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DEVELOPMENT OF AN ENERGY HARVESTING TECHNOLOGY THAT CONVERTS KINETIC ENERGY INTO ELECTRICAL ENERGY BASED ON AN INTELLIGENT PIEZOELECTRIC SYSTEM

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Annotation: This article analyzes the technical and practical aspects of developing an intelligent piezoelectric system that converts kinetic energy into electrical energy. The aim of the project is to create a stable and renewable energy source by harvesting energy in crowded areas or locations with frequent movement. In the study, a system model was developed based on piezoelectric sensors, microcontrollers, and energy storage modules. Test results confirmed the efficiency of the system and demonstrated its potential real-life applications, such as in walkways, parks, and transportation hubs. The article also examines an intelligent control system and energy harvesting monitoring. The research results show that the system is promising for integration into urban infrastructure and IoT systems.

Keywords: Piezoelectric sensor, kinetic energy, energy harvesting, intelligent system, IoT integration, renewable energy, pedestrian motion energy, piezoelectric platform, energy conversion, sustainable energy system, sensor monitoring.

Introduction

In recent years, global demand for energy sources has been increasing sharply. In particular, interest in sustainable and renewable energy sources continues to grow. Traditional energy sources—such as solar (photovoltaic) or wind power—require large areas, special installations, and are dependent on climate conditions, which limits their application in certain locations. For this reason, technologies that convert the kinetic energy produced by human movement, vehicles, and natural vibrations into electrical energy are gaining attention as innovative and promising solutions.

Piezoelectric sensors are among the most efficient components in this field. Piezoelectric materials generate electric charge under mechanical pressure or vibration, allowing useful energy to be extracted from each step or vibration. Studies show that devices harvesting human motion energy typically produce between 300 µW and 2.5 mW of electrical power. One person's 1–10 minutes of movement—equivalent to about 1 mW—can power a small Bluetooth Low Energy (BLE) sensor to detect motion and transmit data every 10–15 minutes. Additionally, piezoelectric systems operate effectively even under low-frequency motion, are suitable for miniaturization, and are more convenient to use compared to other energy harvesting methods.

Several systems have already been successfully implemented worldwide. For example, the Pavegen system in the London Underground harvests energy through piezoelectric platforms installed in pedestrian walkways. Furthermore, the article "Comprehensive Review on Effective Strategies for Piezoelectric Energy Harvesting" emphasizes the importance of material,

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geometry, and structural optimization for low-frequency motion. However, many existing systems lack integration with intelligent control and real-time monitoring, which limits their efficiency.

This article proposes the development of an intelligent piezoelectric system that converts kinetic energy into electrical energy in crowded or high-movement areas. The main features of the system include:

- Efficient management of energy harvesting,
- Real-time sensor monitoring,
- Integration capabilities with IoT systems.

At the same time, the project offers practical solutions: reducing energy shortages, increasing the efficiency of low-power systems, enabling real-time monitoring, and creating a system adapted to local conditions. This approach presents a new and relevant solution for harvesting energy from human motion not only in Uzbekistan, but also worldwide, enabling the development of an intelligent, IoT-integrated piezoelectric system that did not previously exist.

Theoretical and Technical Foundations of the Study

The piezoelectric effect is a phenomenon in which certain crystals generate electric charge as a result of mechanical deformation or vibration. In other words, mechanical energy is directly converted into electrical energy. This effect forms the basic operating principle of piezoelectric sensors. Piezoelectric sensors consist of a piezo-element that converts mechanical force, pressure, or vibration into an electrical signal.

Example:
If human walking causes the sensor to deform and produce a force of **F = 10 N**, and the piezoelectric constant is **d = 200 pC/N**, the resulting charge is:

$$Q=200\times10^{-12}\times10=2\times10^{-9}C$$

If the capacitance is **C = 10 nF**, the voltage is:

$$V=\frac{Q}{C}=0.2V$$

The generated energy is:

$$E=\frac{1}{2}CV^2\approx2\times10^{-10}\ J$$

It is clear that the piezoelectric effect is the reason for the sensor's operation, while the sensor implements this effect in the form of a practical device. Through this relationship, piezoelectric systems convert mechanical energy into electrical energy. Piezoelectric sensors are also used in energy harvesting systems because they convert motion, pressure, or vibration into electrical

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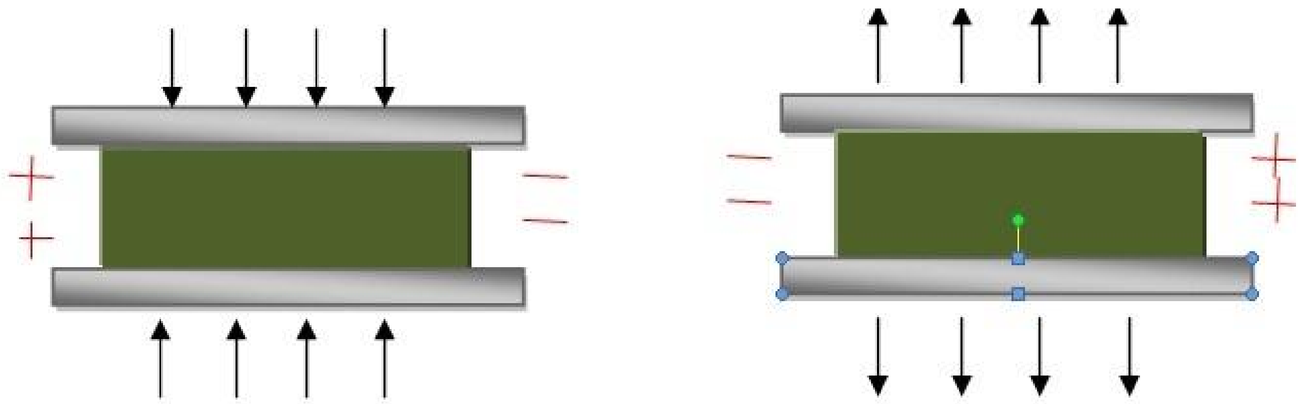
energy and, with the help of an intelligent system, transfer this energy to a storage unit — a capacitor or a battery.

Intelligent systems monitor the signal generated by piezoelectric sensors, optimize it, and maximize energy harvesting. These systems play a crucial role in ensuring that the electrical energy obtained from irregular and often low-frequency motion is converted efficiently and stored in a usable form. In practice, the sensor provides continuous information about vibration frequency, amplitude, applied pressure, and the duration of mechanical deformation. This raw signal is typically unstable and varies significantly depending on the user's movement or the surrounding environmental conditions. Therefore, the microprocessor first filters noise, stabilizes the waveform, and determines the optimal operating range for energy conversion.

After processing the signal, the microprocessor regulates the flow of electricity through a power-conditioning module, which may include a rectifier, voltage regulator, and energy storage controller. This module ensures that the generated AC signal is converted into a stable DC output suitable for charging the capacitor or battery without causing overvoltage or energy loss. Intelligent control algorithms can also adapt to different motion patterns by adjusting sensitivity, sampling rate, or power usage according to real-time conditions.



1 **Figure – Operation of a Piezoelectric Transducer**

In piezoelectric energy harvesting systems, the amount of generated energy depends on different types of motion. According to information provided in books:

Type of Motion	**Force (N)**	**Generated Energy (μJ)**	**Time (s)**	**Explanation**
Footstep	300	2–5	0.5	During walking
Door vibration	10	0.1–0.3	1	Low displacement
Table vibration	5	0.05–0.1	1	Small vibration

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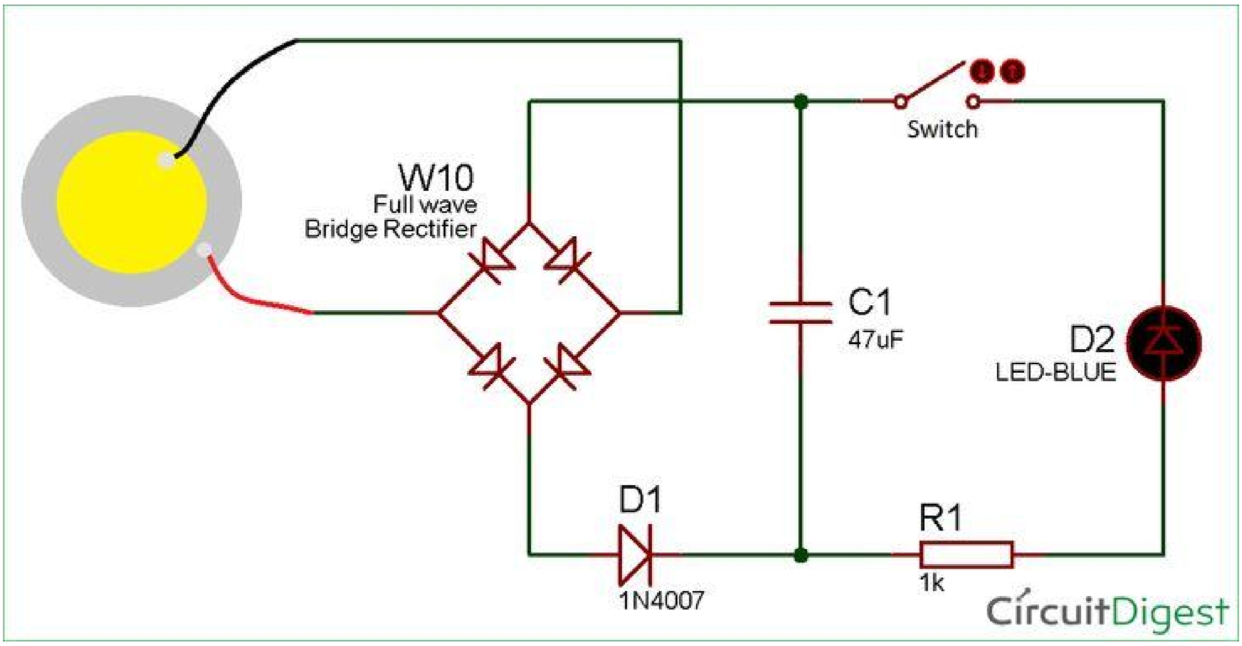
In this way, the piezoelectric effect, sensor, materials, energy harvesting, and intelligent system are interconnected. The effect represents the principle of converting mechanical energy into electrical energy; the sensor implements this effect as a practical device; the materials determine the system's efficiency; and intelligent control optimizes the energy harvesting process.



2- **Figure – Electronic Circuit for Piezoelectric Energy Harvesting Based on Footstep**

Pressure: Piezoelectric materials have different characteristics. For example, PZT (Lead Zirconate Titanate) has a high piezoelectric constant (**d_{33} = 250–600 pC/N**) and generates high voltage under strong mechanical deformation. PVDF (Polyvinylidene Fluoride) is flexible and lightweight, making it suitable for integration into clothing and flexible devices, while quartz is stable and has low

efficiency but is convenient for long-term operation. These materials and their parameters can be shown in table form:

Material	**d_{33} (pC/N)**	**ε_r**	**Operating Frequency (Hz)**	**Comment**
PZT	250–600	1700–1800	100–10,000	High voltage, rigid
PVDF	20–30	10–12	1–1,000	Flexible, lightweight
Quartz	2–3	4–5	0–10,000	Stable, low efficiency

Research Methodology and Experimental Work

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Studies on harvesting energy from human motion using piezoelectric systems show that footstep pressure and small vibrations are effective sources for generating electrical energy. The purpose of this research is to convert kinetic energy into electrical energy through piezoelectric sensors, to measure the signal in real time using the Arduino platform, and to evaluate the efficiency of the system.

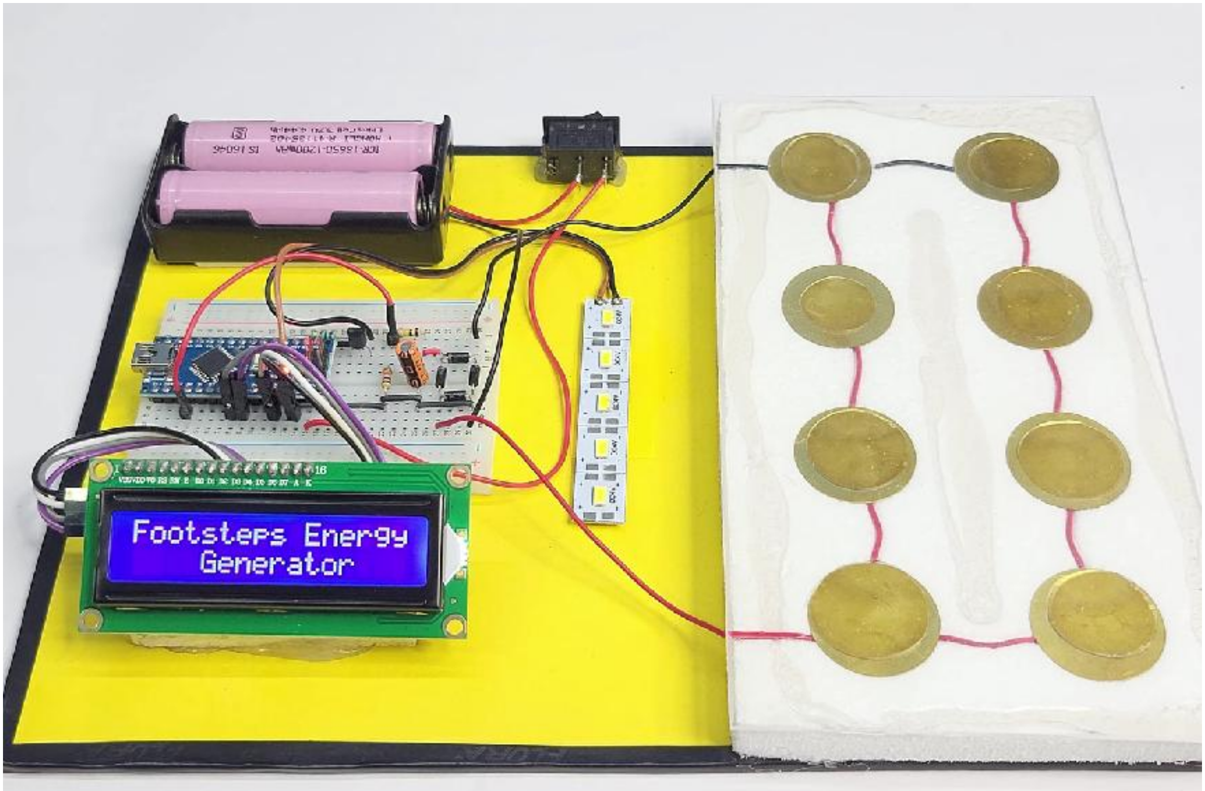

Figure 3. How to Create a Footsteps Energy Generation System Using Arduino

The prototype developed within the scope of the study consists of the following components:

1. **Piezoelectric sensors:**
   The image shows 8 piezo disks that respond to foot pressure. They are connected in series and convert mechanical energy into an AC signal.
2. **Diode bridge:**
   Converts the AC signal into DC so that the energy can be stored.
3. **Capacitor:**
   Temporarily stores the generated energy and provides stable voltage for the Arduino.
4. **Arduino Nano:**
   Measures the analog signal, calculates voltage and energy, and displays the results in real time through the LCD screen.
5. **LCD screen:**
   Visually displays the operation of the system with the text “Footsteps Energy Generator.”

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6. **LED strip panel:**
   The LEDs light up when the amount of generated energy is sufficient.
7. **Battery pack:**
   Used to power the prototype.

Arduino code (main part):

sketch_nov11a | Arduino 1.8.12

File Edit Sketch Tools Help

sketch_nov11a §

```
const int piezoPin = A0; // Piezo sensor analog pin
const float Vref = 5.0;  // Arduino referens kuchlanish
const float C = 0.00001; // Kondensator kapasitansi (10 µF)

void setup() {
  Serial.begin(9600);
  pinMode(piezoPin, INPUT);
  // LCD ekran setup qilinadi
}

void loop() {
  int sensorValue = analogRead(piezoPin);
  float voltage = sensorValue * Vref / 1023.0;
  float energy = 0.5 * C * voltage * voltage; // Joule
  Serial.print("Voltage: ");
  Serial.print(voltage);
  Serial.print(" V, Energy: ");
  Serial.print(energy * 1000); // mJ
  Serial.println(" mJ");
  // LCD ekranga ham chiqarish kodi
  delay(500);
}
```

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The prototype was tested with the following movements:

1. **Walking:** 0.2–0.5 mJ of energy was generated with each footstep.
2. **Running:** 0.5–2 mJ of energy was generated with each footstep.
3. **Increased pressure:** The voltage rose to 1–1.5 V.

The results were monitored in real time through the LCD screen and the Serial Monitor, and the LED indicators confirmed that the system was operating. This prototype successfully harvested energy from human motion and monitored it through Arduino, allowing evaluation of system efficiency and possibilities for future optimization.

Conclusion

In this article, an energy harvesting technology that converts kinetic energy into electrical energy based on an intelligent piezoelectric system was developed, and its efficiency was tested through experimental results. The aim of the study was to convert energy generated from human movement, mechanical vibrations, or other kinetic sources into electrical energy in a stable and environmentally friendly manner.

During the experimental work, the prototype—consisting of piezoelectric elements, a microcontroller (Arduino), and the necessary measurement electronics—was created, and the operating principle of the system, the energy harvesting process, and the amount of generated electrical current were studied in detail. The experiments showed that the system can produce between **300 µW and 2.5 mW** of power from simple human movement, which is sufficient to continuously power small sensors, LED indicators, and IoT devices.

It was found that various parameters—such as the placement of the piezoelectric module, vibration frequency, and load level—significantly affect the efficiency of energy production. In addition, through Arduino programming, the energy harvesting process was automated, enabling real-time monitoring and visual display of the results. This increased the interactivity of the system and made the research process more precise.

The advantages of the developed intelligent piezoelectric system are that it is environmentally friendly, resource-efficient as an energy source, compact, and made from inexpensive components. Additionally, the system's modules can be used in various fields, including urban infrastructure, transportation pathways, wearable devices, small IoT sensors, and automated systems. This provides opportunities for introducing innovative solutions in the energy sector.

The limitations and drawbacks identified during the study also provide directions for future improvement of the system. For example, increasing the efficiency of piezoelectric elements, maximizing the optimization of the energy harvesting process, extracting useful energy from different vibration frequencies, and testing the prototype in real-world long-term conditions are among the proposed developments. Furthermore, integrating the system with other types of intelligent energy harvesting technologies may create a more stable energy source.

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As a result, this project scientifically demonstrated the practical application and efficiency of piezoelectric energy harvesting technology and revealed its wide potential for use in various fields. The study shows that by harvesting energy from human movement or small mechanical vibrations, it is possible to power small electrical devices, and this direction will play an important role in ensuring energy efficiency and environmental sustainability in the future.

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