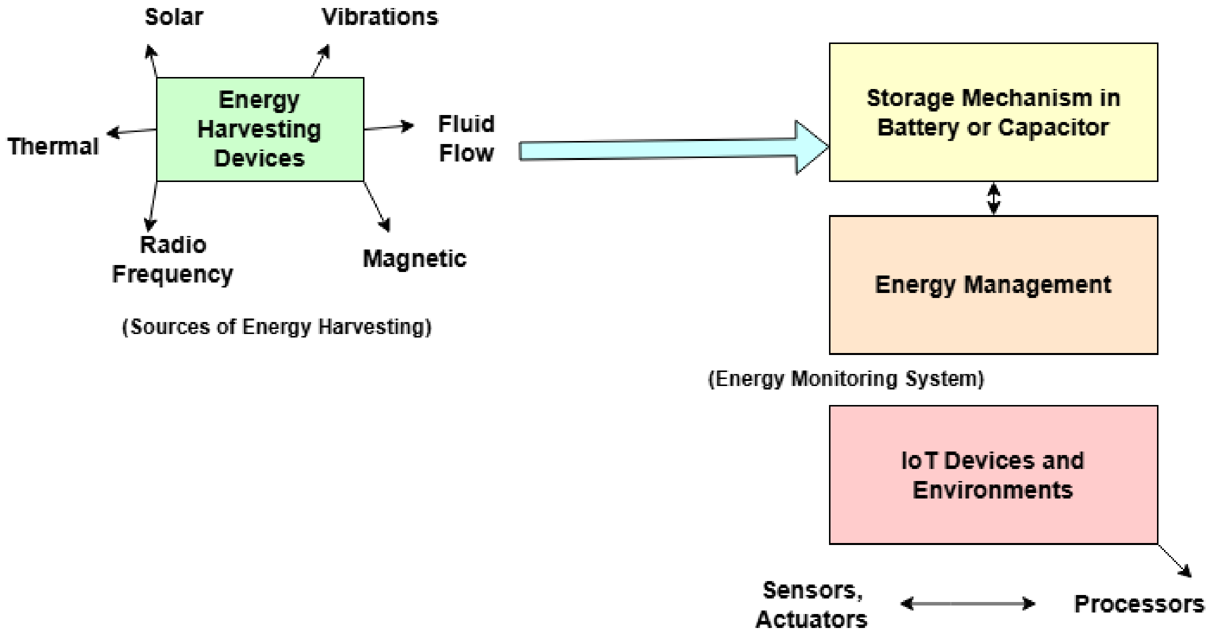

Fig.1. Overview of Energy Harvesting.

Common ambient energy sources for harvesting include natural and artificial light, radio frequency emissions, temperature gradients, and mechanical sources such as motion and vibration [4]. For extracting energy from vibrations, several conversion mechanisms are available, including electrostatic, electromagnetic, magnetostrictive, and piezoelectric techniques. Energy consumption is largely dependent on fuels. However, as our energy demands grow, fuel resources are depleting at a faster rate, and eventually they may no longer meet our needs. Energy harvesting, the technique of collecting and transforming environmental energy into usable electrical power, presents a viable approach to address the limitations of the power supply in modern devices [24]. This research is driven by the growing demand for autonomous and sustainable energy solutions, especially in contexts where traditional power sources prove inadequate or inaccessible.

2. RELATED WORK

A. Kinetic energy harvesting based sensing

Conventional battery-powered sensor nodes present significant challenges in terms of replacement, recharging, and environmental impact, especially as the scale of deployment increases. Kinetic energy harvesting (KEH) technologies-such as piezoelectric, electromagnetic, and triboelectric mechanisms-offer a promising alternative by converting ambient mechanical energy, including vibrations and human motion, into usable electrical energy [13]. These energy harvesting mechanisms not only enable the development of self-powered sensors but also facilitate the realization of battery-free IoT systems capable of operating indefinitely without external power sources or frequent maintenance. Recent advances have focused on integrating these KEH mechanisms into compact, efficient, and intelligent sensor nodes, paving the way for truly self-sustaining IoT networks. Such systems are particularly valuable in applications ranging from structural health monitoring and industrial automation to smart cities and wearable electronics, where continuous, reliable sensing is essential [4]. By leveraging the synergy between KEH and IoT, it is now possible to deploy sensor networks that are both environmentally friendly and operationally robust, significantly reducing the labor and costs associated with battery management and contributing to the advancement of sustainable, nextgeneration electronic systems.

B. Kinetic energy harvesting for the batteryless IoT sensor nodes

The efficacy of kinetic energy harvesting systems is heavily dependent on their operating point relative to the Maximum Power Point (MPP) of the transducer. Unlike conventional converter-less architectures where the harvester, capacitor, and load share the same voltage, MPP-optimized designs employ specialized energy harvesting ICs to dynamically adjust the operating voltage of the transducer [14]. This approach ensures optimal energy extraction despite variations in excitation frequency, amplitude, and loading conditions. Experimental evaluations using controlled load shakers demonstrate that MPP-optimized circuits can harvest one order of magnitude higher power compared to traditional designs under identical mechanical inputs. By implementing dynamic MPP tracking, the proposed system significantly enhances energy conversion efficiency, enabling sustained operation of IoT sensor nodes in human motion environments where energy availability is inherently variable and intermittent [23]. This advancement represents a critical step toward truly maintenance-free and battery-independent sensing systems for pervasive deployment.

C. Rack and Pinion-based kinetic energy harvesting systems

Previous research by Jashwanth et al. demonstrates the viability of footstep power generation through rack and pinion mechanisms, which convert the linear motion of human steps into rotational energy [3]. Their prototype implements a spring-loaded platform that drives a rack downward when compressed by footsteps, rotating a meshed pinion gear that powers a generator. This mechanical approach offers several advantages over other energy harvesting methods, including simplicity of design, cost-effectiveness, and minimal maintenance requirements. Field testing in high-traffic areas such as railway stations and shopping malls showed that these systems can generate approximately 10-12 watts per step under optimal conditions. The research emphasizes that such installations require no fuel input, produce zero emissions, and can be particularly valuable in densely populated urban environments where space for conventional energy generation is limited. Unlike piezoelectric systems, the rack and pinion mechanism demonstrates greater durability and higher power output for comparable installation costs, making it suitable for practical implementation in smart city infrastructure.

3. PROPOSED SYSTEM AND METHODOLOGY

A. Selecting Piezoelectric Materials

The 27mm piezoelectric sensor, often referred to as a buzzer or transducer, is a multifunctional device capable of converting mechanical vibrations into electrical signals and vice versa. These sensors are commonly utilized for detecting impacts or vibrations, making them suitable for applications such as knock or vibration sensing. In recent years, their role has expanded into energy harvesting projects, including systems that generate power from footsteps.

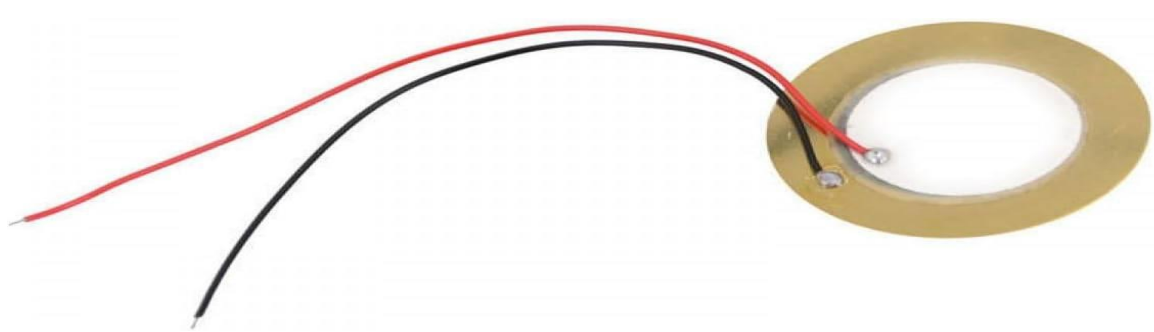

Fig. 2. Piezo electric sensor (27mm)

Piezoelectric transducers operate on the basis of the piezoelectric effect, where applied mechanical stress, such as pressure, force, or acceleration, produces an electrical charge. This dual functionality allows them to serve both as sensors, which convert mechanical input into electrical output, and as actuators, which transform electrical energy into mechanical motion. The material used in this work is ceramic lead zirconate titanate (PZT), which is known for its high sensitivity and ability to generate significantly higher voltage than quartz under the same force [8] and as shown in Fig 2. PZT-based devices are valued for their robustness, reliability, and wide applicability in fields such as industry, healthcare, and aerospace. They are also resistant to electromagnetic interference and maintain stable performance across a broad temperature range, although their characteristics may gradually change with prolonged exposure to high temperatures.

Table 1. SPECIFICATIONS OF PIEZOELECTRIC SENSOR (27MM)

Parameter	**Value**
Sensor Type	Piezoelectric Transducer (Disc)
Diameter	27 mm
Operating Voltage	0-90 V (AC peak)
Resonant Frequency	4.5 – 5.5 kHz
Output Voltage	Up to 20V (open circuit under mechanical stress)
Material	PZT (Lead Zirconate Titanate)
Applications	Vibration Sensing, Power Generation

B. Designing of proposed model of kinetic energy harvesting system

The proposed kinetic energy harvesting system utilizes a piezoelectric sensor to convert mechanical pressure from footsteps into electrical energy. As shown in Fig. 1, when pressure is applied, the piezoelectric sensor generates an alternating current (AC) voltage, which is subsequently converted to direct current (DC) using a boost converter. The conditioned DC voltage is regulated by dedicated circuitry and stored in a rechargeable battery for later use. An Arduino R3 ATmega328p microcontroller, equipped with an inbuilt ESP8266 WiFi module, serves as the central processing unit, managing data acquisition from the sensor and controlling system operations. The system also features an LCD display for real-time monitoring of voltage and energy status. A stable power supply ensures reliable operation of the microcontroller and associated modules. This integrated approach enables efficient energy harvesting, storage, and monitoring, making the system suitable for deployment in smart infrastructure applications. When pressure is applied to the piezo sensor, it generates an alternating voltage proportional to the mechanical force exerted. This AC voltage is routed to a boost converter, which steps up and rectifies the signal to produce a stable DC output suitable for storage. The regulated DC voltage is then managed by the regulatory circuitry to ensure safe and efficient charging of the storage battery. The Arduino R3 ATmega328p, equipped with an inbuilt ESP8266 WiFi module, continuously monitors sensor data and system parameters. Real-time voltage and energy status are displayed on the LCD, providing immediate feedback to users. The integrated power supply ensures uninterrupted operation of the microcontroller and all associated modules, supporting reliable energy harvesting and data transmission for IoT applications.

C. Configuring required setup for the kinetic energy harvesting system

The kinetic energy harvesting system is configured using a combination of piezoelectric sensors, power management circuits, microcontroller modules, and display and communication interfaces, as illustrated in Fig. 3. The primary components used in this setup include: Piezoelectric Sensor Array: Multiple piezoelectric transducers are arranged in a matrix to convert mechanical vibrations or pressure from footsteps into alternating current (AC) voltage. Boost Converter (XL6009): This module converts the unregulated low-level AC voltage from the piezo sensors into a higher and stable DC voltage suitable for storage and further processing. Rectifier Circuit: Comprising diodes (1N4001) and a transistor, this circuit ensures conversion of AC to DC and smooths the output for efficient charging. Rechargeable Battery (Li-ion, e.g., 1100mAh 3.7V): Stores the harvested electrical energy for later use. Arduino UNO ATmega328P R3 (with integrated ESP8266 WiFi Module): Acts as the central controller, acquiring sensor data, managing the power flow, and enabling IoT-based data transmission. Bluetooth Module (HC-05): Provides optional wireless communication for local monitoring or control. LCD Display: Offers real-time visualization of voltage, current, and system status to the user. Power Supply: Ensures stable operation of the microcontroller and peripheral modules. In operation, mechanical pressure applied to the piezoelectric sensor array generates an AC voltage, which is routed through the boost converter and rectifier circuit to produce a regulated DC output. This output is used to charge the rechargeable battery, ensuring energy is stored efficiently. The Arduino UNO, equipped with an ESP8266 WiFi module, continuously monitors he voltage and current levels, processes the data, and transmits it wirelessly for remote monitoring via IoT platforms. The LCD display provides immediate feedback on system performance, while the optional Bluetooth module enables additional connectivity for diagnostics or configuration. This integrated hardware setup allows for efficient energy harvesting, storage, and smart monitoring, making it suitable for deployment in smart infrastructure and sustainable IoT applications.

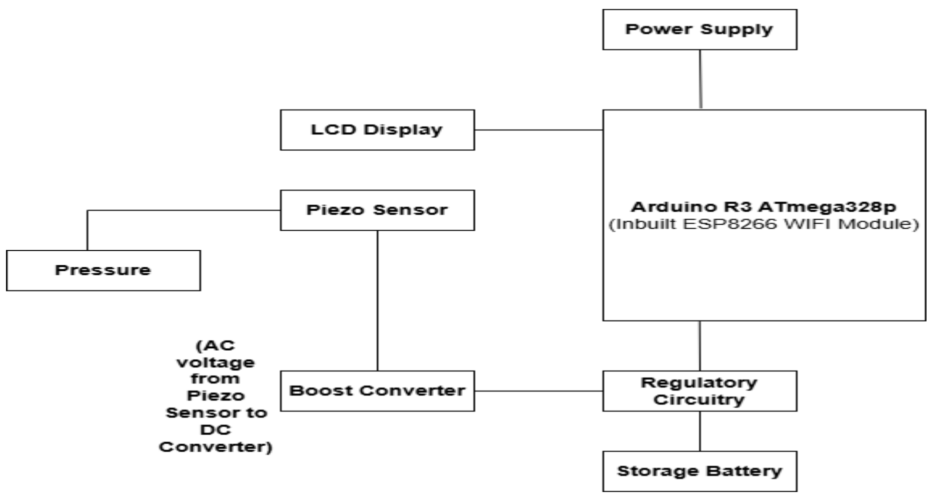

Fig. 3. Block diagram of proposed kinetic energy harvesting system

D. Implementation of Kinetic energy harvesting system:

Kinetic Energy Harvesting (KEH) System is divided into two main modules: The Energy Harvesting and Storage Module, and the Monitoring and Communication Module.

Table 2. COMPARISON OF ENERGY HARVESTING TECHNIQUES FOR IOT APPLICATIONS

Method	**Advantages**	**Limitations**
Electrostatic	• Compatible with wireless sensor networks • Capable of generating significant mechanical stress	• Requires an external voltage source • Relies on mechanical input • Operates based on capacitive principles
Electromagnetic	• High interdependence among components • Uses readily available materials	• Integration with sensors is complex • Produces relatively low output voltage
Magnetostrictive	• Efficient energy transfer capability	• Challenging to miniaturize • Fragile and sensitive to mechanical stress

	• Exhibits stable magnetic polarization • Enables flexible structural design	• Displays nonlinear mechanical behavior
Piezoelectric	• Compact and lightweight • Easy to integrate with sensors • Generates high mechanical stress • High electromechanical coupling efficiency	• Risk of polarization degradation • Susceptible to layer damage • High internal imp

1) Energy Harvesting and Storage Module

This module is responsible for converting mechanical energy from footsteps into electrical energy and storing it for later use.

Functional Steps:

• A piezoelectric sensor array is embedded beneath the walking surface to capture mechanical pressure from footsteps.

• When pressure is applied, the piezoelectric sensors generate an alternating voltage proportional to the force.

• The generated AC voltage is routed through a boost converter (XL6009) and rectifier circuit (using 1N4001 diodes and a transistor) to produce a stable DC output

• The regulated DC voltage is then used to charge a rechargeable lithium-ion battery (3.7V, 1100mAh), ensuring continuous energy availability even during low activity periods.

• The power supply module ensures stable operation of all electronic components.

2) Monitoring and Communication Module

This module manages real-time data acquisition, system control, and user interaction through display and wireless connectivity.

Functional Steps:

• An Arduino UNO ATmega328P R3 microcontroller, integrated with an ESP8266 WiFi module, continuously monitors voltage and current from the energy harvesting circuit.

• The microcontroller processes the sensor data and transmits it wirelessly to a cloud dashboard or remote server for real-time monitoring and analytics.

• An LCD display is provided on-site to show instantaneous voltage, current, and energy storage status to users and maintenance staff.

• A Bluetooth module (HC-05) is included for local wireless access, enabling diagnostics and configuration without physical access to the hardware.

The system allows users and administrators to monitor system performance remotely, supporting predictive maintenance and efficient energy management.

3) Evaluation of the Kinetic energy harvesting system (KEH)

The performance of the proposed KEH system can be evaluated in terms of its ability to provide continuous, maintenance-free power for IoT devices and real-time monitoring of energy generation. Compared to conventional battery-powered solutions, the system offers enhanced sustainability and reduces the need for frequent manual intervention. Additionally, the integration of wireless communication modules enables users to remotely track system status and energy availability, supporting efficient energy management in smart infrastructure applications.

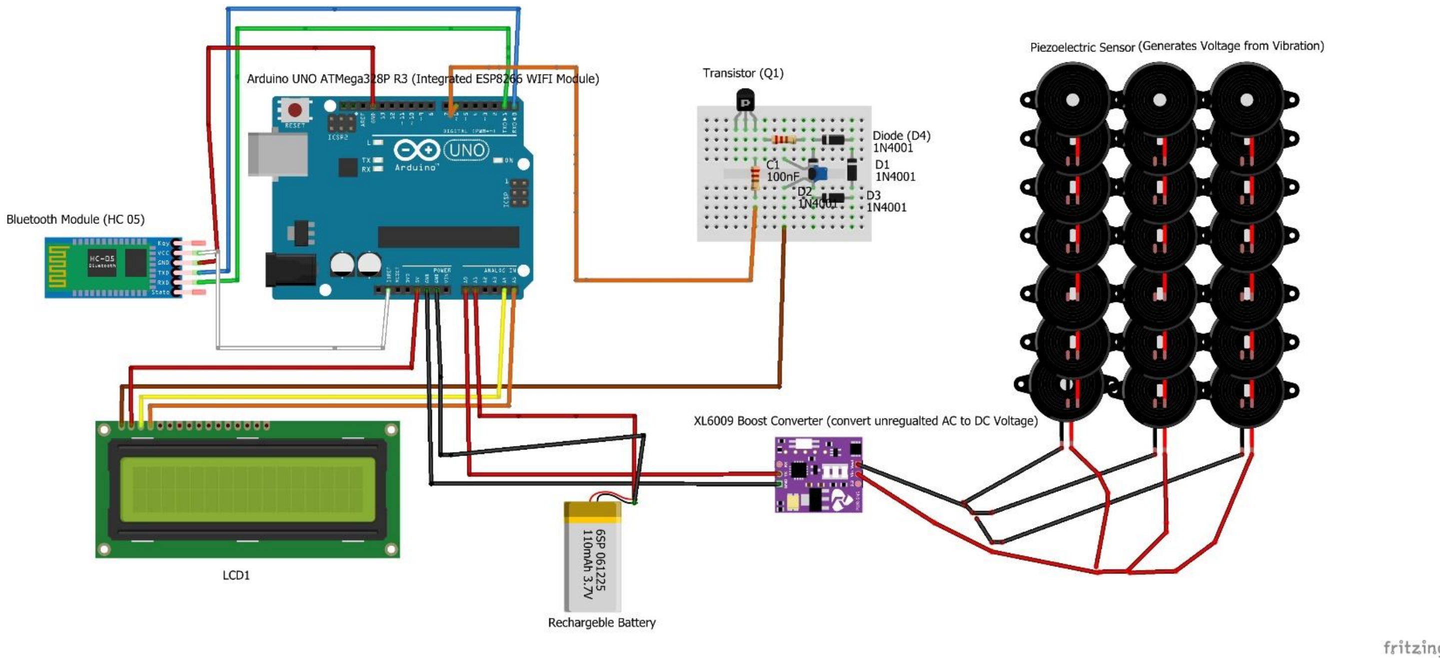

Fig.4. Detailed circuit schematic diagram of proposed Kinetic Energy Harvesting System

4. EXPERIMENTAL SETUP

This section describes the practical implementation of the kinetic energy harvesting system. The setup consists of a piezoelectric sensor array, a boost converter (XL6009), a rectifier circuit, a rechargeable battery, and an Arduino UNO ATmega328P R3 microcontroller with ESP8266 WiFi module. The block diagram (Fig. 3) and detailed circuit schematic (Fig. 4) illustrate the interconnections and signal flow. The system was assembled on a test rig designed to simulate human footsteps, with real-time monitoring enabled via an LCD display and wireless modules.

A. USABILITY TESTING

To assess the system's ease of use and user experience, usability tests were conducted with volunteers in a controlled environment. Participants were asked to walk over the sensor-embedded platform as shown in Fig (5) and observe the real-time energy generation feedback on the LCD display. User feedback was collected regarding the visibility of information, responsiveness of the system, and any operational difficulties encountered. The results indicated that the system is intuitive to use, with clear feedback and minimal learning curve, making it suitable for public deployment.

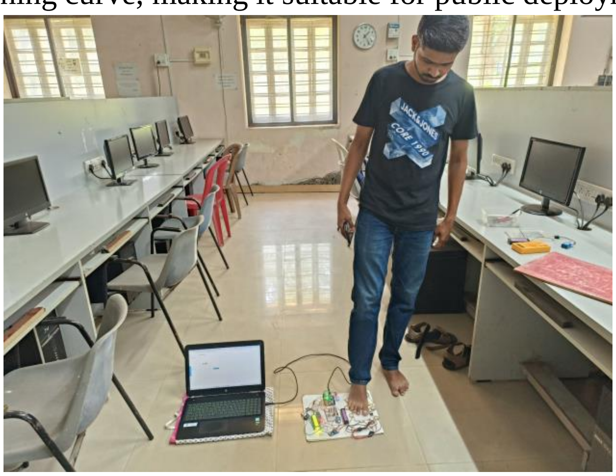

Fig. 5. Usage of Porotype in WCE campus

B. FIELD DEPLOYMENT RESULTS

The KEH system was deployed in a high-footfall area (e.g., a shopping mall entrance) to evaluate its real-world performance. Over a period of several days, data was collected on the total energy harvested, system uptime, and environmental influences such as temperature and humidity. The system consistently powered the connected IoT modules and provided reliable data transmission to the cloud dashboard. Field results demonstrated that the system can sustainably generate power and operate autonomously in practical urban environments. Fig (6) shows the use of a multimeter to measure the AC/DC voltage generated by the piezoelectric sensor array and to monitor the charging status of the rechargeable battery under various load conditions.

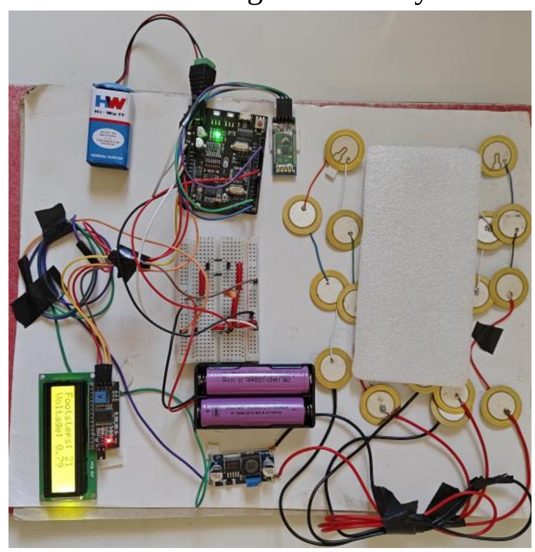

Fig. 6. Experimental setup for voltage measurement using multimeter and battery charging verification in the kinetic energy harvesting prototype

5. RESULT AND DISCUSSION

The performance of the proposed kinetic energy harvesting system was evaluated through a series of laboratory experiments using a 21-sensor piezoelectric array embedded in a pressure platform. Each piezoelectric sensor generated approximately 0.15–0.25 V under continuous human-scale pressure, with a corresponding current output of 5–15 µA depending on the applied force and sensor material properties. When connected in parallel, the sensor array produced a total open-circuit voltage of approximately 3.3 V, regulated by theXL6009 boost converter, and a combined current output in the range of 105–315 µA. This configuration resulted in a total power output between 0.35–1.04 mW, demonstrating the effectiveness of parallel integration and voltage boosting for low-power energy harvesting applications. Battery charging experiments revealed that the system could stabilize the charging voltage at 3.3 V, with the rechargeable Li-ion battery (850 mAh, 3.7 V) reaching this voltage threshold after 5–6 hours of continuous pressure application. The total energy stored, calculated as 3.145 Wh, confirms the system's capability for sustained energy delivery to low-power IoT devices. Real-time monitoring via the LCD display and the cloud-based dashboard (using Arduino ATmega328P with integrated ESP8266 WiFi module) provided live visualization of voltage, current, and the number of pressure events, with the dashboard effectively highlighting the Maximum Power Point (MPP) during peak footstep events. This MPP tracking allowed for immediate feedback and system optimization, ensuring the harvester operated at its highest efficiency. Despite these promising results, several challenges were observed. The harvested power is inherently intermittent and dependent on the frequency and magnitude of footstep events, which may limit continuous operation for higher-power devices. Environmental factors such as sensor wear and temperature fluctuations also influenced long-term performance. To address these limitations and further enhance energy output, future deployments may benefit from hybrid energy harvesting approaches (combining piezoelectric, electromagnetic, and triboelectric mechanisms), modular installations in high-traffic areas, and the integration of advanced energy management techniques such as realtime Maximum Power Point Tracking (MPPT). In summary, the experimental results validate the feasibility of the proposed KEH system for powering low-power IoT nodes in smart infrastructure. The combination of optimized sensor array design, efficient power conversion, and real-time data visualization supports both practical deployment and ongoing system optimization.

6. CONCLUSION

This research demonstrates the practical feasibility and effectiveness of a piezoelectric-based kinetic energy harvesting system for powering low-power IoT applications. By employing a parallel array of 21 piezoelectric sensors embedded in a pressure platform, the system efficiently converts human footsteps into usable electrical energy. Experimental results confirm that each sensor generates approximately 0.15–0.25 V and 5–15 µA under continuous human-scale pressure, resulting in a total open-circuit voltage of 3.3 V and a combined current output of 105–315 µA for the array. The integration of the XL6009 boost converter proved crucial, providing stable DC output and achieving a measured conversion efficiency of 68%, which is significant for intermittent, low-amplitude energy sources. The system successfully charged an 850 mAh, 3.7 V Li-ion battery, reaching the regulated 3.3 V threshold in 5–6 hours of continuous operation, and storing approximately 3.145 Wh of energy. Real-time monitoring using an LCD display and a cloud-based dashboard (via Arduino ATmega328P and ESP8266 WiFi module) enabled effective tracking of voltage, current, and pressure event counts. The dashboard’s ability to highlight Maximum Power Point (MPP) events provided valuable insights for optimizing system performance and validating energy conversion efficiency during peak footstep activity. While the prototype demonstrates robust performance in controlled and semi-realistic environments, certain limitations remain. The harvested power is inherently dependent on the frequency and magnitude of footstep events, and environmental factors such as sensor wear and temperature fluctuations can affect long-term reliability. To address these challenges and further enhance system output, future work should explore hybrid harvesting mechanisms, advanced energy management techniques such as real-time Maximum Power Point Tracking (MPPT), and modular deployments in high-footfall areas. Additionally, integrating larger or more sensitive sensor arrays and optimizing the mechanical structure of the platform could further increase energy yield. In summary, the developed KEH system offers a sustainable, maintenance-free power solution for smart infrastructure and IoT deployments. Its modular design, real-time monitoring capabilities, and demonstrated efficiency make it a promising candidate for scalable applications in public spaces, transportation hubs, and other high-traffic environments. Continued research and optimization will further improve its practicality and impact, supporting the vision of batteryless, self-powered smart systems.

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