

MEMS-Based Piezoelectric smart flooring for warehouse robot localization and energy harvesting

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Abstract—This paper introduces an innovative piezoelectric smart floor system that revolutionizes warehouse robot localization and environmental monitoring while simultaneously harvesting energy. By embedding MEMS-based piezoelectric sensors in floor tiles, our system achieves precise real-time tracking of autonomous mobile robots (AMRs) and human movement without complex onboard odometry, detecting mechanical stresses and vibrations to provide high-resolution spatial and temporal data. This dual-purpose approach not only enables high-precision localization for warehouse automation but also creates a self-sustaining power solution by harvesting energy from mechanical vibrations. Leveraging edge computing for local data processing enhances system efficiency, scalability, and reliability while reducing latency. Our research demonstrates significant improvements in localization accuracy, power efficiency, and system robustness compared to traditional methods, offering seamless integration into existing infrastructure and paving the way for more intelligent and sustainable automated environments beyond warehouse applications.

Keywords—MEMS, Piezoelectric Sensors, Energy Harvesting, Localization, Warehouse Automation, Autonomous Mobile Robots

1. INTRODUCTION

1.1 Piezoelectric effect and energy harvesting

The piezoelectric effect, first discovered by Jacques and Pierre Curie in 1880 [1][2], is a fascinating phenomenon observed in certain materials. When mechanical stress is applied to these materials, they generate an electric charge, and conversely, when an electric field is applied, they exhibit mechanical deformation. This unique property arises from the internal structure of piezoelectric materials, typically crystals or ceramics, where positive and negative charges are separated but symmetrically arranged. When external pressure disturbs this symmetry, it creates a voltage across the material.

Piezoelectric sensors [3][4] exploit this effect to convert mechanical energy into electrical signals. These sensors typically consist of a piezoelectric material sandwiched between electrodes. When subjected to external forces or vibration, the material produces a proportional electrical output, allowing for precise

measurement of pressure, acceleration, and strain. The high sensitivity, fast response time, linear variation, and wide frequency range of piezoelectric sensors make them ideal for various applications, from industrial process control to medical diagnostics. The below figure shows a schematic of a simple piezoelectric sensor.

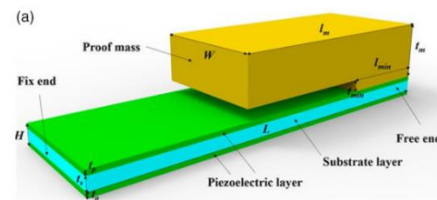


Figure 1: PZT cantilever beam with seismic mass

Energy harvesting [5][6] using piezoelectric (PZT) sensors has gained significant attention in recent years as a promising method for powering low-energy devices and sensor networks. This approach capitalizes on ambient vibrations and mechanical stresses to generate electrical energy, effectively converting wasted mechanical energy into usable power. It involves utilizing the direct piezoelectric effect, where external forces applied to the PZT material generate charges on its surface, leading to current flow when connected to an external circuit. Several studies have demonstrated the viability of this technique. For instance, [6] showed that PZT harvesters a piezoelectric harvester using PZT material achieved 30.7 mW, while under on-resonance conditions, it generated 347 mW with an efficiency of 35%. The review paper [7] demonstrated the development of energy-harvesting piezoelectric tiles capable of generating 2.4 mJ of electrical energy per step. These tiles showed outstanding fatigue resistance, enduring up to 10 million compression cycles without performance decay. Along the same lines, the study [8] Presents an innovative energy-harvesting device using piezoelectric flooring to capture energy from human footsteps. The system integrates piezoelectric ceramic diaphragms beneath floor tiles, converting mechanical pressure into electrical energy. A bridge rectifier achieves a peak output voltage of 33.7 V, capable of powering LEDs. Experimental validation demonstrates the feasibility of generating power from piezoelectric crystals, with an assembly of 30-floor tiles estimated to produce 60 watt-hours over 8 hours. The maximum power

extracted from a single tile is 249.6 milliwatts, costing approximately \$10.2 per tile. This technology shows promise for application in high-traffic areas and smart buildings, paving the way for future advancements in sustainable energy generation.

1.2 Paper Overview

In this paper, we present an innovative method for localizing fleets of autonomous mobile robots (AMRs) using piezoelectric (PZT) smart flooring within dynamic warehouse environments. Unlike traditional localization systems, which often rely on complex and expensive technologies such as LiDAR [9], computer vision [10], or high-precision GPS [11], our approach leverages a more cost-effective and less intrusive solution. By embedding PZT sensors in the flooring, the system can analyze the unique pressure patterns and vibrations generated by robots as they move, allowing it to accurately track their positions in real time without the need for additional onboard sensors or external infrastructure.

This method involves the strategic placement of PZT sensors at critical points throughout the warehouse, including intersections, parking zones, pallet-picking areas, workstations, and assembly units. These locations are chosen to maximize coverage and ensure the system can provide detailed information about each robot's position within the facility. The sensors generate real-time data that can be used to create a comprehensive traffic map, which helps optimize fleet management by tracking which robots are occupying specific stations, lines, or units. This enables efficient task allocation and prevents bottlenecks, improving the overall flow of robot traffic across the warehouse. A key advantage of this system is its suitability for environments where mobile robots follow predefined paths, as it can easily integrate into existing workflows. The fixed nature of these routes makes implementation straightforward, and the system can quickly identify deviations or potential collisions, ensuring safe and effective robot navigation.

Beyond localization, the PZT flooring offers an additional, significant benefit: energy harvesting. When robots or humans move over the sensor-embedded flooring, the system generates energy from the mechanical pressure. This harvested energy can be stored and used to power the robots' batteries, reducing the need for external charging stations and improving overall energy efficiency. Additionally, the energy generated by the flooring can be channeled into other warehouse operations, such as lighting or auxiliary equipment, further reducing the facility's reliance on external power sources. This dual functionality of precise localization and sustainable energy generation represents a major advancement in warehouse management, especially in line with Industry 5.0's focus on integrating advanced technology with human labor to create more efficient and intelligent operations. This innovative solution not only enhances the accuracy and efficiency of managing AMRs but also contributes to the sustainability of warehouse operations by reducing energy consumption and costs. The ability to combine real-time localization with energy harvesting makes this system a valuable tool for optimizing logistics and supply chain management in modern warehouses, paving the way for more adaptive, smart facilities

2. METHODOLOGY

We present a comprehensive analysis of our proposed piezoelectric microsystem for warehouse environments. We begin by modeling the system's core components and mechanical properties, followed by an examination of its integration into the warehouse ecosystem.

2.1 Modeling of the Piezoelectric Vibration Cantilever Beam System

This section focuses on the detailed modeling of the piezoelectric system designed for installation beneath the warehouse flooring. We explore the system's mechanical components, design, actuation, and electrical characteristics. Our design builds upon the double-stage energy-harvesting floor tile proposed in [12], introducing a novel piezoelectric cantilever beam configuration. The system, as illustrated in Figure 4, comprises three PZT 5A (Lead Zirconate Titanate) bimorph vibration beams. [13] arranged in parallel. PZT was chosen for its cost-effectiveness, good piezoelectric properties, balancing performance, and economic feasibility. These beams are housed within a robust structure suitable for integration into warehouse flooring. The overall structure of our energy harvesting system integrates this beam assembly into a durable housing designed for warehouse use. Key components include the three PZT bimorph beams arranged in parallel, with a proof mass (seismic mass) attached to one end of the beam assembly and the other end fixed, four spring-loaded supports at the corners, and circular piezoelectric sensors positioned at each support point.

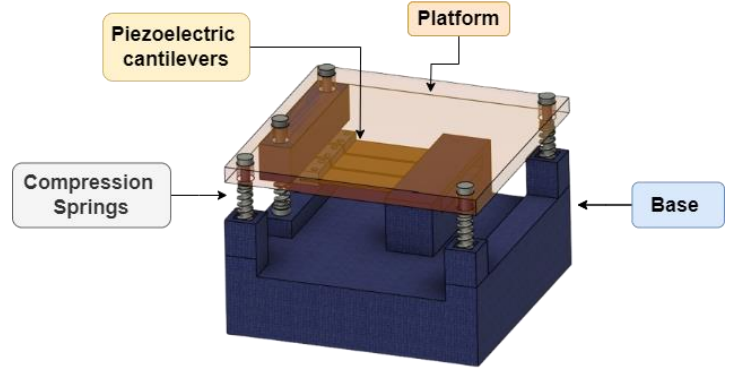


Figure 2: PZT Cantilever System Platform Design

When a mobile robot or human exerts a load on the transparent top platform, it compresses to a height of h , simultaneously deflecting the PZT beams, inducing strain in the piezoelectric material, applying stress to the corner circular piezoelectric sensors, and compressing the spring supports. The mechanical deformation of both the bimorph beams and circular sensors generates electrical voltage through the direct piezoelectric effect. As the load is released, the PZT beams undergo damped vibrations, continuing to generate energy until they return to their equilibrium position. The addition of the proof mass enhances these vibrations, potentially increasing energy output. Concurrently, the compressed springs provide a restoring force, returning the platform to its initial height, while the circular sensors capture additional vibrations during this reset process. Finally, the voltages will be amplified to the needed amount using a Rectifier circuit configuration mentioned in [8] [13]

This design maximizes energy harvesting by utilizing both the initial deformation and subsequent vibrations from the series of beams, while the spring mechanism ensures system reset for subsequent loading events. The combination of the primary PZT bimorph beams with their attached seismic mass and the supplementary circular sensors allows for efficient energy capture from diverse load patterns encountered in warehouse operations.

The parallel configuration of the beams, coupled with the seismic mass, is expected to optimize the voltage output of the system, making it well-suited to the varied and frequent loading typical of warehouse environments.

2.2 Robot Localization and Energy Harvesting

Warehouse operations encompass a diverse range of activities and specialized zones, each contributing to the overall efficiency of logistics and inventory management. In a standard warehouse layout, which we'll assume measures 100,000 square feet (approximately 9,290 square meters), the floor space is strategically divided to accommodate various functions. The receiving area, usually located near the loading docks, handles incoming inventory. From there, goods move to storage zones, including pallet racking systems, shelving units, and bulk storage areas. The order-picking zone is where items are retrieved for outbound shipments, often featuring a mix of manual and automated systems. Packing and shipping areas prepare orders for dispatch, while dedicated zones for value-added services like kitting or light assembly may also be present. Throughout the warehouse, a network of aisles and pathways facilitates the movement of goods and personnel.

Our piezoelectric energy harvesting system, as described in [Section 2.1](#), is designed for seamless integration into this complex environment, with a focus on high-traffic and operationally crucial areas. The system will be strategically installed in flooring sections at key locations, including major intersections where multiple pathways converge, robotic vehicle parking and charging zones, high-activity pallet-picking areas where frequent loading and unloading occur, human workstations that see consistent foot traffic, and assembly units characterized by sustained activity. By concentrating the piezoelectric tiles in these high-use areas, we maximize energy harvesting potential while also creating a network of sensors that can aid in precise robot localization and traffic management.

This targeted piezoelectric (PZT) flooring deployment offers benefits beyond energy harvesting, providing precise robot localization within the warehouse. We propose a dual-technology approach that integrates the PZT system with strategically placed RFID readers, creating a comprehensive localization network. As robots move across these equipped zones, the PZT system detects their presence and approximate positions through pressure and vibration signatures, while RFID readers identify each robot via unique tags. This hybrid system layers localization data, combining continuous tracking through PZT signals, definitive position fixes from RFID checkpoints, time-stamped entries, and a known warehouse layout that guides potential paths.

To process this data, a graph-based algorithm constructs a probabilistic model of each robot's location. It integrates RFID checkpoint data for precise fixes, PZT sequences for tracking movement between reads, historical movement patterns, and time-based analysis of zone transitions. The system dynamically updates a graph representation of the warehouse, mapping PZT and RFID nodes and possible paths between them. This enables accurate tracking even in crowded areas or when RFID reads are intermittent.

This deployment of piezoelectric (PZT) flooring not only enables precise robot localization but also integrates energy harvesting

capabilities. By combining the PZT system with strategically placed RFID readers, the system creates a comprehensive localization network. As robots move across these equipped zones, the PZT system detects their presence and positions through pressure and vibration signatures, while RFID readers provide definitive identification through unique tags. This hybrid approach integrates continuous tracking from PZT signals, position fixes from RFID checkpoints, time-stamped entries, and known warehouse layouts to maintain accurate tracking even in crowded conditions or when RFID reads are intermittent. Additionally, the PZT system can detect pressure variations, helping to distinguish between different robot models or load states and infer each robot's operational status, such as loaded, unloaded, or stationary.

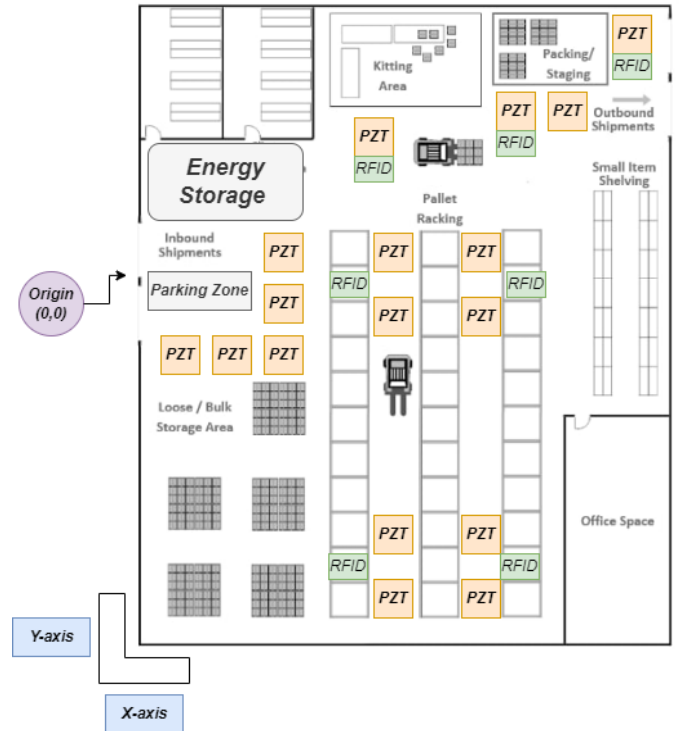


Figure 3: Warehouse Setup - RFID trackers and PZT flooring system

3. RESULTS AND DISCUSSIONS

The PZT (Lead Zirconate Titanate) bimorph cantilever was simulated and analyzed using ANSYS to evaluate its performance under various loading conditions typical of industrial autonomous mobile robots (AMRs). This simulation aimed to understand the behavior of the PZT cantilever in response to varying loads and to quantify its effectiveness in real-world applications. The load was applied harmonically (sinusoidally) to accurately represent the dynamic forces experienced by the cantilever when mounted on a moving robot. This loading pattern simulates the cyclical compression and release of the cantilever as the robot moves across various surfaces, encountering irregularities that cause the robot's body to oscillate vertically.

The simulation parameters included a frequency range typically set from 0 Hz to 1500 Hz, representing slow to rapid robot movements, and various load amplitudes to represent different robot weights and floor conditions. The analysis objectives were to determine the voltage and power output of the PZT cantilever under various harmonic loading conditions, evaluate the stress distribution and deflections along the cantilever to ensure structural integrity, identify resonant frequencies where power generation is maximized, and assess the efficiency of energy harvesting across different robot speeds and floor conditions.

Several assumptions were made to simplify the analysis while maintaining accuracy in the simulation process. These included ideal material properties for the PZT cantilever and consistent loading conditions across all trials. The applied load was divided equally among four support points, with the total power calculated for three PZT beams connected in parallel. Calculations focused on determining the vibration response and the corresponding voltage generated under different loads. A series of graphs were generated to illustrate the vibration-resulting voltage output across the different loading scenarios. These graphical results provide a clear understanding of how the PZT cantilever's response varies with changes in applied force and highlight the dynamic behavior of the system under operational conditions.

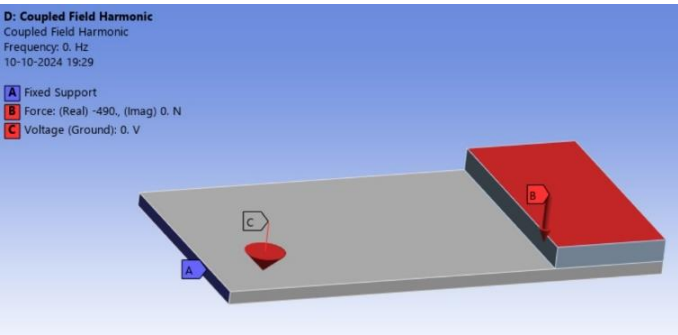


Figure 4: Boundary Condition Setup In ANSYS

Using the ANSYS simulation and analysis, we first evaluated the deflections of the PZT beam for various standard autonomous mobile robot loads, including payloads. The simulation considered a range of typical AMR weights, from lightweight models to heavy-duty variants carrying substantial payloads. The deflection analysis was crucial in understanding the mechanical stress and strain experienced by the PZT beam under different loading conditions. This information not only helps in assessing the structural integrity of the beam but also provides insights into the potential energy harvesting capabilities across different robot configurations. The results were plotted on a graph, illustrating the relationship between applied load and beam deflection. This graph serves as a valuable tool for predicting the PZT beam's behavior under various real-world scenarios and aids in optimizing the design for specific AMR applications.

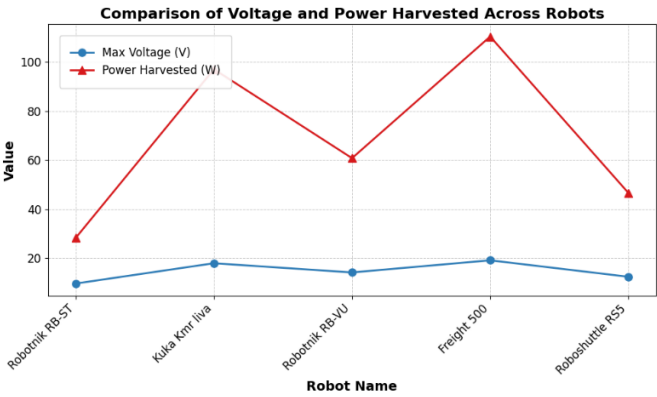


Figure 5: Voltage and Power Harvested Across Robots

Next, we evaluated the power output across all three PZT beams using the voltage response obtained from simulations. The power was calculated using the formula ($P = V^2 / R$), where (V) is the voltage generated and (R) is the load resistance. In our initial calculations, we used a fixed load resistor value of ($R = 10$ ohms) for all cases, ensuring consistency in the comparison of power outputs. To simulate real-world conditions, where the energy harvesting circuit is optimized for the specific characteristics of the PZT beams and the operational parameters of the AMR, we conducted additional simulations with varying load resistances to identify the optimal value that maximized power generation across the frequency range of interest.

Importantly, as the three PZT layers are connected in parallel, they share the same voltage but yield a combined power output that is three times that of a single PZT beam. This parallel configuration effectively increases the total power generated, enhancing the system's overall energy harvesting capacity. The power output was calculated for each loading scenario and frequency, providing a detailed understanding of the energy harvesting potential under different conditions. The maximum power obtained at the optimal load resistance was found to be **109.854 Watts** at **19.184 Volts** given by **Freight 500** which serves as a benchmark for the system's performance. This information is crucial for assessing the viability of the PZT-based energy harvesting system in powering various onboard sensors or supplementing the AMR's primary power source, ensuring efficiency and sustainability in real-world applications.

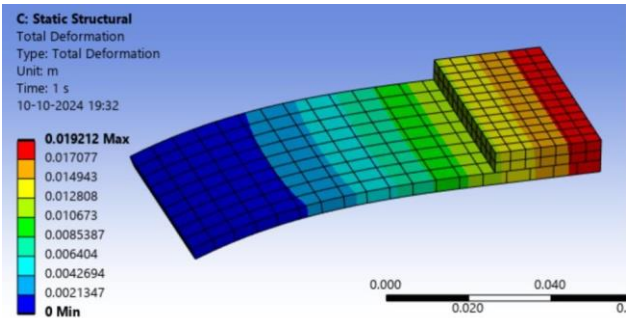


Figure 6: Deflection Analysis in ANSYS

4. CONCLUSIONS

In this study, we proposed a novel design that can be seamlessly integrated beneath indoor warehouse floors, consisting of a PZT bimorph cantilever MEMS system. This design serves a dual purpose—enabling energy harvesting and facilitating precise localization and efficient fleet management of autonomous mobile robots. The energy harvesting aspect leverages the mechanical vibrations generated by moving robots, converting them into usable electrical energy. This can power low-energy systems within the warehouse, thus contributing to overall energy savings and reducing the facility's dependence on external power sources.

The localization system employs a hybrid approach that combines RFID tracking with PZT-based vibration sensing. RFID readers placed strategically throughout the warehouse floor provide precise robot identification, offering absolute position data when a robot crosses specific checkpoints. Meanwhile, the PZT system continuously monitors vibrations to estimate the position and movement patterns of the robots, filling in gaps between RFID readings. This dual-layered localization method ensures accurate tracking even in crowded areas or when RFID signals are temporarily unavailable, offering a reliable and scalable solution for managing robot fleets.

With further prototyping and real-world testing, this system holds significant potential for large-scale deployment in industrial warehouses. It can reduce the need for complex SLAM-based algorithms or extended Kalman filters (EKF) for localization, thereby lowering implementation costs and simplifying maintenance. The integration of this PZT-based approach supports sustainable development goals by improving energy efficiency and operational effectiveness, positioning it as a viable solution for the next generation of intelligent warehouses.

REFERENCES

1. Fukada E, Yasuda I. On the Piezoelectric Effect of Bone. *Physical Soc Japan* 1957; 12: 1158–1162.
2. Ballato A. Piezoelectricity: History and new thrusts. *Proceedings of the IEEE Ultrasonics Symposium* 1996; 1: 575–583.
3. Tressler JF, Alkoy S, Newnham RE. Piezoelectric sensors and sensor materials. *J Electroceram* 1998; 2: 257–272.
4. Gautschi G. Piezoelectric Sensors. *Piezoelectric Sensorics* 2002; 73–91.
5. Li T, Lee PS. Piezoelectric Energy Harvesting Technology: From Materials, Structures, to Applications. *Small Struct* 2022; 3: 2100128.
6. Covaci C, Gontean A. Piezoelectric Energy Harvesting Solutions: A Review. *Sensors* 2020, Vol 20, Page 3512 2020; 20: 3512.
7. Sezer N, Koç M. A comprehensive review on the state-of-the-art of piezoelectric energy harvesting. *Nano Energy* 2021; 80: 105567.
8. Selim KK, Smaili IH, Yehia HM, Ahmed MMR, Saleeb DA. Piezoelectric Sensors Pressed by Human Footsteps for Energy Harvesting. *Energies* 2024, Vol 17, Page 2297 2024; 17: 2297.
9. Yao X, Bai Y, Zhang B, Xu D, Cao G, Bian Y. Autonomous navigation and adaptive path planning in dynamic greenhouse environments utilizing improved LeGO-LOAM and OpenPlanner algorithms. *J Field Robot* 2024; 41: 2427–2440.
10. Ren G, Wu H, Bao A, Lin T, Ting KC, Ying Y. Mobile robotics platform for strawberry temporal-spatial yield monitoring within precision indoor farming systems. *Front Plant Sci* 2023; 14.
11. Mwitta C, Rains GC. The integration of GPS and visual navigation for autonomous navigation of an Ackerman steering mobile robot in cotton fields. *Front Robot AI* 2024; 11: 1359887.
12. Isarakorn D, Jayasvasti S, Panthongsy P, Janphuang P, Hamamoto K. Design and Evaluation of Double-Stage Energy Harvesting Floor Tile. *Sustainability* 2019, Vol 11, Page 5582 2019; 11: 5582.
13. Ajitsaria J, Choe SY, Shen D, Kim DJ. Modeling and analysis of a bimorph piezoelectric cantilever beam for voltage generation. *Smart Mater Struct* 2007; 16: 447.