Kicking Yourself Awake: Towards self-powering mats for room-level localization and occupancy detection

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ABSTRACT

Motivated by the desire to reduce wiring costs in building occupancy monitoring systems, we explore the feasibility of waking a sensor node precisely when an event of interest occurs. We realize this through the use of piezoelectric devices that can be used to sense pressure and to harvest enough energy to wake and power a wireless sensor node. We envision their use in self-powering floor mats that can be placed at the entrance of each room that are awoken by a footstep and send footstep counts to an occupancy monitoring system. Early prototype measurements suggest that sufficient energy is generated from a footstep and that the piezo signal is accurate enough to identify footsteps and their direction.

CCS CONCEPTS

• **Hardware → Sensor applications and deployments**;

KEYWORDS

Battery-free Sensing, Occupancy Sensing, Indoor Localization, Smart Buildings, Piezoelectric

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1 INTRODUCTION

Intelligent HVAC systems, automatic lighting control, and other location-based services rely on indoor occupancy and location tracking [1]. A key need is to generate room-level occupancy counts while minimizing the installation and operating cost per area to facilitate wide adoption [2].

Existing occupant localization approaches that do not require the person to carry a device can be categorized as motion or proximity detection, acoustic listening, signal blocking, fingerprinting or scene analysis. A variety of different signals have been used in these systems, including RF [3] [4], ultrasound [5] [6], and sometimes environmental signals like light, sound, temperature, etc [7] [8] [9]. Some of these wireless techniques seek to reuse existing wireless transceivers, but multipath and noise make room-level localization challenging. Most other approaches rely on sensors (e.g., cameras) that must be wired for power, or require maintenance and replacement of batteries, either of which is a substantial cost driver. Battery maintenance becomes expensive for long term solutions where systems are expected to run for several decades.

To avoid batteries, much research has focused on harvesting energy [10] from radio frequencies [11] or solar panels, for example. Since the harvested power is small this limits the types of sensors and feasible duty cycles. Using short duty cycles is especially difficult when aiming to detect short-lived events such as a person passing by. It is also inefficient to poll the sensor frequently, when the events that the system seeks to detect are relatively rare.

We therefore ask whether it is possible to wake up a sensor precisely when events of interest occur through an integrated approach for sensing and harvesting of energy. We explore this question within the aforementioned occupancy monitoring context. This leads us to a floor mat design where the kinetic energy from footsteps wakes the circuit and also triggers sensing of the walking direction. Specifically, we use piezoelectric devices, which have the ability to convert mechanical energy to electrical energy and offer a path to both sense and power using the same device. We present a circuit design for wakeup, harvesting, and sensing based on the piezo output and incorporate this in multiple floormat designs. We describe early experiments to gauge whether the harvested energy suffices and how accurately the design can sense footsteps.

Switching to a battery-free sensing system, activated by force or pressure, would obviate the need for electrical wiring or battery maintenance, while offering device-free occupancy detection. By combining these two functions into the same component, it promises convenient and low cost occupancy sensing.

The salient contributions are as follows:

(1) Integrating energy harvesting and pressure sensing to explore the feasibility of waking and powering sensor nodes on-demand.
(2) Designing a piezo-powered floormat that detects footsteps and walking direction and can be placed at entrances/exits to support room-level occupancy detection.
(3) Conducting early experiments that show 200uJ of energy can be harvested from a footstep, sufficient to power a transmitter, that suggest that footsteps and walking direction detection is feasible.

2 BACKGROUND & RELATED WORK

Piezoelectric elements, or 'piezos', for short, have been exploited before for their energy harvesting capability [12] [13] [14]. The *piezoelectric effect* is the inherent ability of some materials to generate an electric charge in reaction to a mechanical stress, and vice-versa. Piezos have everyday uses such as in electric cigarette

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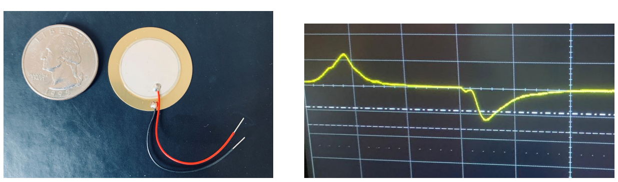
lighters, guitar pickups and fire alarms. They are also used in various large-scale energy harvesting projects. Piezos are high-precision devices; they precisely map applied force to voltage, and applied voltage to vibrations. This precision enables them to be used in ultra-precision positioning systems as actuators [15] [16], as well as in sensing extremely small vibrations, forces, or strains [17].

Types of piezos. Piezoelectric devices come in different materials and structures. In terms of materials, PZT (lead zirconate titanate), or piezo-ceramic material, provides high, consistent power generation [14] [12] and robustness to being embedded in structures [18]. PVDF, a polymer, might be more suitable for energy harvesting for its flexibility [19], which in turn allows it to be used in wearables. We however choose PZT as it is more easily accessible and the most common piezoelectric material.

These materials can be used in piezos of different structures. Diaphragm piezos (also known as 'buzzers') are cheap, commonly employed and easily accessible; hence used. It comprises of a piezoelectric ceramic disc stuck to a brass plate on one end. When there is an upward or downward displacement of that ceramic disc due to flexing, a voltage appears across the top and bottom of the ceramic due to charge accumulation, as can be seen in Fig. 1. Wires can be soldered on to either end of the ceramic, allowing for current flow. Cantilever piezos, which are equivalent to two diaphragm piezos, are more flexible and would produce twice the energy output for the same footstep. They are, on the contrary, more than twice as expensive and structurally more difficult to design around. This is an engineering trade-off made for our implementation.



(a) A diaphragm piezo. The white disc in the middle is piezoelectric ceramic.

(b) Output voltage waveform from flexing the piezo.

Figure 1: The piezo and a sample output voltage waveform. Peak positive voltage corresponds to maximum positive displacement. The voltage decays while it is held at that position, all the way to 0V. Once the piezo is released, the negative peak voltage is when the piezo comes back to its original state.

Fig. 1 shows an example PZT diaphragm piezo, the 7BB-27-4L0 diaphragm element from Murata electronics, which we will use in our feasibility experiments. They cost 20-30 cents each in low quantities.

Related Work. Prior research has used floor sensors to detect the intrinsic static traits of people [20] and estimate presence. It has been shown that the ground reaction forces from shifting body mass across the floor can be used as a weak biometric [21]. The *ORL active floor* [22] requires installation of tiles; each floor tile has load cell sensors under its corners—the aggregate pressure at a tile's corners corresponds to the presence of a person. Smart Caregiver manufactures cordless, weight sensing floor mats to be placed next to beds, for caregivers to be alerted if their elderly patient leaves their bed [23]. The system sends a wireless alert to a remote monitor up to 300 feet away. *SensFloor* [24] uses capacitive proximity sensing to detect people in a room. It is installed under the flooring as a microelectronic-embedded textile. Radio modules transmit the values of the measured capacitances to transceivers. All these systems require batteries or wiring for power.

Ambient energy harvesting research seeks to avoid the need for batteries or wiring. In [25], a 1.9GHz transmitter is powered from vibrational and solar sources, employing a piezoelectric generator and a solar cell with a capacitor to store the ambient energy. A battery-free cellphone [26] was developed to consume only milliwatts of power, harvesting energy from RF signals and ambient light. Thermal energy is harvested using screen-printed PZT and commercial PVDF films in [27] form pyroelectric cells. This line of research purely focuses on energy harvesting and does not attempt to sense events. These use RF signals and thermal energy; other vibrational techniques of harvesting exist. [28] uses triboelectric film in a manufactured shoe insole, which can produce up to 1.4mW of power while walking. It exploits current flow due to triboelectric charge build up on different surfaces. An energy harvesting shoe with a PVDF insole and a PZT dimorph heel insert was implemented and shown to generate at least 1.3mW [29]. However, these fall into the device-based localization category, where users have the sensing devices on their body. Piezos have been embedded in roads to harvest energy to power streetlamps from cars driving over them [30]. They have also been embedded in the floor of high traffic areas to generate electricity such as in a Tokyo train station [31].

Prior work has also investigated battery-free transmitting devices powered by a piezo button. Mathis et al. develop a battery-free classroom response system in [32] called the HSRvote system. Students press down on one of four piezo-buttons, which both powers a transmitter and denotes which answer the student is answering. Paradiso and Feldmeier implement a wireless, batteryless push-button that can transmit a 12 bit RFID with a 50ft range using a 418MHz transmitter, powered by a handmade piezoelectric generator [33], and extend this design to energy harvesting insoles which transmit while the user is walking [34]. Schneider Electric makes a batteryless, button-powered transmitter [35], with a similar setup in which the user presses a button to trigger a packet. Such systems all require a precise, deliberate act from the user and cannot surreptitiously detect the presence of a users as we explore here.

Earlier work has also sought to detect people crossing doorways. Doorjamb uses ultrasonic ranging sensors mounted on the top of doorways, pointed downward to sense people as they walk through the doorway [36]. An RF 'doormat' in [37] uses webcams on top of doorways, pointed downwards to create RF sensing zones that tracks RFID ankle bracelets worn by users. These systems require continuous power, and samples data even when there isn't any activity.

Arguably most related to our work, there has been research into using piezoelectric sensors embedded in the floor for harvesting and powering a transmitter to signal presence. In [38] and [39], tiles with custom-made piezoelectric sensors power wireless transmitters, signalling to turn on devices when they stand on the tile. Both of these studies use custom piezo designs and focus on the design of a single tile.

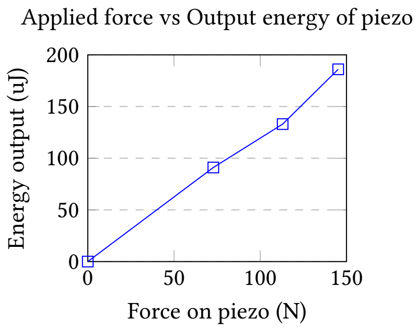


Figure 2: Plot of force on the piezo vs its energy output.

None of the aforementioned work has studied, however, whether self-powered sensing can enable lower-cost building-scale occupancy monitoring.

In the following sections, we will start to address this question, by studying whether it is feasible to:

(1) use off-the-shelf piezoelectric sensors in self-powered floor-based sensing designs.
(2) embed such sensors into a floormat design that simplifies retrofit applications.
(3) obtain direction information from temporal differences in piezo activation to determine the direction the user is walking in, to aid in estimation of room-level occupancy.

3 PROTOTYPE DESIGN

The Mat needs to be designed keeping in mind the energy constraints, while ensuring the data obtained by the piezos is usable for pinpointing where, when and in what direction the footstep occurred. Detecting walking direction is useful for systems that seek to maintain an approximate count of occupants since walking direction allows determining whether a person entered or exited a room when a Mat is placed at the entrance. Every component in the system can be traced back to these requirements.

3.1 Sensing Footsteps with Piezos

We start our feasibility exploration with footsteps since significant energy can be harvested in this domain. We choose a floormat as an enclosure for the piezos to sit in due to their versatility.

The objectives for the physical arrangement are threefold: (i) to maximize energy output of the piezos, (ii) to allow capturing footsteps in a broad range of location on the mat, and (iii) to allow sensing direction of movement of the occupants.

Maximizing energy output of the piezos. A piezo's energy output increases with the degree of flex.[1] To enable maximum flexing, the outer rim of the diaphragm piezo element needs to be held stationary, while allowing the center to move down several millimeters freely. An example of implementing this is through a ring-shaped holder of 4mm height (a washer, see Fig. 3) that the rim rests on. The center of the piezo rests under a small, hard cylindrical plastic stopper of 3mm thickness that presses down on the piezo with a footstep. The thickness of the stopper together with the height of the rim can be used to control the maximum possible displacement of the piezo.

[1]This corresponds to the amount of work: force applied, multiplied by the displacement that the center of the disc undergoes.

(a) Metal disc used to secure the rim of the piezo, allowing flexing.

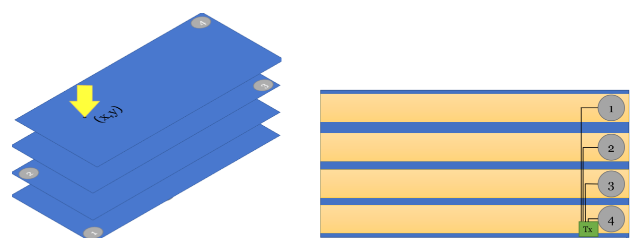
(b) Metal disc with piezo fixed.

Figure 3: Metal structure used to fix piezo with center free to move downwards.

Arranging Piezos on the Mat. Piezos could be arranged in a grid pattern across the Mat so that for typical shoe sole sizes at least one piezo is activated for any possible foot position on the Mat.

To sense the walking direction, grid density could be increased so that at least two piezos are activated. This seeks to exploit the typical series of step phase in human locomotion [40] [41] wherein a heal strike occurs before a mid stance phase followed by heel rise until the toes lift off the floor. Walking direction can be detected with multiple piezos since the piezo closer to the heel and the piezo closer to the toes will be activated at slightly different times. Such a dense grid can increase material and wiring costs, however.

We therefore consider two designs that embed larger inflexible surfaces into the mat. These surfaces are designed to allow a single piezo to capture footsteps from a larger area.



(a) A piezo in each corner of the mat is used for triangulation.

(b) Here, the mat is split into four strips, each strip activating one piezo, and the output waveforms are connected to the transmitter.

Figure 4: Two designs for direction detection.

Striped-surface design. As shown in Fig. 4(b), this design contains several inflexible strips, each set up with a lever like mechanism so that a step force on any part of a strip would act on its piezo off to the side. Assuming the standard crossing direction that is perpendicular to the longer side of the mat, walking direction can be detected through the order or timing sequence of piezo activations. This requires good isolation between the striped surfaces so that touching one strip does not trigger adjacent strips as well.

Single-surface design. This mat contains one large inflexible surface that can press on piezos situated on its four corners (see Fig. 4(a)). When a footstep falls onto the surface, its force will be distributed across the four piezos based on the exact position on the surface. Since the charge accumulation at each piezo depends on the local force, the distance of the footstep from each piezo, and therefore the exact contact location can be estimated. In contrast to the preceding design, this assumes that charge accumulation at each piezo can be measured with sufficient resolution and accuracy. It does not require measuring activation time differences between piezos. To detect walking direction this design would track contact location over the different stance phases.

3.2 Wake-Up on Footstep

Since a piezo in this design both acts as a sensor and provides power for activation and transmission, we design a circuit that separately conditions a piezo's output signal for both purposes.

Conditioning for Sensing. To measure the charge accumulation, we integrate piezo output voltage over time. Piezos generate high voltage outputs in the order of hundreds of volts. This needs to be scaled down into the input voltage range of the analog-to-digital converter. We therefore tap a line from the output of the piezo through a voltage divider, for voltage scaling, and a capacitor for integration to the analog pin of the transmitter. The ADC effectively measures the voltage across the capacitor which is directly proportional to the force applied on the piezo.

Conditioning for powering the transmitter: The output of the piezo needs to be conditioned to be able to power the transmitter. Recall, that piezos generate high voltage outputs in the order of hundreds of volts with current in the order of hundreds of microamps, only as long it is being flexed. Microcontrollers and transmitters, however, require lower voltages over longer durations. Energy harvesting circuit designs exist to perform this conditioning.

As depicted in the bottom half of Fig. 5, the output of the piezo can be passed through several well-known conditioning stages to power the transmitter:

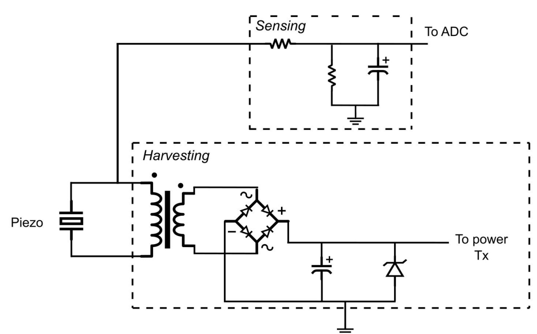


Figure 5: Proposed circuit diagram to power and transmit using piezo output.

(1) **Rectify the output.** The AC output of the transformer is fed into a full-wave bridge rectifier. Note that the rectified waveform is not a steady and smooth DC voltage, but a 'dirty DC' signal, with the negative half flipped to be positive. A low loss bridge rectifier chip should be used here.
(2) **Store energy.** We use a capacitor with low leakage current to stretch energy availability over a longer duration and to conserve residual energy from previous footsteps. This, along with the rectification stage, is commonly used in piezoelectric harvesting [42].
(3) **Regulate the output.** To ensure the voltage is capped at an acceptable level for the transmitter, a Zener diode is added in reverse bias. This passes all the available current to the transmitter, but limits the voltage to avoid damage to it. The diode's Zener voltage is matched to the transmitter's input voltage rating.
(4) **Optional: Decrease voltage, increase current.** A step-down audio transformer is chosen to reduce the voltage and increase the current obtained out of the piezo, with very low energy loss in the process. This type of transformer accepts a large range of frequencies, and lowers the output impedance. Compared to other converting methods like a buck converter, which contains active elements, this is a passive component.

3.3 Implementation

For our experiments we implemented the rectification, regulation, and storage stages, leaving the optional step-down transformer for future work. The piezo is connected to four Schottky diodes implementing the bridge rectifier. This full wave rectified output is then passed to a transmitter tag through a reverse biased 3.3V Zener diode.

As an ultra-low power transmitter, the Pip Tag [43] is chosen to transmit data and be powered from the footsteps. The pip tag can support up to twenty piezos per mat. It needs 1.8-3.3 volts of input voltage. Its current draw in standby mode is 0.5uA, due to the onboard MSP430G2553 microcontroller (configured in Low Power Mode 3). In this mode, the Pip Tag takes 1us to fully wake up, using 0.55uJ to start up its microcontroller. A total of 47uJ is consumed by the Pip Tag to startup and transmit a 20 byte packet. Of this, 32.83uJ are used for radio transmission (at 0dBm transmit power).

The packet length is a key factor for limiting the transmission energy consumption. We therefore minimize the payload and transmit simply a timestamp, transmitter ID, a configurable number of bits per piezo, and a CRC.

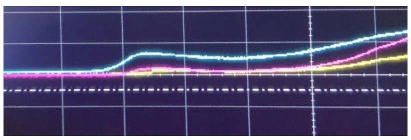
4 PRELIMININARY EVALUATION

We conduct first feasibility experiments to determine whether (i) they allow sensing of footsteps as well as their direction of movement and whether (ii) the piezo design produces sufficient energy to wake and power the transmitter tag.

Feasibility of Sensing Footsteps and Direction. Fig. 7(a) depicts the prototype following the striped surface design. Three piezos are raised from the ground with two parallel metal strips spaced less than an inch from each other. The piezos are insulated from the strips using electrically insulating epoxy. Perpendicular to this, three overhanging longer metal strips with plastic stoppers rest above the centers of the piezos. The setup is placed under a doormat. Probes are connected to the output of the three piezos,

(a) Experimental setup with three piezos to show the timing difference of the waveforms. A mat is placed over the metal strips. Probes are connected to each piezo to record the waveforms.

(b) In the experiment, piezos are under the mat; colors denote the waveform representing the corresponding piezo in (c). The step is taken as though the user is stepping from bottom to top.



(c) The blue trace starts before the pink trace, which starts before the yellow, implying the bottom piezos started displacing before the top.

Figure 6: The experimental setup for validating that distance of applied force from piezo can be estimated from the output waveform of the piezo. In these two trials, the bottom piezo's output waveform is the pink trace, and the top piezo's output waveform is the yellow trace.

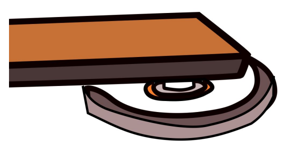
and the voltage waveforms are monitored on an oscilloscope. The time resolution of the oscilloscope is 20ms per division. The experimenter crosses and steps on the mat barefoot 10 times in both possible directions.

For all ten trials, the step results in clear voltage signatures on multiple piezos and the voltage peaks across piezos occur with a time difference, in the order of position in the mat. This is a clear indication that direction can be determined since the piezo generating energy first was closer to the heel.

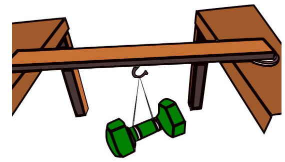
Feasibilty of powering the transmitter tag. The graph in Fig.2 shows the amount of energy that is obtained at the output of the full wave bridge rectifier stage, made from schottky diodes. The rectified output was fed into a $C = 55$uF capacitor. By measuring the voltage V at the capacitor after applying a force to the piezo, we can determine the generated energy as $\frac{1}{2}CV^2$. As can be inferred from the graph, for forces on the piezo around 150N, close to 200uJ can be obtained after losses from rectification, and even a small force of 50N can provide the 50uJ necessary to wake the transmitter tag and transmit a packet.

Feasibility of Single Surface Design. To determine how accurately we can estimate the distance from the piezo the force was applied using the output from the piezo, we conduct controlled measurements by hanging weights from a board pressing onto piezo.

As shown in Fig. 7 the end of a pine board presses onto a piezo with a plastic stopper, and allows hanging weights onto the hooks at different distances from the end. The other end is rendered immobile with a large weight. The weights emulate the force of a footstep at a specific distance from the piezo but allow applying a well-known



(a) Beam with plastic stopper over center of piezo.

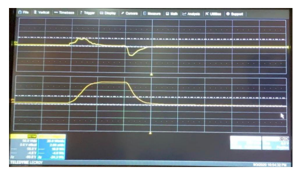


(b) Full setup, with weight to be hung at different distances from the piezo on the right

Figure 7: The experimental setup for validating that distance of applied force from piezo can be estimated from the output waveform of the piezo.

force (a 20lb dumbbell) at a controlled distance. To dampen the force we use an elastic cord. We measure the voltage between the piezos output terminals with an oscilloscope.

Fig 9 shows area under the voltage curve for 20 trials at different distances. While there is high variance when the force is close to the pieze the results show a clear effect of distance on the piezo output.



(a) Positive peak: 56 volts. Negative peak: -69.6 volts. Area Under Curve: 62.4 volt-seconds.

(b) Positive peak: 73.2 volts. Negative peak: -75.6 volts. Maximum Area Under Curve: 61.8 volt-seconds.

Figure 8: Oscilloscope displays for two trials hanging a 20 pound weight, 8 inches away from the center of the piezo. Output waveform of the piezo on the top, area under the curve with time on the bottom. As can be seen, while the peak voltages are not consistent between trials, the area under the curve varies less.

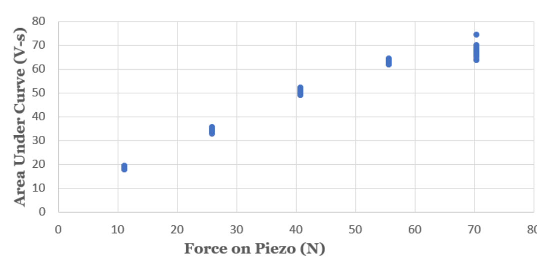


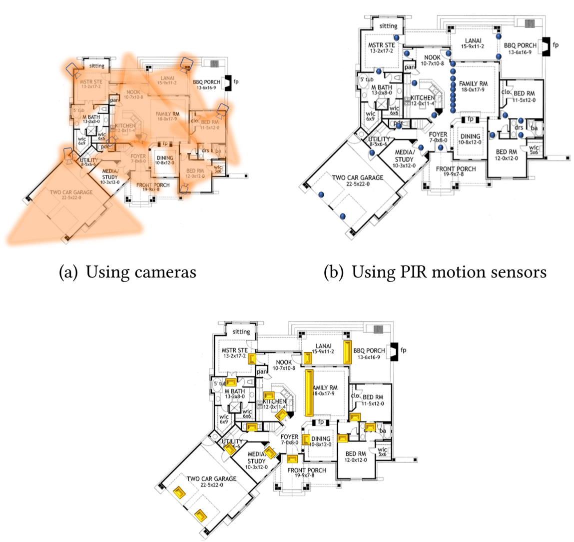
Figure 9: Scatter plot of all trials, applying the simulated footstep at different distances from the piezo and plotting the corresponding charge accumulation.

Cost Analysis. Given the motivation of this work, would the envisioned floormat design reduce the cost of occupancy monitoring system? Table 1 compares cameras, PIR sensors, and our floormat design. We determine the number of sensor units required to cover

Type of sensor	Using cameras	Using PIR sensors	Using piezo-mats
No. of sensors to cover sample floorplan	7	27	25
Electrical wiring needed?	✓	✓	✗
Approx. installed cost per unit (USD)	hundreds	hundred	tens
Approx. total cost (USD)	thousands	thousands	hundreds

Table 1: Cost comparison of different sensing techniques.

the reference residential building floorplan on ARPA-E's website [2] and achieve room-level occupancy detection. The installed sensor unit cost includes electrical wiring for PIR and cameras. These estimates show that despite the need for more sensor units compared to cameras, the floormat design promises significant cost savings.



(a) Using cameras

(b) Using PIR motion sensors

(c) Using piezo-mats

Figure 10: Comparing costs of using cameras, PIR sensors and piezo mats for room-level localization, for the same house layout. The cameras are denoted as camera icons, with their field of view highlighted. The PIR sensors are denoted with blue dots, and the piezo-mats with yellow rectangles.

5 DISCUSSION

While the controlled experiments show promising results, this study does not address the variations in pathway, occupants, behavior among other complexities that arise in real-world deployments (although the practical feasibility of using a floor-based piezoelectric harvesting system has been evaluated in [18]).

Pathway dimensions. Given the simplicity of the piezo design, we expect that it can be adapted to fit a variety of mat dimensions to cover different pathways in buildings. Generally, the mat needs to cover an area large enough to detect at least one footstep from each person in a doorway or other passage between rooms. For the striped-surface design, a minimum of two piezos per mat are needed to tell direction; the single-surface design would require four. For wide passages, a longer mat covering the entire opening of the pathway, along with additional piezo sensors can be used.

Multiple and different persons. The current design does not discriminate between people when multiple person step onto the mat simultaneously. With more piezos and algorithmic enhancements, this may be possible.

The study also does not address physical differences among people. In [44], a 2012 anthropometric survey of 6068 men and women, the body weight of the adults ranged from 46kg to 125kg. This equates to 451N to 1226N of force acting on the floor from a person's body weight. The lower bound of this force is theoretically more than what is required to be exerted on the piezo to transmit one packet from a low-power transmitter, as shown in Fig. 2. Additional research is needed to evaluate the detection accuracy of the mat for different levels of traffic and walking speeds.

Direction and occupancy detection. In order to interpret the direction information and turn it into occupancy counts, the systems needs knowledge of the mat orientation. Any solution should also mitigate or tolerate accidental mat movement or orientation changes, for example due to wrong placement after cleaning. While we do not address this in detail here, the solution space ranges from explicitly marking the the mat orientation and position on the floor, over maintenance apps for periodic recalibration, to self-learning solutions that exploit contextual awareness to learn mat positions and orientation from the observed foot traffic.

6 CONCLUSION

This paper explored a self-powered smart floor mat for occupancy detection and room-level localization using piezoelectric sensors as both a powering and sensing device. We design a combined wakeup, harvesting, and sensing circuit to sense a footstep, power the floor mat and transmit the corresponding waveform. Early experiments show that 200uJ of energy can be obtained from an applied force of 200N, sufficient to wake and power at transmitter tag. They also suggest that it is feasible to sense footsteps and detect crossing direction over the mat using the piezo output signal. Moreover, first estimates show that such battery-free occupancy sensing promises to significantly lower the cost of building occupancy monitoring. Some future uses could exploit a self-powering setup that can track vibrations and does not need to be maintained, could be used in structures like skyscrapers and bridges. With the COVID-19 pandemic, the need for filtration of air has increased. Piezo-mats could estimate the number of people in the room and could also be attached to existing HVAC systems to monitor how many times per hour the air circles through the filter.

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