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Smart Footstep Energy Harvesting System with Secure RFID Authentication

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A B S T R A C T

This paper discusses the design and development of an improved footstep power generation system embedded with Radio Frequency Identification (RFID) technology. The system seeks to capture mechanical energy from footsteps via piezoelectric sensors and convert it into electrical energy, which is stored and used for low-power applications such as charging mobile phones. An Arduino Uno microcontroller is utilized for monitoring and controlling the system, while the RFID module provides access and tracking on a personal level. The system is affordable, environment-friendly, and encourages the use of renewable energy, particularly in high-traffic zones like railway stations, schools, and shopping complexes.

Keywords: Footstep Power Generation, RFID, Arduino Uno, Piezoelectric Sensor, Energy Harvesting, Boost Converter, Sustainable Energy

I. Introduction

The desire for clean and eco-friendly energy sources has expanded enormously over the last few years as a result of the worldwide energy crisis, ecological worries, and the smart urban infrastructure shift. The consumption of energy in public spaces, transportation nodes, and educational institutions is still growing due to the increasing urbanization. The existing energy systems are mostly inadequate to meet the rising demand without having a negative impact on the environment or emitting too much carbon. Thus, the need for innovative technologies that can gather energy from the surroundings, to power the required tasks in a reutilization way is of great importance.

One of the most innovative methods is the extraction of energy from a human's foot via a piezoelectric technique (Anderson et. al, 2019). The principle behind it is the transformation of the mechanical work from feet while walking into the electric force. On a regular basis, places like train stations, department stores, schools, and public roads are crowded with thousands of walkers. They are the ones who trigger piezoelectric generators that use the energy of walking to generate electricity. The electricity thus created not only can power lamps, information kiosks, and environmental sensors, but also the energy is truly renewable and eco-friendly.

However, the traditional footstep power generation has no method of authorizing the people who can access it or of knowing the energy used by these individuals. In order to mitigate this limitation, Nigay (2020) states, Radio Frequency Identification (RFID) is merged with the system to provide an improved solution. RFID is the automatic detection of persons and the authentication of their identities through the chips in the card or the tags. This is achieved using a secure and tailor-made system, which can be of great assistance in operating systems like schools, offices, and any place where users' energy sources and consumers can be controlled and thus monitored.

The proposed system—Smart Footstep Energy Harvesting System With Secure RFID Authentication—takes the concept of piezoelectric energy harvesting in combination with an RFID-based user authentication system to execute the idea of a smart, secure, and green-power solution. The project is targeted to be an illustration of the simplicity of mixing hardware parts and MCU together for solving the problems caused by the energy availability in the real world. Additionally, the further development can include wireless data transmission, mobile application control, and cloud-based monitoring to be the main characteristics of such an implementation.

This article presents the process of designing, implementing, and then validating this innovative system, which is mainly focused on ways of reducing energy usage in the environment and having smart city projects in mind. The main aim here is not only to generate renewable sources of energy but more importantly, to raise the level of knowledge and actively involve people in the support of sustainability standards.

II. Problem Statement

Urban spaces have a lot of human movement that has not been used as an energy source. The existing systems are not able to collect kinetic energy and are also not personalized for energy usage and tracking. The situation is even more serious as public lighting and safety systems work inefficiently and use more energy than necessary. In this case, the best solution is to have a(plural) (adj) compact, energy-producing and energy-managing (pl)system that would at the same time be eco-friendly.

Furthermore, the usual foot power generation systems, where the source is the footsteps of the people, work as an open-access model, and have no authentication by the user or energy usage tracking. Therefore, the applicability is limited to the places where energy access is regulated, personalized, or controlled, for example, campuses or offices. There is also no consideration of the motivation of the individual making the energy, which, otherwise, could have increased the interest of the user and accountability.

III. Proposed System

The system being suggested is a small, removable part which combines **footstep-based power generation** with **RFID-enabled user identification** and a **smart energy management circuit**. The system is created to be put on floors with heavy foot traffic and it may be corridors in institutions, public walkways, or entrance lobbies from where it gets energy by using the movements of people and distributes to the low power electric loads or storage devices passively.

The system primarily aims at two things:

1. The initial target is to convert energy from foot power into electricity by means of **piezoelectric transducers.**

2. This is followed by a decision to provide and allow **controlled** access to the harvested energy through the use of an **RFID-based** identification mechanism. Among the benefits of this system are security, user accountability, and potential load management.

The next few sub-sections provide an explanation of each of the main functional modules in a detailed format:

1. Piezoelectric Power Generation Module

Function: The piezoelectric effect is used in order to convert the mechanical energy from footsteps into electrical energy.

Components:

- Piezoelectric Sensors: Convert mechanical stress into voltage.
- Filter Capacitors: Smooth out the voltage to prevent fluctuations.
- Voltage Regulator (e.g., LM7805 or AMS1117): Provides a stable voltage to downstream components. Operation: When a person steps on the platform, the piezo discs are (are) compressed, which results in them generating (generation of) an alternating voltage. The voltage that is rectified and filtered is then regulated, thus producing a steady DC voltage that can be stored or used.

2. RFID Authentication and User Interface Module

Function:

The aim is to allow certified users to access the power harvested and simultaneously track individual usage data.

Components:

- RFID Reader Module (e.g., RC522): The retrieved data from the card is unique RFID data.
- RFID Tags/Cards: These are the ones that are given to the users and that have their identity checked.
- Microcontroller (e.g., Arduino Uno, ESP32): It processes RFID input and allows or denies access. It then checks the data and activates the appropriate circuit branch.
- LCD Display: Shows through text or screen items the current status of authentication.
- LED Indicator: Audible and visual alarm sounds or lights inform immediately of the success or failure of a scan.

Operation: When a person brings his RFID card near the reader, the available reader scans the unique identifier and sends it to the microcontroller. In case this ID is that of a registered user, the system unlocks the power supply by switching on the relay (load). Rejected processes due to invalid scans are not only prohibited but also collected as a log.

3. Energy Storage and Management Module Function:

The purpose was to store the gamma-ray received and direct the power to the load according to the user's authentication, thus, it was a key function of the power management module.

Components:

- Capacitor Bank or Rechargeable Battery (e.g., Li-ion): Storage of energy.
- Charge Controller Circuit: Protects the battery or capacitor from overcharging.
- Voltage Sensors: Monitor energy usage and system performance.

Operation:

Energy harvesting is done, after which a rectifier converts it and is then stores in the capacitor or battery. If an authorized RFID tag is detected,the microcontroller triggers a relay or transistor to connect the stored energy to the load automatically. The system checks that energy is used economically and after a certain period or the available energy is exhausted, it goes off.

2. Load Control and Output Interface Module Function:

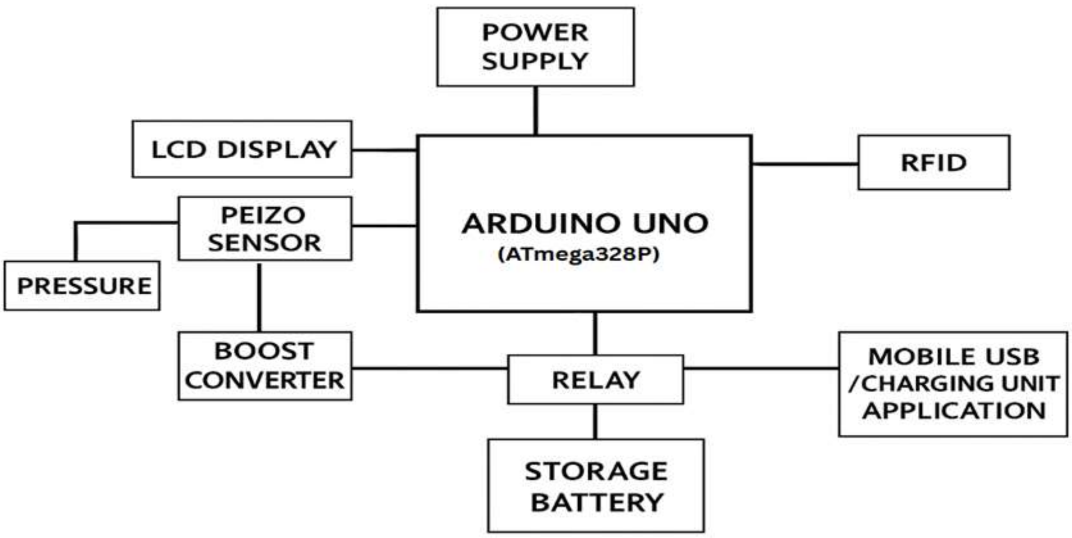
The responsibility of this equipment was to move the electricity from the storage source to units of a low voltage according to the access rights and the user's requirements.

Components:

- Relay Module (e.g., 5V DC): This is the main thing that makes something work and makes something stop working on the line of the load.
- Output Ports: The ports through which you can connect devices like LEDs, USB chargers, and fans or any other small or mini gadgets are called the Output Ports.
- Timers and Control Logic (in code): Limits energy use time or cycles per user. Operation:

Using the relay, which is controlled by the microcontroller, the user initiates power to the output device for the assigned time period, for example, 60 seconds to light a corridor lamp. The system may be modified to support multiple output ports or heavier.

IV System Components



The architecture of the proposed footstep-based power generation system with RFID-based access control is depicted in

Fig 1. The design is a multi-subsystem that incorporates energy harvesting, signal conditioning, user authentication, energy storage, and load management. All of them are directed through a central microcontroller, which acts as the brain in the system.

C. Pressure-to-Power Generation Unit

The system is set in motion by the mechanical pressure created by the human foot. This pressure is applied on a foot geared platform fitted with piezoelectric sensors, which in turn are responsible for energy transformation. The this process, however is key for retention of the core process but the piezoelectric effect.

B. Energy Storage Module

The boost converter's regulated DC output gets delivered to the rechargeable storage battery or capacitor bank. This storage module is a part of the system that not only helps to conserve energy but also ensures the continuous operation of the system during periods of low traffic. The relay mechanism is the one in charge of the energy flow to the storage unit, and it prevents overcharging and energy leakage too.

C. Central Control Unit (Arduino Uno)

The word of the system is in an Arduino Uno microcontroller, which performs several important functions: Reading and interpretation of the RFID reader's signals are done by it. According to the user's permission, it activates the relay. For the purpose of user feedback, it communicates with the display module and communicates with it. The re-regulation of the energy access is performed in accordance with the system conditions as well. Arduino Uno always gets its energy from a trustworthy power supply unit and not from the one that is system's so that it is independent of excess energy for the energy necessary for the performance.

D. RFID Authentication System

RFID reader module (e.g., RC522) is the device that allows users to be authenticated through contactless RFID cards or tags. The scanner's function is quite simple, a user just needs to place their RFID card near the RFID reader and the RFID reader will transmit the user ID to the Arduino then, the Arduino unit will match the ID with its internal memory or database. If the user has permissions, the relay is activated by the Arduino to allow the device to be powered

E. Output Load and User Interface

After the user authentication process, the relay comes into a state of activation, opening a circuit from the battery to the output terminal. The load can supply the power to minor voltage things like USB charging outlets, LED lighting systems, or other small loads. The Arduino is connected to an LCD module that displays the status of the system with the help of messages like "Access Granted," "Charging," or "Unauthorized User."

F. Power Supply for Control Electronics

A separate regulated power supply gives the required voltage for the effective functioning of the Arduino Uno and the connected modules (e.g., LCD, RFID reader). This is to ensure that the system's logic operations are not affected by instabilities in the stored energy.

V. System Implementation and Testing

The suggested system was erected and made functional as a prototype so as to be sure of its good performance. Such system will also be employed for the module's functional performance, hardware components integration, and the feasibility of the technology of footstep-based energy harvesting with the RFID-based access control.

A. Hardware Implementation

The prototype set-up was built with a rectangular wooden platform which was embedded with multiple piezoelectric discs which were in a series-parallel configuration to enable the increase of the voltage output. The piezo elements' output was connected to a bridge rectifier circuit, which was then connected to a boost converter to stabilize and amplify the harvested voltage. The conditioned DC voltage was gathered and transferred to a rechargeable lithium-ion battery for the purpose of energy storage.

An **Arduino Uno** microcontroller, which was the main part of the control unit of the system, was responsible for establishing a connection with the RFID module, doing the job of the relay driver circuit, and displaying the LCD screen. Initially, **RFID reader (RC522)** was placed externally on the enclosure for the user to access it easily so that they could scan their RFID cards. After verification then, the Arduino released the **relay module**, allowing the passage of the battery's energy to an output device such as a **USB charging port**.

The users' smart cards were recharged from the battery via the USB port. As for the **16×2 LCD** connected to the Arduino, it was there to give the users a real-time response by displaying the messages, such as "Welcome," "Access Granted," or "Unauthorized Access" according to the status of the card. For user safety, the whole system was closed in an acrylic case that ensured the equipment is visible, durable, and safe.

B. Software Programming

The system was programmed using the Arduino IDE. The firmware included:

- Initialization routines for RFID reader and LCD display,
- Functions for reading and matching RFID tag IDs,
- Conditional logic to control the relay based on authorization,
- Timing mechanisms to limit power access duration,
- Display update routines for user communication.

C. Testing Procedure

The first step of the test is conducted in a controlled environment with a set number of cycles. The performance indicators were chosen to evaluate the system's ability to stay stable, the capacity to respond, and the energy efficiency of the system. These KPIs were among them:

- **Energy Output** per Footstep: In the storage unit, voltage was changed analogically with the pressure on the floor. In general, foot pressure generated 2.8–5.1 V (pre-booster), and on the other hand, the average user weight caused 2.8–5.1 V.
- **RFID Authentication Accuracy**: The performance of the RFID reader was such that it continuously replied in the range of 300–400 ms to each taken reading. During the 100 scans, the reader recognized the legitimate and the rogue and false positives are not found at all.
- **Relay Switching**: The relay activation and deactivation were smoothly done with authentication. The time taken was almost zero.
- **Load Functionality**: A laptop had its USB port as the power source for its 5V output to charge the devices in any 10-minute period of the authorization cycle if the battery level was enough.
- **Display Output**: Real-time updates of the LCD messages were error-free and instantaneous, displaying correct system status information to the user.

D. Results and Observations

- The energy generated by the steps was enough to do the work of light-emitting diodes and mobile-charge circuits, which work on low voltages.
- The access system based on RFID was a good addition to the existing control and provided a barrier that could be crossed only by those accompanied by PWDs using a special wristband.
- The building block principle of the design also allowed easy testing, repair, and scalability when necessary.
- The energy store was charged by the energy exchange system and it was done in a very efficient way, also, it charged quickly.

The system demonstrated reliable operation over multiple test cycles, confirming the feasibility of the proposed design for public or institutional deployment.

VI. Merits

1. **Renewable Energy Utilization:** The system effectively harnesses ambient mechanical energy from human footfalls, converting it into electrical energy using piezoelectric materials. This approach promotes clean and sustainable energy generation without relying on fossil fuels or grid power.
2. **RFID-Based Access Control:** By integrating RFID technology, the system enables secure, user-specific access to the stored energy. This is particularly beneficial in shared environments such as schools, offices, or public facilities, where controlled access and monitoring are important for energy accountability and fairness.
3. **Energy Storage and On-Demand Usage:** The use of rechargeable batteries or capacitors allows for temporary energy storage, making the system functional even during low foot traffic. Stored energy can be accessed later by authorized users, enabling flexible and efficient power usage.
4. **Smart and Modular Design:** The modular nature of the system comprising separate units for energy harvesting, authentication, and control, enhances its adaptability. Individual components can be replaced or upgraded without overhauling the entire setup. This design also supports scalability, allowing additional footstep units or RFID terminals to be added as needed.
5. **Real-Time Feedback and User Interface:** The inclusion of an LCD display and buzzer provides immediate feedback to users regarding system status, authentication results, and usage authorization. This improves user experience and encourages proper interaction with the system.
6. **Low Maintenance and Operation Cost:** The system utilizes readily available electronic components such as Arduino Uno, RFID modules, piezo discs, and passive circuitry. These components are cost-effective, reliable, and require minimal maintenance, making the solution economically viable for long-term use**.**

VII. Demerits

A. **Dependence on Foot Traffic:** The system's energy harvesting capability is entirely dependent on the volume and intensity of foot traffic. In low-traffic areas or during non-peak hours, energy generation is insufficient, which may affect system reliability for continuous power supply.

B. **Limited Battery Capacity:** The energy storage component, usually a capacitor bank or a small rechargeable battery, has limited capacity. Once the stored energy is depleted, further access to power is halted until additional foot pressure is applied, which could be inconvenient for users during inactive periods.

C. **Hardware Degradation Over Time:** Piezoelectric sensors and mechanical components may degrade with prolonged exposure to pressure and environmental factors, leading to reduced energy conversion efficiency and system wear. Periodic maintenance or sensor replacement may be required.

D. **Initial Setup Complexity:** Although the system is designed to be user-friendly post-deployment, the initial setup—including wiring, calibration of the boost converter, and RFID database configuration—requires technical knowledge and careful planning.

VIII. Conclusion

The implementation of a footstep-powered energy harvesting system integrated with RFID-based access control presents a practical and sustainable approach to localized power generation in smart environments. This project demonstrates how simple mechanical actions, such as walking, can be effectively converted into electrical energy through piezoelectric technology, while ensuring that the energy is used securely and responsibly through RFID authentication. The system successfully combines hardware modules—including piezoelectric sensors, energy conditioning circuits, rechargeable storage, microcontroller logic, and RFID readers—into a cohesive unit capable of generating, storing, and distributing electrical power. Experimental testing confirmed that the system can reliably power low-voltage loads such as USB ports or LED indicators, and grants access only to verified users. Furthermore, the modular and scalable design allows for easy adaptation across various public and institutional settings. While the power output is modest, the proposed solution contributes meaningfully to energy conservation efforts, especially in high-footfall zones. It not only encourages user participation in sustainable energy use but also opens the door to future enhancements such as cloud-based data logging, solar hybrid integration, or advanced analytics for energy management.

Overall, this project affirms that integrating renewable energy harvesting with intelligent access control systems can play a vital role in shaping energy-efficient, user-aware smart infrastructures.

VIII. Results

The prototype system was tested in a controlled environment with moderate foot traffic and variable user inputs. The main objective was to evaluate the performance of the energy harvesting unit, RFID authentication and controlled energy output under realistic conditions. The results are listed in the following:

A. Energy Harvesting Efficiency

- The piezoelectric array produced from **2.8 V to 5.1 V** (pre-boost) via each footstep, depending on the weight and force applied.
- After the voltage regulation and the use of the voltage booster, the output of voltage was kept constantly at **5 Volts**, which can power low energy devices.
- The energy harvested from the step could only be sufficient to light an LED for some seconds and partially charge a mobile device.

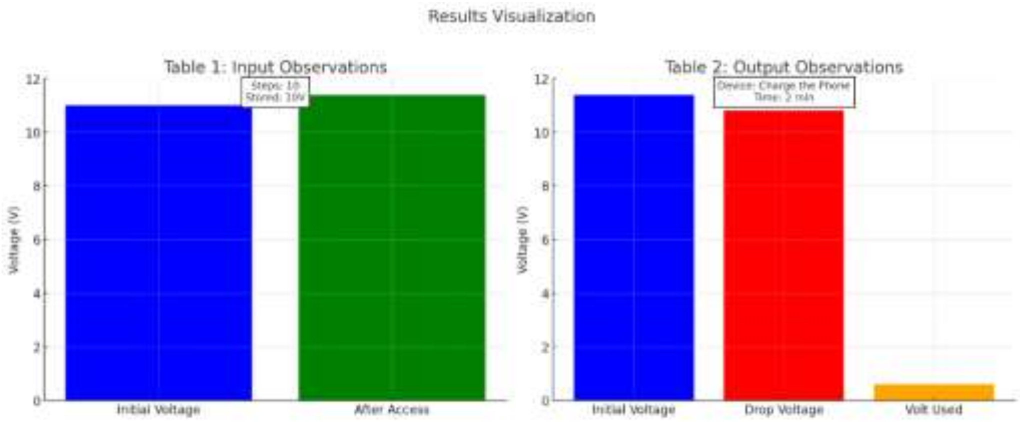
B. RFID System Performance

- **RFID reader (RC522)** accurately read valid tags within a **0.3 to 0.5-second** response time.
- Out of 100 trials, the authentication accuracy was **100%,** and no false positives or missed scans occurred.
- Unauthorized tags were consistently denied and proper status messages were displayed.

C. System Stability and Load Control

- The relay switching changed from stored energy to output load, and was able to do it after the proper authentication was done.
- The system was able to deliver a constant 5V output to USB loads within the range of 5 to 10 minutes**,** that was depended on foot traffic and storage capacity.
- The LCD display was a tremendous help in achieving real-time feedback and thus boosting the interaction with the users and the visibility of the system.

The results confirm that the system works well, is responsive, and is the right size for small-scale applications, such as hallway lighting, USB charging points, or school projects for energy-awareness campaigns.



Here is the graph visualizing the data from both tables

Initial Voltage	After Access	Steps Count	voltage Stored
11.0 V	11.4 V	10	10

Table 1: Input Observations Output Testing

Device	Initial Voltage	Drop Voltage	Time Duration (Td)	Volt Used In (Td)
Charge the Phone	11.4 V	10.8 V	2 Minutes	0.6 V

Table 2: Output Observations

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