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Predictive Analysis of Power Generation from Footsteps Using Machine Learning

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Abstract: *Energy has long been the pulse of human civilization, fueling progress and innovation. Yet, as conventional sources dwindle, the search for sustainable alternatives becomes not just a necessity but an inevitability. This project explores a concept hidden in plain sight harnessing the energy of footsteps. Every step carries kinetic potential, an untapped rhythm of daily life waiting to be transformed.*

Piezoelectric tiles embedded in high-footfall areas homes, schools, railway stations capture this overlooked energy, converting motion into electricity. Each step, no longer just a movement, becomes a contribution to a self-sustaining cycle, where human activity fuels itself. But beyond the conversion of energy, intelligence refines its efficiency. Machine learning breathes adaptability into this system. By employing Linear Regression and Random Forest Regression, the technology does not merely generate power it learns. Real-time data analysis predicts and optimizes energy output, creating an evolving system that grows smarter with every footstep. The results unfold on an interactive Python-powered dashboard, where raw motion turns into visualized potential.

In a world that never stands still, where crowded streets and bustling transit hubs define the pulse of modern life, this idea aligns seamlessly with the natural flow of human movement. Especially in a country like India, where millions move in unison every day, the potential is immense. This is more than an experiment in alternative energy it is a vision of sustainability woven into the fabric of urban existence. One step, one spark, one future powered by motion itself.

Keywords: Footstep Energy Harvesting, Machine Learning, Predictive Analysis, Sustainable Energy, Smart Cities, Piezoelectric Sensors..

I. INTRODUCTION

Energy is the invisible force that fuels our world, shaping how we live, move, and connect. Yet, as traditional sources diminish, the search for new ways to generate power becomes more urgent. What if energy could be found not in vast power plants or deep beneath the earth, but in something as ordinary as walking? This research explores an idea both simple and extraordinaryharnessing the energy of footsteps to generate electricity.In places where people move endlesslytrain stations, schools, shopping mallsthe rhythm of footsteps creates an unnoticed pulse of kinetic energy. By embedding special sensors into these spaces, this movement can be transformed into electrical power. Each step carries untapped potential, a fleeting burst of force that fades unless captured. This project envisions a world where no step is wasted, where movement itself contributes to a greener, more sustainable future.

The goal is not just energy generation, but accessibility. The electricity produced can power small applications, from lighting to low-energy devices, bringing sustainability into everyday life. Unlike large-scale power plants, this technology thrives in human spaces, working in harmony with the natural flow of urban existence.

Beyond practicality, this project invites a shift in perspective. It asks us to see energy not as something distant and mechanical, but as an extension of our own motion. Every step, whether taken in haste or leisure, holds the promise of power. In a world that never stops moving, this idea blends seamlessly with daily life, offering a renewable source of energy that grows with the footsteps of the people. This vision of sustainability is not confined to grand innovations. It is found in the simplest of actions, reminding us that change begins where we stand and moves forward with every step we take.

A. Objectives:

Unseen energy lingers in every step, waiting to be discovered.
As footsteps whisper across the earth, a silent current awakens.
Movement becomes more than motionit carries the promise of power.

B. Paper Organization:

This paper is structured as follows: Section 2 covers related work on piezoelectric energy harvesting and ML-based energy prediction. Section 3 details the proposed methodology, including system design and ML models. Section 4 analyses performance through experiments and accuracy metrics. Section 5 summarizes key findings. Section 6 explores future advancements. Section 7 lists references.

II. RELATED WORK

Deep Learning Techniques for Energy Prediction in Piezoelectric PowerSystems

Convolutional Neural Networks (CNNs) have been employed to enhance energy forecasting in piezoelectric systems. These models analyse intricate footstep patterns, particularly in varying traffic conditions, improving adaptability and prediction accuracy for energy harvesting [1].

Predictive Analytics for Piezoelectric Energy Generation Using Machine Learning

Decision trees and ensemble learning techniques have been utilized to estimate energy production in high-footfall areas. Parameters such as step force and frequency influence predictive models, aiding in energy optimization for locations like transport hubs and sports arenas [2].

Real-Time Monitoring of Piezoelectric Energy Harvesting with IoT Integration

The integration of IoT with piezoelectric tiles enables real-time energy monitoring and prediction. Neural networks process sensor data from high-footfall environments such as malls and hospitals, improving system efficiency and reliability [3].

Enhancing Footstep Energy Harvesting Efficiency Using Machine Learning Models

Regression models have been employed to predict power output from piezoelectric sensors based on parameters such as pressure and footstep frequency. These models facilitate optimized energy utilization in urban infrastructures such as railway stations and airports [4].

Piezoelectric Energy Harvesting Using Advanced Machine Learning Models

This research investigates the application of advanced machine learning models such as Support Vector Machines (SVM) for predicting energy generation from footstep pressure in different environments. The study emphasizes improving predictive accuracy for more efficient energy harvesting systems [5]

Comparative Analysis of Machine Learning Models in Piezoelectric Energy Harvesting

III. PROPOSED METHODOLOGY

A. Power Generation from Footsteps

This project leverages the piezoelectric effect to convert mechanical energy from footsteps into electrical energy, specifically utilizing the direct piezoelectric effect, which transforms vibrations or applied stress into electrical signals. The sensors used are piezoelectric disk sensors, which contain quartz crystals or other piezoelectric materials. When mechanical pressure is applied, these crystals generate an electrical charge due to their internal atomic structure shifting under stress.

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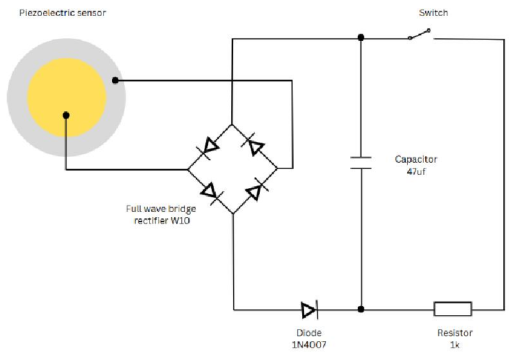
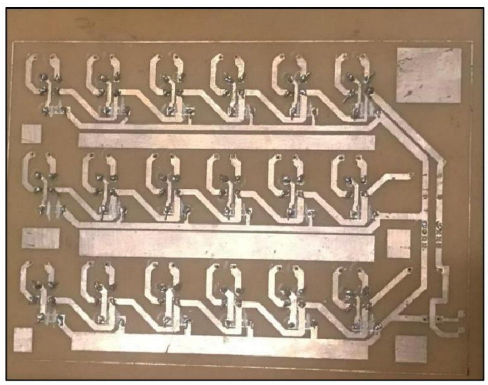
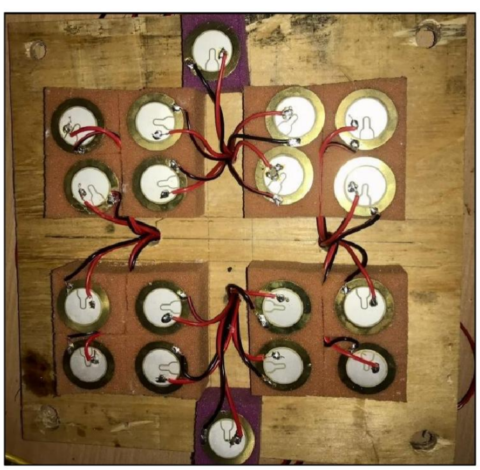
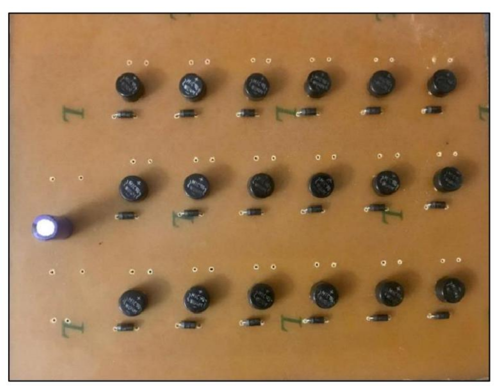


The energy conversion process begins with piezoelectric transducers embedded in tiles, capturing mechanical force from footfalls. The resulting alternating current (AC) is converted into direct current (DC) through a full-wave bridge rectifier. The rectified DC is then filtered and stored in capacitors or batteries, making it suitable for low-power applications like streetlights and digital signboards.



To optimize energy output, the piezoelectric transducers are arranged in different configurations—series, parallel, and series-parallel. A series connection generates higher voltage but lower current, whereas a parallel connection increases current but reduces voltage. To strike a balance, a series-parallel configuration is implemented, ensuring an optimal combination of both voltage and current.





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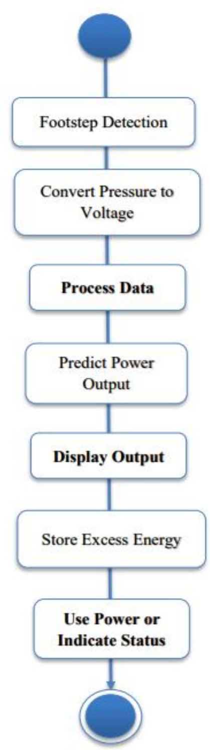
A custom-designed piezoelectric tile, consisting of a wooden frame housing 18 piezoelectric transducers placed between two spring-supported plates, is used to capture footstep energy. The tile was tested with individuals weighing between 45 kg and 60 kg, who applied foot pressure and engaged in pumping actions for 5, 10, 15, and 20 seconds. A Multimeter was used to measure voltage output, andresults were analysed.To facilitate real-time data collection, an Arduino Uno is integrated into the system, recording energy readings for further analysis. Findings revealed a linear relationship between applied force and voltage generation, indicating that heavier individuals produced higher voltage outputs. The highest voltage was observed during continuous pumping activity lasting 20 seconds. This approach demonstrates an effective and sustainable method of footstep energy harvesting, offering a practical solution for powering small-scale devices in high-traffic areas while also enabling precise data analysis for system optimization.

Study	Model Used	Key Findings	Research Gap
Deep Learning for Energy Prediction[1]	CNNs	High adaptability and improved forecasting accuracy	Limited real-time applicability, optimization needed
Machine Learning for Piezoelectric Energy Estimation[2]	Decision Trees, Ensemble Learning	Effective estimation in high-footfall areas with multiple parameters	Lacks IoT integration for real-time monitoring
IoT-Based Monitoring for Energy Harvesting [3]	Neural Networks + IoT	Enables real-time performance tracking and efficiency enhancement	Requires predictive optimization for energy efficiency
Footstep-Based Energy Harvesting Optimization [4]	Regression Models	Accurate power output estimation based on step dynamics	Needs consideration of external environmental influences
Advanced ML for Energy Harvesting [5]	SVM	Enhanced predictive accuracy	Needs hybrid modelling for improved efficiency

B. Predictive Analysis Using Machine Learning



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The study uses an Arduino Uno microcontroller, programmed via the Arduino IDE, to gather voltage readings from piezoelectric transducers placed in the experimental setup. Subject weight and step count are manually entered during data collection. The voltage generated by the piezoelectric sensors during each step is recorded, and the data is transmitted via a serial interface. This data, which includes voltage output, weight, and step count, is stored in a CSV file using Python's pandas library for further analysis. This dataset is used to explore patterns and trends in energy generation based on footstep data, with the goal of developing predictive models for energy forecasting.

In this study, we use Arduino Uno to gather voltage data from piezoelectric tiles as people walk over them. The data includes voltage output, subject weight, and step count, which are stored for later analysis. Data preprocessing involves managing missing data with pandas and handling outliers using basic statistical techniques. We use MinMaxScaler to normalize the data so all features are on the same scale. If there are any categorical variables, we apply encoding methods like one-hot encoding or label encoding to transform them into a numerical format.

In Exploratory Data Analysis (EDA), we explore patterns and trends using pandas, NumPy, Matplotlib, and Seaborn. We look for relationships between variables, such as how weight and step count affect the energy generated. Visual tools like heatmaps, scatter plots, and line graphs help reveal these insights.

For predictive modelling, we use Linear Regression and Random Forest Regression to predict the energy output based on the input data. Linear Regression is chosen for its simplicity and easy interpretation of results. It establishes a direct relationship between footstep parameters and energy output, making it useful for understanding the fundamental dependencies in the data. However, energy generation is influenced by multiple nonlinear factors, making Random Forest Regression a better choice for capturing complex dependencies and improving accuracy. Random Forest, being an ensemble learning method, reduces overfitting and provides better predictions for datasets with diverse input conditions. The dataset is divided into a training set (80%) and a testing set (20%). Model performance is evaluated using Mean Absolute Error (MAE), Mean Squared Error (MSE), and R^2 score. Results indicate that Random Forest Regression provides more accurate predictions due to its ability to handle variations in energy output.

By integrating machine learning with hardware-based energy harvesting, the system can provide real-time insights and trend forecasting. A dashboard is created using Streamlit to visualize sensor readings in real time, predict energy output, and alert users in case of anomalies. The system is built using Python for data processing and modelling, C++ for Arduino programming, and libraries such as scikit-learn, pandas, and Matplotlib. This approach enhances energy optimization while demonstrating the potential for data-driven renewable energy solutions.

C. Algorithm Implementation

1) Algorithm 1: Piezoelectric Sensor Data Processing

(a) Initialization

Initialize LCD, Serial communication, and piezoelectric sensor.

Display "Piezo Energy" on LCD.

(b) Sensor Data Processing (Loop)

Read voltage from the piezoelectric sensor.

If voltage increases beyond the threshold:

Increment step count.

Set step detected flag.

If step detected:

Display voltage and step count on LCD.

Send voltage and step count over Serial.

Update previous voltage.

Wait for a short delay.

(c) Data Logging in Python

Connect to Arduino via Serial.

Create or open a CSV file.

Continuously read voltage and step data from Serial.

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If step count increases and voltage is valid:
Log data with a timestamp in the CSV file.
Update real-time visualization using Streamlit.
Stop on user interrupt or invalid data.

2) Algorithm 2: Predictive Analysis using Machine Learning
(a) Load Data
Load the latest CSV file from the data folder.
Check if 'Voltage' and 'Steps' columns exist.
(b) Feature Engineering
Calculate energy using the formula: $0.5 * C * V^2$.
Compute moving average of voltage.
Calculate voltage change and rate of change.
(c) Data Splitting
Split data into training and testing sets.
(d) Model Training
Train a RandomForestRegressor using the extracted features.
(e) Model Evaluation
Evaluate performance using Mean Absolute Error (MAE).
(f) Save Model
Save the trained model to a file for future use.

3) Algorithm 3: Real-Time Visualization Using Streamlit
(a) Initialize System
Load the trained AI model.
Configure the Streamlit dashboard.
(b) Set User Inputs
Add sliders in the sidebar to adjust efficiency and resistance.
(c) Load Data
Load the latest CSV file from the data folder.
(d) Process Data (If CSV contains 'Voltage' and 'Time')
Compute physics-based power and energy.
Extract features and predict AI-based energy output.
Display voltage and energy stats in the sidebar.
Show key metrics and comparison charts on the dashboard.
Provide an option to download processed data as an Excel file.
(e) Error Handling
Display warnings for missing or invalid data.

D. Mathematical Modelling

1) Piezoelectric Energy Harvesting Model

The energy generated by a piezoelectric element under mechanical stress can be modelledby the classic capacitor energy formula:

$E = (1/2) * C * V^2$

where C denotes the capacitance of the piezoelectric material (in Farads), and V representsthe voltage generated due to mechanical deformation. This relationship forms the basis ofenergy estimation in conventional physics-based models [6].

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2) Power and Energy Over Load

The harvested voltage is subjected to a resistive load R, where the instantaneous power canbe expressed as:

P = V^2 / R

Over a time interval Δt, the total harvested energy is computed as:

E_physics = Σ (V_i^2 / R) * Δt_i

where V_i and Δt_i represent the voltage and sampling time difference for the i-th reading,respectively. This model assumes ideal conversion without system losses.

3) AI-Driven Regression Model

In addition to the physics-based model, we develop an AI regression framework to predictenergy using a trained Random Forest Regressor. The model utilizes time-series-derivedfeatures:

X = {V, MA(V), ΔV, ΔV / MA(V)}

where:

- V is the instantaneous voltage,
- MA(V) is the moving average of voltage over a sliding window,
- ΔV is the voltage difference between consecutive samples,
- ΔV / MA(V) captures the relative voltage change rate.

The model is trained to approximate:

f: X → E_ai

where E_ai denotes the AI-predicted energy output.

4) Model Evaluation Metric

The performance of the AI model is assessed using the Mean Absolute Error (MAE):

MAE = (1/n) Σ | y_i - ŷ_i |

where y_i is the ground truth energy derived from the physics model, and ŷ_i is the AI modelprediction.

IV. PERFORMANCE ANALYSIS

The system works by capturing the energy generated from footsteps and converting it into electrical power, all while using artificial intelligence to help understand and predict how much energy will be produced.

No. of Footsteps	Voltage Generated on 2 Tiles	Time
1	0.2 volt	1 second
5	1.0 volt	5 seconds
10	2.0 volt	10 seconds
20	4.0 volt	20 seconds
100	20.0 volt	100 seconds

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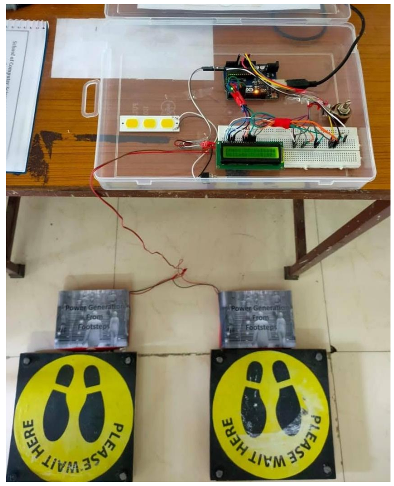
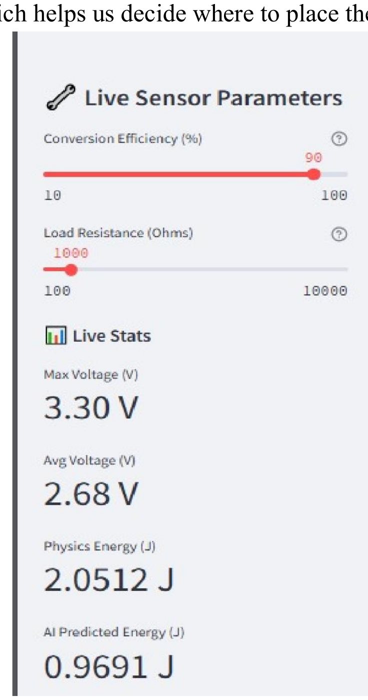


As more people walk and as their weight increases, the energy produced also rises. For example, a person weighing 45 kg creates a small amount of energy in just a few seconds, while someone heavier generates more. In places with a lot of people walking around, this energy could be enough to power things like lights.

Artificial intelligence plays a key role in analysing this energy data. The system collects information like the voltage, step count, and weight, then organizes it for analysis. The data is cleaned up and adjusted so we can make accurate predictions about future energy output. We use tools to visualize how different factors—like weight or the number of steps—affect the amount of energy being generated.

For predicting energy production, we use two methods: one that looks at simpler patterns in the data and another that finds more complex relationships. After comparing these methods, we found that the more complex approach worked better at making accurate predictions, which helps us decide where to place the tiles for the most energy.



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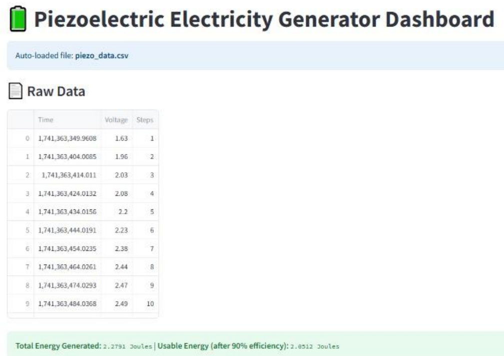

Piezoelectric Electricity Generator Dashboard

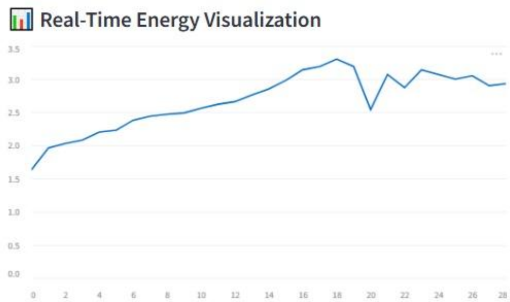
Auto-loaded file: piezo_data.csv

Raw Data

	Time	Voltage	Steps
0	1,741,363,349.9608	1.63	1
1	1,741,363,404.0085	1.96	2
2	1,741,363,414.011	2.03	3
3	1,741,363,424.0132	2.08	4
4	1,741,363,434.0156	2.2	5
5	1,741,363,444.0191	2.23	6
6	1,741,363,454.0235	2.38	7
7	1,741,363,464.0261	2.44	8
8	1,741,363,474.0293	2.47	9
9	1,741,363,484.0368	2.49	10

Total Energy Generated: 2.2791 Joules | Usable Energy (after 90% efficiency): 2.0512 Joules

The system also has the ability to make predictions in real-time. As people walk, the system predicts the energy that will be generated right then and there.



The data flows smoothly through the system, and we can see everything on a dashboard. This makes it easy to spot any problems and keep everything running at its best.

V. CONCLUSION

The Footstep Energy Harvesting System converts human movement into electrical energy using piezoelectric technology. It collects real-time foot traffic data through an Arduino microcontroller and processes it using Python-based analysis. The harvested energy can be stored and used for low-power applications like lighting. This system offers a practical approach to integrating renewable energy into urban spaces, contributing to sustainable infrastructure.

VI. FUTURE SCOPE

- AI-Driven Optimization: Improve energy efficiency using machine learning to analyse foot traffic patterns.
- Footfall-Based Resource Planning: Predict high-traffic periods for better facility management in public spaces.
- Hybrid Energy Solutions: Integrate with solar and wind energy for sustainable urban infrastructure.
- Wireless Energy Transfer: Develop efficient methods for transmitting harvested energy without physical connections.
- Scalability & Mass Adoption: Expand implementation in rural electrification projects and smart city developments.

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