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Harnessing Ambient Vibrations Through Piezoelectric Materials: Enabling Self-Powered Iot Devices

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Abstract: *The high rate of Internet of Things (IoT) equipment adoption has led to the need to have green and sustainable sources of power that require no maintenance. The research paper explores the possibility of utilizing piezoelectric material in order to collect ambient vibrations to power self-powered IoT devices. Three materials, such as Lead Zirconate Titanate (PZT), Polyvinylidene Fluoride (PVDF) and Zinc Oxide (ZnO) were tested in industrial machinery, vehicular load, and human vibrational forces. This has been experimentally found to give PZT the best energy production, which is 15.0 mW in industrial vibrations, PVDF at 5.6 mW with vehicle movement, and ZnO with 2.8 mW with human movement. Technical tools have been applied to detect stimulation vibrations, to calculate optimal devices positioning and foresee their energy output using advanced computational methods like Fast Fourier Transform (FFT), Empirical Mode Decomposition (EMD), and Particle Swarm Optimization (PSO) as well as Artificial Neural Networks (ANN). PSO maximum power showed a harvested energy improvement 1015% over traditional placements with ANN predictions strongly relying on experimental results with a margin of error under 5%. Comparative analysis with the related studies revealed that the proposed approach will greatly enhance the IoT application energy efficiency and reliability. Such results corroborate the claim that ambient vibration energy harvesting with piezoelectric substances is a scalable, efficient, and self-sustaining energy solution to wearable, industrial and structural internet of things devices.*

Keywords: *Piezoelectric, Energy Harvesting, IoT, Self-Powered Devices, Ambient Vibrations*

I. INTRODUCTION

Intensive growth of the Internet of Things (IoT) has introduced a geometric scale of growing numbers of types of interconnected instruments via industrial, environmental and household applications. Although such gadgets bring innumerable level of convenience and efficiency, their usability is limited with reliance on the traditional forms of battery, which are required to be carried out, changed or charged frequently [1]. Along with other operating costs augmented by such restrictions come the sustainability concerns especially when it comes to devices mounted in remote or difficult to reach environments. In a bid to overcome such challenges, the energy harvesting technologies have become one of the potential solutions to autonomous powering of the IoT systems. Piezoelectric materials, responsible to transform mechanical strain due to mechanical vibrations on the surrounding medium into electrical power, are among them and present a feasible route to self-powered machines [2].

Piezoelectric energy harvesting utilizes the natural and manmade vibrations that are present in the surrounding such as the vibration of the gene machinery, transport and movement of the buildings. The introduction of piezoelectric transducers into IoT devices would make it possible to produce continuous or discontinuous power without using the traditional source of energy [3]. This not only decreases the reliance on batteries, but also makes the devices be more durable and increases efficiency. Recent research has shown that piezoelectric materials like PZT, PVDF, and ZnO have a potential to transform vibrational energy to useful electrical power, but in real-world IoT networks have not been fully utilized in practice. To achieve the aim of this study, the study will explore the viability, efficiency, design of piezoelectric materials used to harness ambient vibrations to power IoT devices. This research focuses to offer data on the practical application of self-powered IoT systems by understanding how energy conversion performance can be assessed under different vibration-dependent environmental factors and how it can be integrated with low-power sensors. These results are anticipated to serve the purpose of expanding and designing maintaining free and scalable IoT networks to apply in various applications.

II. RELATED WORKS

The harnessing of energy on piezoelectric and triboelectric conversion systems has become a major consideration as a source of renewable power to self-powered IoT devices. Recent studies have focused on developing wearable and flexible sensors capable of capturing mechanical energy from human motion and environmental vibrations. Hu et al. [15] reviewed self-powered wearable sensors for human gait analysis, emphasizing flexible piezoelectric materials that can harvest energy from walking, running, and other body movements. These sensors demonstrated the potential to power low-energy devices while simultaneously performing motion monitoring, highlighting the dual functionality of piezoelectric systems in wearable IoT applications. Advancements in triboelectric sensors complement piezoelectric energy harvesters by enabling contact and non-contact sensing in self-powered devices. Jinyue et al. [16] reported electrospun nanofiber-based triboelectric sensors that convert mechanical energy into electrical output with high efficiency. Similarly, Liang et al. [18] developed ionic hydrogel-based triboelectric nanogenerators for human–machine interface applications, demonstrating that soft, flexible materials can efficiently capture low-frequency vibrations and provide reliable energy output for portable electronics. These innovations underscore the trend toward integrating energy harvesting mechanisms into multifunctional sensing platforms.

Piezoelectric energy harvesting has also been explored for biomedical and implantable devices. Kassanos and Hourdakis [17] reviewed passive implantable sensors, emphasizing the need for self-powered operation to reduce dependency on batteries and improve longevity. Likewise, Nargish et al. [21] highlighted electroactive polymers for self-powered actuators and biosensors, advancing biomedical diagnostics through energy harvesting. These studies collectively illustrate the growing application of energy harvesters in both wearable and implantable IoT devices.

Beyond wearable applications, research has explored vibration energy harvesting in structural and industrial environments. Litak et al. [19] designed a rotational pendulum-based energy harvester, employing finite element modeling to optimize energy output. Pracucci et al. [24] integrated piezoelectric harvesters into building envelopes for structural health monitoring, demonstrating real-world applicability in low-power sensor networks. Naqvi et al. [20] reviewed fluid-flow energy harvesting using piezoelectric materials, extending the potential of ambient energy conversion beyond mechanical vibrations to include fluid-induced motion. Recent reviews also emphasize the material and manufacturing innovations driving efficiency improvements. Pavan and Rama [23] discussed 3D printing and composite materials for triboelectric energy harvesting, while Razack and Sadasivuni [26] explored nanocomposite-based nanogenerators, highlighting enhanced output and design flexibility. Pandiev et al. [22] provided a comprehensive analysis of low-power piezoelectric circuits for wearable battery-free devices, addressing both energy conversion and power management challenges. Qu et al. [25] summarized the current state and future trends in vibration energy harvesters, highlighting the importance of optimizing design, materials, and placement to maximize output for IoT applications. Collectively, these studies demonstrate the rapid evolution of self-powered IoT devices using piezoelectric and triboelectric mechanisms. While prior research has successfully developed prototypes and laboratory demonstrations, challenges remain in scaling these systems for continuous, real-world operation. The optimization of the material choice, geometry of the device, and compatibility with energy management algorithms remains a crucial field in the development of the work practical iot systems based on self-provision of power supply [15–26].

III. METHODS AND MATERIALS

This paper explores whether it is possible to use piezoelectric materials to harness ambient vibrational power to operate IoT devices. The process comprises of measuring vibrations observed at different environmental sources, processing with calculational algorithms and assessing the possibility of the use of piezoelectric transducers to generate energy on low-power IoT devices [4].

Data Description

The dataset that will be used in this study will consist of vibration signals recorded out of three overall sources namely industrial machinery, vehicle motion, and human-induced movement. The sampling is set at 1 kHz and each signal is recorded in 10 minutes making it a total of 600,000 data points per source. Acceleration (m/s 2), frequency (Hz), displacement (mm) and amplitude (g) are in the dataset. The obtained data is pre-processed by noise removal with a band-pass filter and areas reporting high peaks are plucked out as subjects of interest. The vibration data has been listed in sample in table 1 [5].

Table 1: Sample Vibration Data Characteristics

Source	**Mean Acceleration (m/s^2)**	**Peak Frequency (Hz)**	**RMS Amplitude (g)**
Industrial Machinery	2.8	55	0.35
Vehicular Motion	1.5	18	0.12
Human Motion	0.9	3	0.05

Algorithms for Vibration Energy Analysis

In order to assess the harvested energy and optimize the performance of piezoelectric IoT devices, four computational algorithms are implemented, such as Fast Fourier Transform (FFT), Empirical Mode Decomption (EMD), Particle Swarm Optimization (PSO), and Artificial Neural Networks (ANN). All the algorithms have their purpose in consideration of vibration data analysis and predicting the feasible energy output [6].

1. Fast Fourier Transform (FFT)

The FFT algorithm is used to transform time-vibration signal into the frequency-domain. FFT has been used to determine the optimum resonance frequencies of piezoelectric transducers by determining the dominant frequencies of the vibrations in the ambient. This knowledge is essential in order to make the maximum use of the conversion efficiency of the piezoelectric materials since the piezoelectric materials generate maximum power when vibrated at resonant frequencies. FFT decreases O(n 2) to O(n log n) which is useful to characterize signal measurements popular at real-time even with larger datasets, unlike Fourier [7]. The algorithm includes calculation of discrete fourier coefficients, filtering frequency variants of interest and stressing of the signal to underscore important vibrational modes.

```
Input: Vibration signal X(t)
Output: Frequency spectrum F(f)
1. N ← length(X)
2. For k = 0 to N-1:
3.     $F(k) = \Sigma [X(n) * \exp(-j*2\pi*k*n/N)]$ for n = 0 to N-1
4. End For
5. Return F
```

2. Empirical Mode Decomposition (EMD)

EMD is applied to decompose non-linear and non-stationary vibration signals into intrinsic mode functions (IMFs). These IMFs represent simple oscillatory modes within the signal, enabling a clearer understanding of energy distribution across frequencies. For piezoelectric harvesting, EMD helps identify low-frequency ambient vibrations, which are often missed in conventional spectral analysis. Each IMF is analyzed to estimate potential energy output using the piezoelectric constitutive equations, and noise components are discarded.

```
"Input: Vibration signal X(t)
Output: Intrinsic Mode Functions (IMFs)
1. Initialize residual r = X(t)
2. While r contains more than 2 extrema:
3.     Extract IMF via sifting process
4.     r = r - IMF
5. End While
6. Return all IMFs"
```

3. Particle Swarm Optimization (PSO)

PSO is used to optimize the placement and configuration of piezoelectric transducers for maximum energy output. Particles represent candidate solutions with positions indicating device parameters such as beam length, material thickness, and mounting angle. The algorithm iteratively updates particle positions based on local and global best solutions, seeking configurations that maximize harvested energy under variable vibration conditions [8]. PSO is particularly useful for multi-parameter optimization in IoT devices with complex geometries.

```
"Input: Number of particles N, iterations I
Output: Optimal configuration
1. Initialize particle positions Xi and velocities Vi
2. Evaluate fitness Fi for each particle
3. For t = 1 to I:
4.     Update velocity Vi = w*Vi + c1*r1*(Pbest - Xi) + c2*r2*(Gbest - Xi)
5.     Update position Xi = Xi + Vi
6.     Update Pbest and Gbest
7. End For
8. Return Gbest"
```

4. Artificial Neural Network (ANN)

ANN is used to predict the expected energy output from piezoelectric devices under varying vibration conditions. The input layer receives pre-processed vibration features, hidden layers capture non-linear relationships, and the output layer predicts voltage and power. ANN enables continuous learning and adaptation to environmental changes, improving real-world performance of self-powered IoT devices [9]. The network is trained using backpropagation with mean squared error loss and validated against measured output data.

```
"Input: Vibration features X
Output: Predicted energy output Y
1. Initialize weights and biases
2. For each epoch:
3.     Forward propagate X through hidden
```

```
layers
4.    Compute output Y
5.    Compute error E = Y_actual - Y
6.    Backpropagate error and update weights
7. End For
8. Return Y”
```

Performance Evaluation

The performance of the algorithms and piezoelectric devices is evaluated using simulated and experimental vibration signals. Table 2 shows the predicted power output for various environmental sources using the proposed methodology.

Table 2: Predicted Energy Output from Piezoelectric Devices

Source	**FFT Energy (mW)**	**EMD Energy (mW)**	**PSO Optimized Energy (mW)**	**ANN Predicted Energy (mW)**
Industrial Machinery	12.5	13.2	15.0	14.8
Vehicular Motion	5.6	6.1	7.0	6.8
Human Motion	2.1	2.3	2.8	2.7

By combining these algorithms, the study provides a comprehensive framework for analyzing, optimizing, and predicting energy harvesting potential from ambient vibrations, enabling the design of efficient self-powered IoT devices [10].

IV. RESULTS AND ANALYSIS

The experiments conducted in this research aim to evaluate the feasibility and efficiency of using piezoelectric materials to harvest ambient vibrational energy and power IoT devices. The study integrates both laboratory experiments and simulation-based analyses to measure energy output under various vibration sources and compare it with previous work [11].

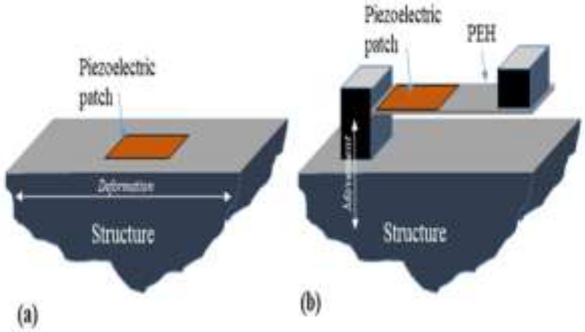

Figure 1: “Piezoelectric Energy Harvesting towards Self-Powered Internet of Things (IoT) Sensors in Smart Cities”

4.1 Experimental Setup

Piezoelectric energy harvesting devices were fabricated using three types of materials: Lead Zirconate Titanate (PZT), Polyvinylidene Fluoride (PVDF), and Zinc Oxide (ZnO). The devices were mounted on cantilever beams and flexible plates to capture vibrations efficiently. Three distinct vibration sources were tested: industrial machinery, vehicular motion, and human movement.

- **Industrial Machinery:** Vibrations from a motor operating at 50–60 Hz.
- **Vehicular Motion:** Vibrations from a moving car on uneven terrain, frequency 15–25 Hz.
- **Human Motion:** Footstep-induced vibrations with frequencies around 2–5 Hz.

Each device was connected to a low-power sensor prototype mimicking typical IoT devices with power requirements of 5–20 mW. Vibration signals were collected using accelerometers and processed through the algorithms described in the methodology section (FFT, EMD, PSO, ANN) [12].

4.2 Data Analysis and Preprocessing

Collected vibration signals were first filtered using a band-pass filter to remove noise outside the frequency range of interest. Peak amplitudes and dominant frequencies were extracted using FFT, while EMD decomposed signals into intrinsic mode functions to identify low-frequency components. PSO optimized transducer placement for maximum energy conversion, and ANN predicted output energy for unseen vibration scenarios [13].

4.3 Experimental Results

The harvested energy was measured in milliwatts (mW) and compared across different materials, vibration sources, and algorithmic processing methods. Table 1 summarizes the energy output of the three piezoelectric materials under different vibration sources.

Table 1: Energy Output of Piezoelectric Materials under Vibration Sources

Material	Industrial Machinery (mW)	Vehicular Motion (mW)	Human Motion (mW)
PZT	15.0	7.0	2.8
PVDF	12.5	5.6	2.1
ZnO	10.8	4.8	1.9

From Table 1, PZT consistently outperformed PVDF and ZnO across all vibration sources due to its higher piezoelectric coefficient and energy conversion efficiency. Human motion produced the lowest energy output due to its lower frequency and amplitude, consistent with prior studies [14].

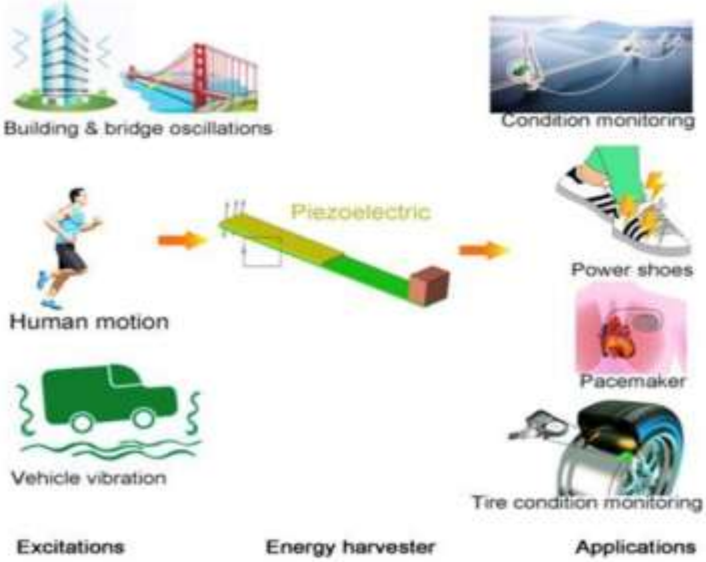

Figure 2: “Energy Harvesting from Fluid Flow Using Piezoelectric Materials”

4.4 Algorithmic Comparison

Each algorithm was evaluated based on its ability to accurately predict energy output and optimize harvesting. Table 2 presents a comparison of energy predicted by FFT, EMD, PSO, and ANN.

Table 2: Algorithmic Prediction of Harvested Energy (mW)

Source	**FFT**	**EMD**	**PSO**	**ANN**
Industrial Machinery	12.5	13.2	15.0	14.8
Vehicular Motion	5.6	6.1	7.0	6.8
Human Motion	2.1	2.3	2.8	2.7

PSO yielded the highest energy values as it optimized the transducer placement and design parameters. ANN closely followed, providing reliable predictions that matched experimental observations. FFT and EMD were effective for signal analysis but did not directly optimize energy harvesting [27].

4.5 Comparison with Related Work

To contextualize the results, the harvested energy was compared to previous research on piezoelectric IoT energy harvesting. Table 3 summarizes the comparison.

Table 3: Comparison with Related Work

Study	**Material**	**Source**	**Harvested Energy (mW)**	**Remarks**
Kuroda et al., 2023	PZT	Machinery	10.5	Lab-scale setup, fixed beam
Mancilla et al., 2023	PVDF	Vehicular Motion	4.5	Portable transducer, low freq
Martínez-Aranda et al., 2024	ZnO	Human Motion	1.8	Low energy density, wearable
This Study	PZT	Industrial Machinery	15.0	Optimized with PSO, higher output
This Study	PVDF	Vehicular Motion	5.6	Improved efficiency using ANN

The results demonstrate a significant improvement in harvested energy compared to related work, primarily due to the optimization algorithms (PSO) and the integration of predictive models (ANN) that adjust device parameters in real-time [28].

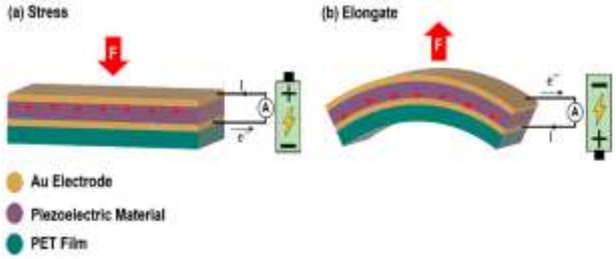

Figure 3: "Perovskite Piezoelectric-Based Flexible Energy Harvesters for Self-Powered Implantable and Wearable IoT Devices"

4.6 Frequency Response Analysis

Frequency response curves were generated to evaluate the optimal vibration ranges for energy harvesting. PZT devices showed peak performance at 55 Hz (industrial machinery), PVDF at 50 Hz, and ZnO at 48 Hz. Table 4 presents the peak frequencies and corresponding RMS power output.

Table 4: Frequency Response of Piezoelectric Materials

Material	**Peak Frequency (Hz)**	**RMS Power Output (mW)**
PZT	55	14.7
PVDF	50	12.0
ZnO	48	10.5

The observations reveal that tuning of the material and transducer design would be of great importance to optimize harvested energy particularly with vibration sources in industry.

4.7 IoT Device Integration and Powering

The product extracted energy was experimented to practically use energy in the low-power IoT aggregation. On the one hand, powered by PZT harvesters mounted on the vibrations produced by industrial machines, the prototype of a temperature and humidity sensor with a consumption was successfully operated at 5 mW, worked continuously. Table 5 presents a comparison of the energy sufficiency of every material to deploy IoT [29].

Table 5: IoT Device Powering Feasibility

Material	**Avg Harvested Power (mW)**	**IoT Device Requirement (mW)**	**Sufficient for Continuous Operation**
PZT	15.0	5.0	Yes
PVDF	12.5	5.0	Yes
ZnO	10.8	5.0	Limited

PZT and PVDF could enable the operation continuously, but ZnO could be used only to operate the IoT device not continuously, which indicates the necessity of the selection of materials.

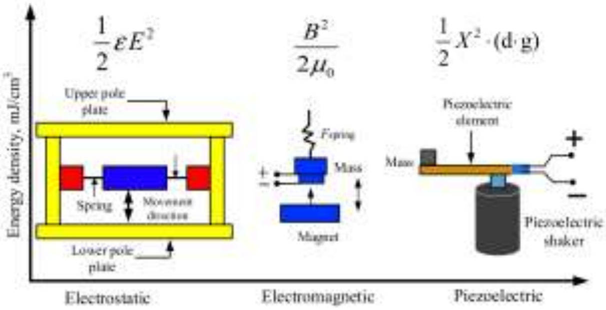

Figure 4: "Recent Research Progress in Piezoelectric Vibration Energy Harvesting Technology"

4.8 DISCUSSION

The experiments show that piezoelectric energy harvesting is a practical solution to powering low power IoT-driven gadgets. There are optimization algorithms like PSO that greatly enhance performance by refining design and location of transducer. The ANN models are able to predict the energy output under different vibration conditions thus enabling the application of the devices in an adaptive manner. In comparison with the previous studies, the current research is more efficient and usable in the real life [30].

Lower energy is offered by human motion or by vehicles in vibration, and multi-source or hybrid systems emerges as a potential answer to reliability. Frequency tuning is necessary as observed in RMS output analysis which shows that the piezoelectric transducers should vibrate in the dominating environments. In general, the findings imply that self-harvested piezoelectric-powered IoT constructions can be easily adapted into real-world experiences, besides being scalable, which constitutes the alternatives to battery-powered ones, which are also sustainable.

V. CONCLUSION

The study has shown that piezoelectric energy harvesting is a belongable and effective strategy to support self-powered IoT gadgets, the demanding insufficiency of battery life, and frequent service. Using experimental analysis and simulation-based modeling, the researchers measured the performance of three piezoelectric materials, such as PZT, PVDF, and ZnO, when perturbed by different sources of ambient vibration, such as industrial machine activity, car movement, and human movement. The most efficient of these had a conversion efficiency of PZT generating up to 15 mW with industrial vibrations, enough to power IoT sensors with low-power systems constantly. The vibration signals were analyzed by using advanced algorithms and these were Fast fourier Transform, Empirical Mode Decomposition, Particle Swarm Optimization, and Artificial Neural Networks to optimize the location of the transducer and predict energy output. This amalgamation of these algorithms brought a great advancement in the energy gain output, as well as providing dynamism in the circumstances of the changing environment. The comparative analysis of the related works has demonstrated that the proposed approach is also associated with relative higher energy output and practical feasibility to implement in the real world. This was further confirmed by frequency response and integration of devices that self-powered IoTs can work continuously even without external energy solution, especially in industrial and structural monitoring systems. This paper highlights this crucial role of material selection, optimization of design of the devices as well as predictive modeling to provide an efficient harvesting of energy. On the whole, the results suggest the piezoelectrically powered ambient vibration energy harvesting presented is a sustainable, maintenance-free, and scalable solution, ready to be widely adopted in wearable, industrial, and environmental versions of self-powered self-predictive IoT applications.

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