Batteryless Occupancy Monitoring with Reflected Ambient Light

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Reliable and accurate room-level occupancy-tracking systems enable intelligent control of building functions like air conditioning and power delivery to adapt to the needs of their occupants. Unfortunately, existing occupancy-tracking systems are bulky, have short battery lifetimes, or are not privacy preserving. Furthermore, retrofitting existing infrastructures with wired sensors is prohibitively expensive.

In this paper, we present Waldo, a *batteryless*, room-level occupancy monitoring sensor that harvests energy from indoor ambient light reflections, and uses changes in these reflections to detect when people enter and exit a room. Waldo is mountable at the top of a doorframe, allowing for detection of a person and the direction they are traveling at the entry and exit point of a room. We evaluated the Waldo sensor in an office-style setting under mixed lighting conditions (natural and artificial) on both sides of the doorway with subjects exhibiting varying physical characteristics such as height, hair color, gait, and clothing. We conducted 651 experiments in 6 doorways with 12 individuals and achieved a total detection accuracy of 97.38% and movment direction accuracy of 95.42%. Waldo demonstrates that ambient light reflections provide both a promising low-cost, long-term sustainable option for monitoring how people use buildings and an exciting new research direction for *batteryless* computing.

CCS Concepts: • **Computer systems organization → Embedded systems**; *Architectures*; • **Human-centered computing** → *Ubiquitous and mobile computing systems and tools*;

Additional Key Words and Phrases: Occupancy, Batteryless, Intermittent, Energy harvesting

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1 INTRODUCTION

Understanding how people move, work, and live within a workplace or residence is essential for enabling health, efficiency, and security applications in smart buildings. Appliances, computers, lighting, heating and cooling systems can adapt their behavior depending on the number of occupants, their needs, and the context of their interactions. Smart buildings can automatically identify indoor traffic patterns, poorly-used space, and congested walkways, helping us better understand how people interact with the indoor spaces they use. We can only achieve these benefits if we can effectively sense how people move indoors.

Unfortunately, current occupancy-tracking systems are large, expensive, and high-maintenance—too expensive for large-scale deployments and too high-maintenance for long-term use. Existing systems use a variety of techniques, including ultrasound[16], images[27, 28], wearables[11], instrumented objects[3], structural vibrations[23], and opportunistic data leaked from existing meters and security systems[32]. Some gather identifiable information. Others require building remodeling, force users to change their behavior, or require structural models of the building. For any of these solutions to work, we must either provide wired power to the sensors (which is usually

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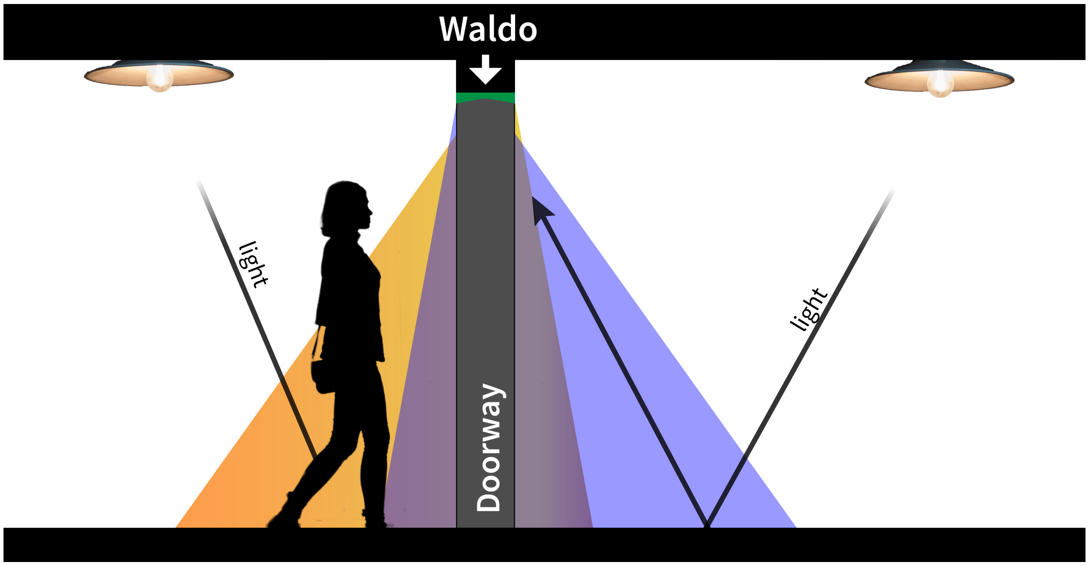


Fig. 1. The overall system concept of Waldo, a batteryless, energy-harvesting, doorway mounted occupancy tracking and person detection enabling system. This system uses reflective indoor lighting to both power the system and detect person entry and exit activity to a room.

both expensive and invasive), or use batteries which increase cost, environmental impact, and fire risk, and which must be replaced every few years (even rechargeables).

In this paper we present Waldo (overview shown in Figure 1), an occupancy-monitoring sensor that is low-cost and low-maintenance, preserves occupant privacy, and can operate for decades[1] without wired power or batteries.

Like the UVa doorjamb sensor [16], Waldo attaches to the top of a door frame and monitors movement in and out of the doorway. Unlike previous solutions, Waldo does not use active sensors (like ultrasonic range finders), but instead senses movement using the same ambient light reflections that power the sensor. Waldo harvests solar energy from indoor lights to power all operations, and uses a combination of hardware and software techniques to detect human movement and direction as solar energy availability changes. Waldo stores this information on device, and opportunistically transmits occupancy information to a basestation using its radio.

Contributions:

1. We present a novel system design for unobtrusive, long-term, low-cost, zero-maintenance occupancy tracking.
2. We explore design considerations for batteryless, intermittently-powered sensing systems for detecting ephemeral events that can be broadly applied to other batteryless sensing applications.
3. An implementation, deployment, and evaluation of Waldo that explores the strengths and limitations of our methods.

Waldo is, to our knowledge, the first batteryless occupancy-monitoring system, and demonstrates the potential and usefulness of long-lived, energy-harvesting, batteryless sensing operation in the built environment. In this paper we present our design, a working prototype, and evaluation results showing efficacy of the approach.

[1] Actual lifetimes depend on environmental conditions, enclosure quality, and rates of decay for silicon and other circuit materials. Without the usual bottleneck (the battery), lifetimes of 10–50 years are realistic but not guaranteed.

2 BATTERYLESS PEOPLE SENSING

Energy-harvesting batteryless sensors are critical to an affordable and sustainable Internet-of-Things (IoT) and the future of smart buildings. Running wires to power new sensors and other devices is expensive and not always feasible. On the other hand, batteries are expensive, bulky, and often hazardous. Even rechargeable batteries wear out after a few years, and replacing trillions of additional batteries every year would be both expensive and irresponsible. In contrast, batteryless sensors powered entirely with harvested energy cost less, weigh less, and can operate for decades with minimal maintenance and environmental impact.

However, batteryless sensing is challenging. Energy is stored in one or more small, cheap capacitors to improve efficiency and responsiveness [13]. Harvested energy is variable and difficult to predict. Power failures are common, interrupting computation and data processing, sensing, and communication. Clocks reset and volatile memory is lost frequently, complicating a developer's ability to build robust and sophisticated applications.

Recent advances in checkpointing [1, 24], consistent execution [5, 20], timekeeping [15], energy management [13], testing [12], and debugging [7] address key challenges and have enabled new and interesting applications: tracking building and appliance energy consumption [4, 9] and monitoring greenhouses [13].

In spite of these improvements, current batteryless sensing applications are limited and typically fall into one of two categories: those that depend on an RFID reader and those that opportunistically detect valid, useful data whenever measured. Power failures and long outages make it difficult or impossible to gather streams of uninterrupted data, inevitably resulting in an inferior quality performance when compared to reliably powered sensors. This has complicated the design and deployment of such batteryless sensors in many application areas.

Occupancy-monitoring applications try to instrument buildings, people, or other indoor elements to get a better understanding of the number of people in a room. This information is the baseline data for successful operation of smart building functions such as intelligent temperature and HVAC control, efficiency monitoring, elderly tracking, and other applications. Existing occupancy-monitoring systems use many sensing techniques and deploy in many different form factors, with doorway-based sensing being one promising method [16, 18]. In this paper, we implement a doorway-mounted batteryless sensor for occupancy monitoring and investigate the challenges posed by an unreliable power supply to achieving a reasonable quality of sensing. We recognize three major aspects to implement a successful sensing system with unreliable power:

Intermittence: Small energy storage combined with unpredictable energy harvesting means that batteryless devices must be equipped to handle intermittent operation. Specifically, batteryless occupancy sensing devices must be careful to (1) optimize operation to make best use of available energy, (2) use ultra-low-power techniques and passive methods to perform the actual sensing and support the applications, and (3) be failure resistant, gracefully handling power failures and returning to deterministic states.

Energy harvesters as sensors: A sensing system traditionally consists of a dedicated sensor to gather data, along with some form of processing and communication, powered from a reliable energy source. We propose an alternative to this approach by inferring the signal from variations in the harvested energy, instead of using that energy to power an explicit sensor.

For example, door-mounted occupancy sensors can harvest energy from indoor and ambient lighting using solar panels pointed towards the floor or other reflective surfaces. Concurrently, this energy is also a *signal* that can be processed to gain insight into the changing environment of the building, the movement of people and objects, or even the time of day. We can use this correspondence between energy and data to enable passive sensing and consequently, batteryless occupancy detection. If a door-mounted entry and exit sensor has solar panels that point down towards the floor, a person walking through the doorway would occlude the light, lowering the energy harvested for that point in time. This event could be tracked passively, transforming the solar panels into practically free sensors. This signal will be affected by the changing power draw of the system (an artifact of the I-V curves of solar panels) and will have a changeable resolution and magnitude depending on the incident light intensity. These factors make the overall signal noisy. However, careful signal processing in the energy constrained computational environment can provide useful information, freeing up energy that would otherwise have been consumed by an explicit sensor (potentially expensive such as an ultrasonic range finder).

Human and building confounds: Harvesting both energy and signal from solar panels introduces confounding factors from the variability of lighting in buildings, and the variability of people and their habits. Many buildings will have some well-lit rooms bordering dim hallways, or vice-versa. Other rooms may have an abundance of natural light, while some have only artificial light. Also, clothing, hair color, skin color, walking speed, and height will all affect and potentially change the readings on the solar panels. Any system that promises robust occupancy monitoring using energy harvesting must be able to handle these confounding factors.

Batteryless occupancy sensing has never been done; but can take advantage of a key observation to provide reliable service—the reality that the applications' harvested energy can also be used a data stream that serves as a sensor. By taking advantage of the temporal locality of energy harvesting and data in occupancy sensing, we can build a long-lived sensor that detects and identifies the movement of people as they enter and exit rooms. In the following sections we discuss Waldo, a novel sensing system that demonstrates the feasibility and utility of intermittently powered, energy-harvesting devices, for sensing in the sustainable future Internet-of-Things.

3 WALDO

Waldo is a slim, batteryless, occupancy-monitoring sensor system mounted to the top of a doorframe. It is powered by energy harvested from two arrays of indoor solar panels pointed at the floor. The panels serve two roles: 1) energy harvester and 2) sensor. These panels gather **energy** for computation, sensing, and signaling while also providing the **signal** that Waldo uses to detect when a person walks through the doorway in the form of variations in the harvested energy. Waldo records the direction—entry or exit—of each doorway event and stores this information in non-volatile memory for later transmission.

Design Goals: Unpredictable power availability coupled with confounding factors of human-based sensing make designing an intermittently powered occupancy sensor challenging. We designed Waldo to meet the following design goals which address specific challenges:

(1) **Availability:** Doorway events can occur at any time. While many intermittent sensors are able to gather data opportunistically as energy is available, Waldo is designed to conserve its harvested energy so that it is available to detect ephemeral doorway events, whenever they occur.
(2) **Accurate direction:** In addition to detecting someone passing through the doorway, Waldo uses angled solar panels to accurately determine their direction. This plays a crucial role in inferring the occupancy of rooms and buildings.
(3) **Variable lighting conditions:** Indoor lighting conditions can change over time, due to human behavior and the relative movement of the sun. We have designed Waldo to work in a range of different lighting conditions by using detection circuits that respond to changes in light level, independent of the absolute amount of light, as well as tuning mechanisms built into the prototype.
(4) **Variable human characteristics:** An effective occupancy sensor should work well in spite of variations in clothing, hair, height, walking speed, and skin color. By focusing on changes in total reflected light, Waldo is robust to these human variations.
(5) **Form factor:** We want Waldo to be easy to deploy, to fit unobtrusively inside a door frame, and avoid contact with doors (on frames with doors). We could harvest more energy by wrapping Waldo around the doorframe, but the system would be more expensive, harder to deploy, and more likely to interfere with doors, while also changing the aesthetics of the doorway.

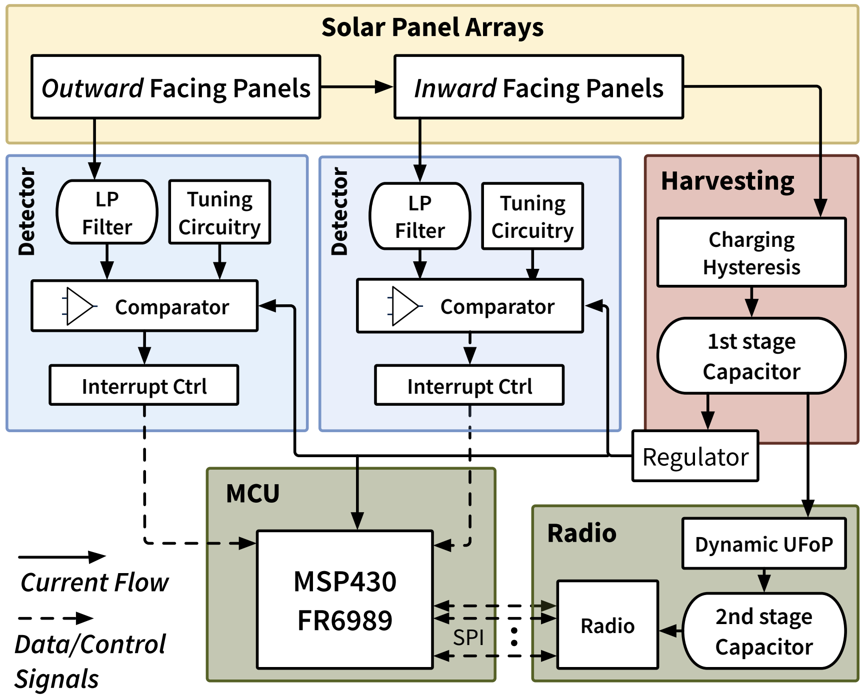


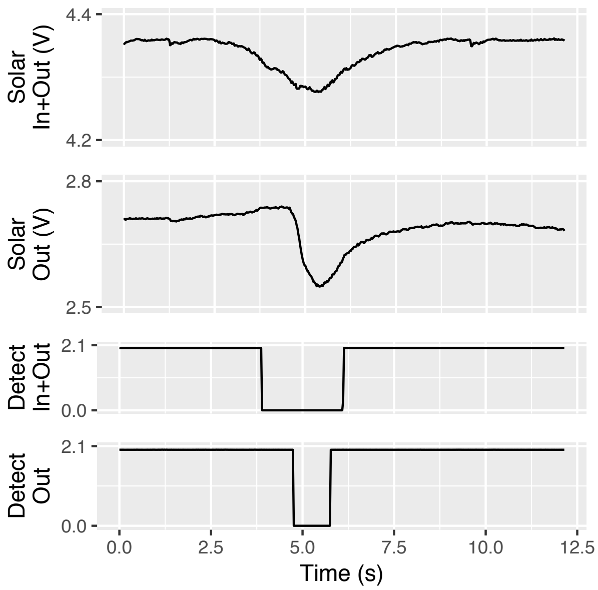
Fig. 2. The Waldo architecture overview. Waldo uses the energy and signal from two sets of solar panels to both power the sensor and detect people passing into and out of a doorway. Two detector circuits each monitor half of the solar panels mounted in series that face inward, and outward in the doorway. On detection, the detectors wake up the MCU to process, log, or communicate occupancy information.

What Waldo is not. We also want to be clear about what Waldo is *not*. Waldo is *not* a security device. Waldo helps building owners and managers understand how people move through buildings, but it is *not* designed to thwart malicious behavior. We can easily trick Waldo with a flashlight or reflective materials, and we can disable it completely by covering its solar panels or turning off the lights. Users looking to prevent shenanigans or tomfoolery should use a different device. Users looking for a long-lived, low-maintenance, best-effort batteryless occupancy sensor for monitoring normal behaviors should read on.

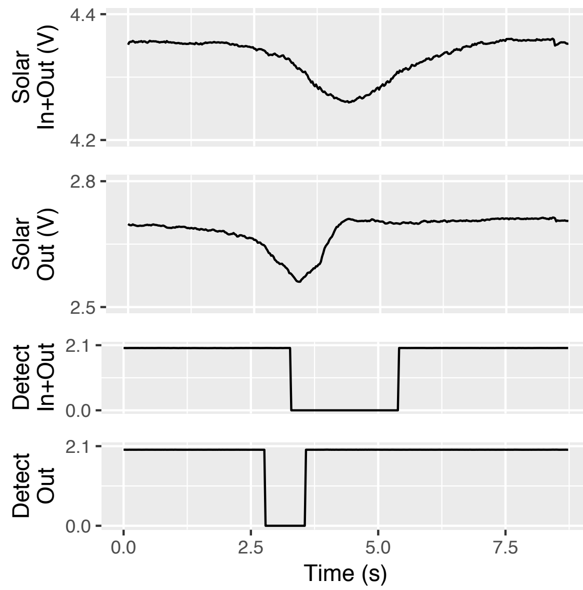
An overview of the Waldo architecture is shown in Figure 2 and our Waldo prototype device is shown in Figure 5. We detail our approach to meeting these design goals and answering their associated challenges in the rest of the section — specifically we describe the Waldo architecture and design, the detection mechanism, and the energy management operations.

3.1 Energy Harvesting and Management

Waldo takes advantage of the ubiquity of indoor light in homes and offices. Solar panels are mounted to the top of the door frame, pointing down toward the floor—half tilted 20° inward and half tilted 20° outward. Pointing the panels downward is not ideal for energy harvesting but effective for detecting doorway events and provides a slim, easy-to-deploy form factor. The 20° tilt helps Waldo determine walking direction, as a person will affect one half of the panels before the other.



(a) Walking in.



(b) Walking out.

Fig. 3. These traces show example solar panel voltages and detector outputs over time when a person walks through a Waldo-enabled doorway. The top traces show how the solar panel's voltages are deformed during the doorway event. The detector triggers are used to wake up the microcontroller and detect events and their direction. The angling of the panels cause the inward facing and outward facing detectors to trigger at different times depending on the direction the person is walking.

To maximize energy harvesting, we connect the two sets of solar panels—the inward-facing set and the outward-facing set—in series. A series configuration conveniently combines the two panel sets into a single power source, but we can't directly measure the raw voltage on each set since the sets lack a common reference ground[2]. Instead, we measure the voltage of the outward-facing set alone, and the combination of the two sets. We could compute the inward panels' voltage by subtracting the two; however, we have found that we can skip this step and just compare the two measurements directly, as shown in Figure 3, to determine walking direction.

Waldo uses federated energy storage [13] to power its microcontroller and peripherals. Harvested solar energy is fed into a common first-stage storage capacitor and then automatically federated to its peripherals. Federating energy allows us to prioritize detection and computation while saving up energy for more energy-expensive radio transmissions. It also improves harvesting efficiency and allows separation of peripherals without fear that the microcontroller will lose power due to a radio transmission. Waldo currently supports connections for two peripherals — a Texas Instruments CC1101 radio and an extra slot for potential expansion to be used in future work.

3.2 Detection

When someone walks under Waldo, they block some of the reflected light hitting the solar panels. In Figure 3, the "solar" traces on top shows how the voltage from the solar panels changes during a doorway event.

[2]For a series connection, we connect the positive terminal of the first panel set to the negative terminal of the second.

In order to detect a doorway event, we could use an ADC to continuously measure the solar panel voltage over time and analyze those readings to detect the presence and, more importantly, direction of motion. Voltage levels and waveform shapes vary with lighting conditions, especially when one side of the doorway has more natural light. This approach would require sophisticated signal analysis and prohibitive energy consumption. Instead, Waldo uses a **detection circuit** that wakes up the microcontroller when it detects a significant change in the solar panel voltage over a short period of time. This circuit consists of a passive first-order capacitive filter connected to a nano-power comparator—producing a square wave that transitions when the voltage increases or decreases faster than a set rate. These transitions trigger interrupts that help Waldo detect when someone is passing through the doorway.

In order to determine movement direction, we use two detector circuits: one that detects change on the outward-facing panels and another that detects change on the combined inward- and outward-facing panels. When someone walks through the doorway, the detectors trigger at different times, depending on the walking direction, as shown in Figure 3. Waldo compares the timing of these detector interrupts to distinguish incoming and outgoing doorway events.

Removing light flicker. Many fluorescent indoor lights flicker at 60 Hz or higher—a much higher frequency than the events Waldo is designed to detect. These fluctuations can confuse the detection circuit and produce false positives unless they are filtered out. We add a low-pass filter to remove noise above 10 Hz from the solar panel signal.

Isolating harvesting from sensing. If connected directly, Waldo's harvesting and event detection circuits conflict in two important ways. First, the harvesting circuit stores harvested energy in a 100 μF capacitor—a size that ensures that Waldo can store enough energy for short-term tasks and dampens the low-frequency voltage fluctuations that we need in order to detect doorway events. Second, short-term power spikes from interrupt service routines and other computation cause high-frequency dips in the solar voltage, which can confuse the detection circuits. We address both of these challenges by adding an additional low-pass filter between the detection and harvesting circuits. This isolates the solar panel from the load, and allows the solar panel voltage (after the initial flicker filter) to fluctuate over a wider range in response to doorway events with less interference from the storage capacitor, the microcontroller power draw, and the detector circuit power draw.

Detection algorithm: A high-level overview of our detection algorithm is shown in Figure 4. During normal operation, when no doorway events are detected, Waldo's MCU remains in deep sleep. While in deep sleep, the MCU is only triggered awake by the detector circuits going from high to low—designating the beginning of a doorway event, from the change in solar harvesting energy from the light occluded by a person walking through the doorway. Once triggered, the MCU starts a timer (a few seconds), and records the time at which the interrupt occurred, then goes into sleep mode, waking up throughout the doorway event to capture the length of time between each detector's status change (from HIGH to LOW and vice versa). Multiple interrupts often fire during a single doorway event as a person does not block light to the panels in an exact and smooth manner. The timer defines the boundaries for what will be considered part of the event.

Times are recorded for the first falling edge interrupt and the last recorded rising edge for both solar panel groups. When the timer fires, both solar panel groups' start and end times are compared to determine the direction of the event (entry or exit), and the Waldo stores the detected event in non-volatile memory.

In rare cases, only one detector detects the event. These events are reported as a partial event, which doesn't have direction information. Partial doorway events can occur when a person walks by the doorway, but not through it (just close enough to interfere with one panel group).

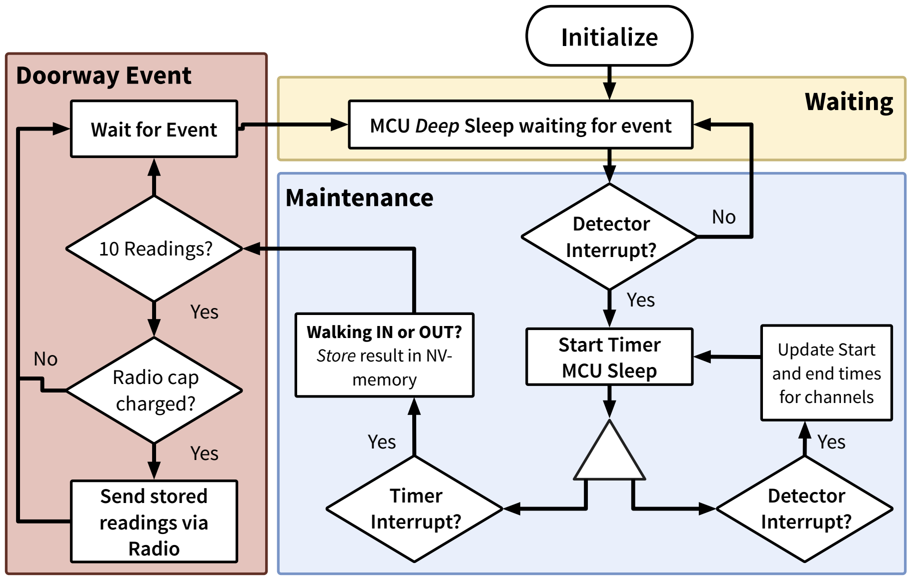


Fig. 4. The Waldo detection algorithm and system decision flowchart. The algorithm is composed of three parts that handle doorway events, maintenance, and idle waiting.

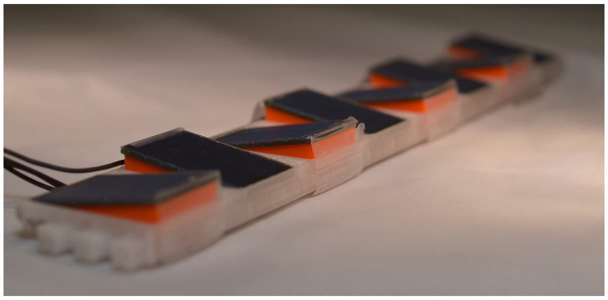
3.3 Communication and Infrastructure

The data that Waldo collects about people walking through the doorway is stored in non-volatile memory until the system has enough energy to make a radio transmission. The current setup collects data for a certain fixed number of events before it polls the radio to see if it is available. If there is enough available energy, the system will send statistics for the collected data, clearing its buffer. If the capacitor for the radio isn't sufficiently charged, it will go back to sleep and try again after each subsequent event. This way, we can keep collecting data as events occur and transmit it all to the base station when we have sufficient power to do so.

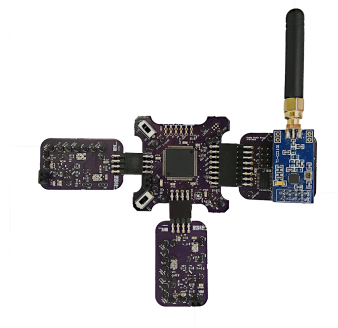
4 IMPLEMENTATION

We have implemented a prototype Waldo sensor for evaluating our approach, including custom hardware in the form of a Printed Circuit Board (PCB) (shown in Figure 5b), firmware for managing the doorway sensing application, and a custom 3D printed doorway mounting system that holds the assembled PCB and solar panels in a slim profile Figure 5a.

Hardware: Our prototype hardware integrates four (4) RL-55x70 solar panels (70.00mm x 55.00mm) from Seeed and a custom printed circuit board (PCB) held together by a 3D-printed plastic enclosure, detailed later in this section. The prototype's hardware is composed of an MSP430FR6989 microcontroller from Texas Instrument's (TI) FRAM line of ultra-low-power processors. The newest FRAM-based MSP430s have several advantages over previous models: lower sleep-mode currents, shorter wake-up latencies, and faster non-volatile FRAM. Using the faster wake-up capabilities, Waldo is driven entirely by interrupts and remains asleep most of the time to conserve energy when not in use. The solar panels are connected in two banks, where both of these banks are made up of two panels connected in parallel. Both these banks are connected in series with each other to increase the harvesting voltage, allowing for greater volatility in voltage which makes it easier to recognize features of the signal. This configuration provides enough current to power the circuit with sufficient voltage levels for detection,



(a) 3D printed solar panel enclosure with angled slots for solar energy harvesters.



(b) Waldo prototype PCB.

Fig. 5. Waldo implementation

Table 1. Detailed breakdown of the Waldo prototype

Components	Cost per individual unit	Unit Cost for 1000 units
Solar Panels	$ 7.8	$ 7
Microcontroller (MSP430FR6989)	$ 8.3	$ 4.71
Components	$ 18.26	$ 8.72
PCBs	$ 19.44	$ 2.2
Entire Waldo Prototype	$ 53.8	$ 22.63

as well as powering the system. The detector circuitry is made using nano-power comparators (TI TLV3691) and a passive RC filter network. The RC filter network is tunable using trim potentiometers pre-installation, or digital potentiometers in deployment. The Waldo PCB also has a TI CC1101 radio for communication. The hardware used in the Waldo prototype, shown in Figure 5b, is not prohibitively expensive or obtrusive. The total cost of the current prototype, including all PCB, parts, assembly costs, and solar panels is $22.63 per unit if ordered in quantities of 1000. The distribution of the prototype costs are showed in Table 1. The current prototype has several components that are meant to enable experimentation and testing (modular board design, jumpers, headers, test points, etc) – a commercial version of Waldo will be dramatically cheaper and smaller.

Firmware: The Waldo firmware implements the detection algorithm discussed in Section 3. Monitoring the interrupts from the detectors and deducing the direction of motion upon triggering are the main tasks of the system. The firmware is designed to be ultra-low power, even in active mode, and has low computational complexity, offloading the bulk of the detection to the hardware circuits. The Waldo firmware is composed of 398 lines of commented C code, compiling to a 2110 byte image. This code size comprises only 1.6% of the available code space on the MSP430FR6989 (128KB), leaving ample room for implementing custom tasks, recognizers, or multiprogramming operating systems.

Mechanical Design: The 3D printed mounting system (shown in Figure 5a) is made of PLA plastics and contains the PCB, solar cells, and necessary wiring connecting them. Waldo's 3D printed enclosure measures 13.2 cm by 47.0 cm by 1.0 cm at its thickest point. The enclosure provides a nesting place for the solar cells, pointing downward. The angle of the solar cell slots is set such that some solar cells tend toward the entry, while the rest toward the exit.

Doorway #	Light Intensity (lux)		Flooring		Enough Light?	Total Events #	Detection Accuracy(%)	Direction Accuracy(%)
	Inside	Outside	Inside	Outside				
1	86	96*	Tile	Tile	Yes	162	93.82	98.02
2	86*	64	Carpet	Tile	Yes	63	90.48	78.94
3	71	55	Carpet	Tile	Yes	106	100	98.11
4	96	111*	Tile	Tile	Yes	106	100	98.11
5	55	55	Tile	Tile	Yes	112	99.1	94.59
6	55	71	Tile	Tile	Yes	102	100	96.08
7	40	71	Carpet	Tile	No	-	-	-
8	24	72	Carpet	Tile	No	-	-	-
9	24	55	Tile	Tile	No	-	-	-

Table 2. Evaluation results with 12 test subjects having variable heights, hair color, and clothing as described in Section 5.2. We tested 9 different doorways, from which 6 had enough light to power Waldo. We ran multiple people through each of these 6 doorways, noting the detection accuracy and how many of the detected events had correct direction. These results show that an adequately-lit Waldo occupancy monitor can accurately detect doorway events and their directions.

*Mixed Lighting — Combined natural and artificial light

All software, firmware, hardware schematics and layouts, and 3D printed mounting system will be made freely available at publication time.

5 EVALUATION

In order to evaluate the efficacy of our approach, we evaluated Waldo in three phases:

In the **first phase** (Section 5.2, we ran experiments on multiple doorways, with different characteristics—like light levels, flooring, doorway heights and doorway widths. For each experiment, we primarily evaluated Waldo's ability to detect someone passing through and determine the person's direction of movement. In this phase, we also tested the systems robustness to human variations, such as height, clothing, and hair color by considering a diverse group of subjects. Our study was conducted on 6 different doorways with 12 different people for a total of 651 different doorway events (each person walked through multiple times per doorway).[3]

In the **second phase** (Section 5.3), we tried to push the limits of the device, examining the factors that affect its accuracy, performance and availability. These factors included the effect of adverse lighting conditions, walking speed and shorter delays between doorway events. We also investigated other events that might get falsely detected as doorway events.

In the **third phase** (Section 5.4) we explore the energy harvesting ability and gather microbenchmarks of the energy consumption of the parts of the Waldo system.

5.1 Methodology and Claims

The following experiments attempt to address the goals defined in Section 3. We address system availability (Goal 1) by demonstrating the low power draw of the system itself and the number of times it caught doorway events (and the number of doorway events missed) for each doorway test. Further, we evaluated the accuracy in determining the direction (Goal 2) by observing how often Waldo correctly determined walking direction. We explored variable lighting conditions (Goal 3) by testing the device under 6 different doorways with diverse lighting conditions, both typical and adverse. We address human variation (Goal 4) by evaluating different walking

[3]This study was approved by our Institutional Review Board.

speeds and the effect of clothing and hair color/hair covering on detection patterns. We claim that (Goal 5), concerning form factor, is addressed by our prototype and slim mechanical design, described in Section 4.

We also have attempted to test the limits of the device, by varying different factors to see when the device stops working and generating conditions that can confound the sensor. We acknowledge that these experiments are best effort, and cannot hope to cover all variability and confounding factors of tracking of diverse persons and buildings, but they do give a broad sense of the capabilities and limitations of Waldo.

To process and enable data collection in our experiments, we gather all electrical signal measurements, except where specified otherwise, using the Saleae Logic 16 logic analyzer[4], at a sampling rate of 5KS/s. The analyzer has high impedance ADC's allowing for unobtrusive monitoring of all signals. This sampling rate is sufficient to detect events on the doorway as we are monitoring fairly slow-varying events. We manually recorded the direction of each doorway event as ground truth to verify the accuracy of Waldo in event detection, then compared the ground truth results with the results measured by the logic analyzer. The light intensity levels were measured using the TSL2561 Light-to-digital converter from Texas Advanced Optoelectronic Solutions.[5] These converters were aligned to the same angle as the solar panels in both directions to get accurate light intensities falling on the panels.

Finally, we note that it is difficult to fairly compare the performance of different occupancy-monitoring systems except in their accuracy. For example, CeilingSee [33] uses 16 devices to instrument a room, while Waldo and SonicDoor [18] place one device in the doorway, and AURES [25] places a single device in the middle of a room. For this reason, we investigate the accuracy of Waldo against our manually gathered ground truth (visually verifying a person entering or exiting the room) instead of comparing to another occupancy-detection system.

5.2 Normal Operation

Experiment Goals: This section presents a thorough testing of the Waldo sensor across multiple different doorways with a diverse group of subjects. The goal of this evaluation is to understand how well Waldo can perform occupancy monitoring. The definition of occupancy monitoring in this context is detecting doorway events caused by people walking *under* the doorway, and further detecting the direction of their movement.

Experiment Overview: We ran the experiment with twelve (12) different participants, with different physical characteristics—heights ranging from 5'4" to 6'4" and hair color ranging from blond to brown and black. Our test group included a wide range of clothing colors (light and dark) and a variety of head coverings.

For this experiment, we affixed the Waldo prototype to the top of 6 different doorways. We have summarized each doorway in Table 2, outlining details such as the light intensity levels on both sides, type of flooring, etc. For each doorway, we maintained test subject diversity, in order to characterize Waldo's performance, independent of the characteristics of individual subjects. For doorways with doors, the door remained open all through the experiments. Each participant walked in and out of the room five times in each direction.

Results: The results of this experiment are shown in Table 2, where we tested the system on a total of 651 individual events. Each *event* consists of one person walking through one doorway one time. Waldo was successful in detecting doorway events and also the direction people were traveling through the doorway. It detected a total of 634 events out of 651, giving an overall detection accuracy of 97.38%. Furthermore, it determined the walking direction correctly for a total of 605 events, which is 95.42% of the total events detected. Waldo's performance was consistent across all test subjects, independent of human variations like height, hair color, and clothing.

[4]https://www.saleae.com
[5]https://cdn-shop.adafruit.com/datasheets/TSL2561.pdf

5.3 Factors affecting Waldo's operation

Experiment Goals: The effectiveness of Waldo in occupancy monitoring is demonstrated through the experiments outlined in Section 5.2. In this section, we examine factors that affect Waldo's performance as an occupancy-monitoring sensor. It would be impossible to exhaustively study all possible combinations of every factor. Instead, in this section we explore how Waldo reacts to a variety of conditions and behaviors that it will encounter in actual deployments.

We explored the following factors:

5.3.1 Light intensity: We tested the availability of Waldo on different doorways and have reported our findings in Table 2. The solar panels powering Waldo are sensitive to light in the visible as well as the IR spectrum. As a result, to provide a more complete analysis of the illumination around a doorway, we could not rely simply on a lux meter, which only provides information about visible light. We used a TSL2561 sensor that measures both mixed signal (visible and IR) data along with purely IR data, and outputs the combined illumination value in lux. After analysing the data in Table 2, we can see that our current prototype is fully functional on doorways with light levels above at least 55 lux on both sides. An average room/hallway in an office-style setting has light levels around 70 lux, which is sufficient to power the Waldo sensor. It is worth noting that we can customize Waldo for exceptionally dark doorways either by increasing the number of solar panels without changing the working of the system itself, or by employing input booster circuits like the ones used in CleanCut [6].

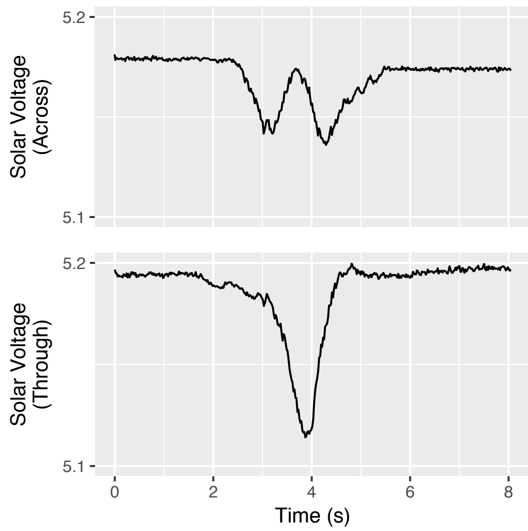
5.3.2 Walking Speed: Waldo detects people walking under doorways based on the changes they cause in the amount of energy harvested. This means that there exists a theoretical limit to how slowly someone can walk through before their movement becomes imperceptible to the system. In order to evaluate this limit, we asked test subjects to walk under the sensor at different speeds. We used a metronome to which the subjects could match their steps in order to achieve a consistent even speed. With extremely slow walking (slower than 1 ft/s), we did observe decreased accuracies. Waldo occasionally detected a slow-moving doorway event as two events. No test subjects have yet been able to walk slowly enough to avoid detection entirely. We don't consider this to be a problem for Waldo, since in practice, people don't often move at such slow speeds.

5.3.3 Door Width and Height: All doors except door #4 (in Table 2) were 80 inches tall, door #4 was 87 inches tall. All doors except door #6 were 34.5 inches wide, while #6 was 58.5 inches wide. A typical interior doorway is 32 inches by 80 inches. In our experiments, the door width and height had no significant effect on the accuracy, however, we only tested when a single person went through a wide door, and we did not control for participants walking through the middle or side of the door (they were asked to walk naturally).

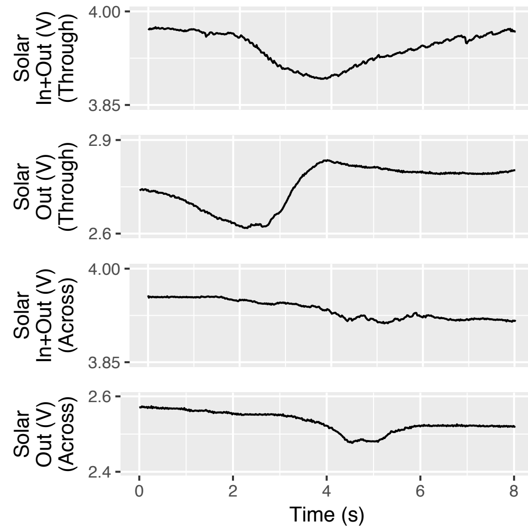
5.3.4 Multiple people: Section 5.2 showed the ability of Waldo to detect individual people walking through. A practical consideration would be to consider the performance of Waldo when multiple people walk through.

In order to evaluate this, we tested two subjects walking through doorway #1 with varying time delay between them. This gave us control over the time separation between two events, and allowed us to examine how closely can two people walk in without being detected as one, quite large person. We discovered that as long as two people have at least 3-4 seconds between them, Waldo can accurately distinguish between them. This limitation is introduced due to the time required by the solar panels to reset or stabilize before the next event can occur. A subsequent logical conclusion is that if two people walk side-by-side, *i.e.,*with zero separation between them, the current setup of the system is unable to detect them as two events.

5.3.5 The "Spotlight" effect: A very interesting consequence of light-based detection is what we affectionately call the *spotlight effect*. This effect appears in the presence of a very focused source of light that dominates the illumination around the doorway, such as a spotlight or a west-facing window in late evening when the sun



(a) These traces show the solar panel output in the presence of the "Spotlight" effect. The top figure shows the response when someone walks *across* the "Spotlight", while the bottom one shows the response when someone walks *through* the door.



(b) This figure provides a comparison between a person walking *through* the doorway (top two traces) versus walking *aross or by* the doorway on the outside. There is a clear delay between the two solar panel channels when someone walks through, whereas the change is reflected simultaneously when someone walks by.

Fig. 6. Factors affecting Waldo operation.

blazes directly through. When someone walks across such a focused light source, even if it's far from the doorway, it is detected falsely by Waldo as someone walking through. This happens because Waldo detects people based on a decrease in the harvested energy, which also occurs when somenone momentarily blocks the focused source of light. Interestingly, we can see from Figure 6a that the raw output of the solar panels look sufficiently different for someone walking *across* the focused source as compared to when someone walks *through* the doorway in presence of a focused source. At present, Waldo is equipped to detect events with good accuracy. With further signal processing, the difference between these events can be extracted so that such events will not cause false triggers.

5.3.6 Detection Range/Walking across, not through: Considering that Waldo uses the blocking of light to detect a person, there will be an influence radius inside which a person starts affecting the harvested energy of the sensor. If someone walks by either side of a doorway monitored by the Waldo sensor and are within the influence radius of the sensor, they will affect the sensor readings. We ran an experiment to determine this radius of influence where the subject was directed to walk by on either side of the doorway at increasing distances from the sensor. We started with a distance of 1 foot and went up to 5 feet, in increments of 1 foot. For each distance, we asked the subject to walk by multiple times and recorded how many false triggers were detected. Our findings are presented in Figure 6b. We have observed that for distances greater than 3 feet away from the doorway, there is a negligible chance of triggering false events.

It is interesting to note from Figure 6b that there is a distinguishable difference between this event as compared to someone walking through the doorway. Since they are walking only on one side of the doorway, their effect

Table 3. Microbenchmarks for Waldo energy consumption.

State	Avg. Power	Peak Power	Energy Cost	MCU Active
Waiting (Deep sleep)	7 µA	11 µA	-	✗
Maintenance Actions	220 µA	500 µA	140 nJ	✓
Doorway Event Handler	220 µA	500 µA	4424 nJ	✓

on both channels is not delayed by the angling of the solar panels, as is the case with walking through. As with the "Spotlight" effect, we should be able to extract this difference with further signal processing and learning.

5.3.7 Lingering in the doorway: Another situation that causes false triggers is when a person comes up to the doorway, but simply pokes their head in. Upon evaluation, we discovered that as long as the person is poking their head in the doorway, the solar panel output remains at a lower level, and when they exit, it rises back again. Although the current system implementation isn't equipped to differentiate between someone passing through and someone lingering in doorway, there is a clear difference in the raw waveform outputted by the solar panel. This case is similar to Section 5.3.6 in terms of being distinguishable from a person walking through and with some careful, direct signal processing it is definitely possible to differentiate between the actual and the confounding case.

5.4 Microbenchmarks

The more effective Waldo is at maintaining a low-power state when idling, the more available Waldo is for detecting doorway events and monitoring occupancy. The energy requirements for detection and active computation must be kept low as well. Unlike intermittent computing sytems, Waldo must intentionally avoid power failures. We measured the current draw of our Waldo prototype while it was mounted on doorway #1. The idle draw of the system was 18 µA, showing that Waldo can survive in a doorway with minimal light and energy harvesting. We gathered other benchmarks of system energy performance in each mode of operation Waldo enters; the results of our experiments are shown in Table 3. These measurements were made after the MIC841 hysteresis chip, so the actual power and energy is slightly higher (by 1.5 µA according to the datasheet).

Table 3 shows a low quiescent current where the MCU is asleep (the Idle state) of 7 µA on average. Maintenance events (from timer firing or single detectors firing from noise or people passing by the doorway but not walking through) only require 140 nJ to handle in active mode with the MCU running. The most expensive compute operation is when the detectors fire and the MCU must compute the direction and store the results to non-volatile memory: FRAM. This costs 4424 nJ. Overall the energy consumption of the system is low, but could be further improved with careful tuning of resistance values, sleep states, and the analog circuitry.

6 RELATED WORK

Waldo is closely related to other occupancy-monitoring sensing systems—especially those using doorway mounted sensor suites. Waldo also draws from the literature on sensing systems that treat harvested energy both as energy and data signal; deriving application information from the energy source. We detail the work related to Waldo below.

Occupancy-Monitoring Systems: Several different methods for detection of occupancy and inter-room movement have been explored. Existing occupancy monitoring systems use ultrasound[16], imaging[27, 28], wearables[11], instrumented objects[3], structural vibrations[23], and opportunistic data leaked from existing meters and security systems[32]. Each of these systems accurately performed occupancy detection (and often provided further features such as activity and person recognition), however, each suffered from the maintenance cost associated with battery powered systems.

AURES [25] attempted to address this concern by using a rechargeable battery and a indoor solar panel. AURES estimates the number of occupants in a room by using wide-band ultrasonic signals. It needs to be installed in a central location on the room ceiling and near a light source to function properly. AURES, as an energy-neutral system, features an extended lifetime using energy harvesting to recharge a battery. However, all batteries wear out (usually in a few years) meaning replacement is inevitable. In comparison, Waldo has the dual advantage of being both easy to install (on the doorway) and batteryless i.e. maintenance free.

Like AURES, EnOcean [10] and Leviton [19] are commercial ceiling-mounted occupancy sensors that are also powered by harvested ambient light and utilize passive infrared sensors (PIR) for detecting occupancy through motion detection. These sensors are equipped with wireless communication capabilities for transmitting the occupancy status (occupied/not occupied) of specific rooms or areas. This is useful in controling the lighting, HVAC and other electric loads. On the other hand, Waldo utilizes the information present in harvested energy variations to detect individual doorway movements as well as the direction of those movements. This information can not only be used in making smarter building utility decisions, it also provides a more detailed insight into area/room-wise usage of buildings in terms of occupancy count. This fine-grained occupancy information can possibly be used in optimizing the layout of a building and to provide higher flexibility in utility control.

CeilingSee [33] attempts to eliminate the extra power consumption of the monitoring tools by alternating existing LED lighting fixtures between being light sources and sensors in a duty cycle manner. It uses reflected light and machine learning to distinguish between the fixed objects in the room and the rooms occupants. CeilingSee offers a promising direction for new buildings, where custom lighting installations present an incremental cost. In contrast to Waldo however, applying CeilingSee to legacy installations (old buildings) would be expensive, as this would include construction costs, computational infrastructure, and IT staff maintenance. CeilingSee could also put extra constraints on how a building can be lighted.

Recent work focuses on using multiple data sources that feed into a machine learning model to estimate the number of occupants in a building [8]. Using the number of connected WiFi devices to detect occupant count can provide coarse-grained information, however it's severely limited by several possible cases such as single occupant connecting multiple devices, use of wired internet access, or not having any device connected to WiFi. This issue is addressed by monitoring utility data, such as water and electricity consumption, weather temperature, and building functions and size along with the number of WiFi devices. This combination works well at the building level. Unlike that, Waldo is designed to monitor occupancy at room-level and communicate with other similar devices to deduce building-level occupancy.

Doorway Occupancy Monitoring: Closely related to Waldo are a few other doorway occupancy monitoring systems; the UVa Doorjamb sensor being the first significant work [16]. UVa Doorjamb enabled room-level tracking of people as they moved through a house, by way of ultrasonic range finders mounted in the top of the doorway, pointing towards the ground. Doorjamb could differentiate people by height, and detect direction of entry and exit into the doorway. Doorjamb was plugged into an outlet and used high-power sensors to gather data, which was processed later. Recently, SonicDoor [18]—an update to Doorjamb—was developed which identifies occupants by sensing their body shape, movement and walking pattern using ultrasonic ping sensors embedded in the sides, and top of the doorway. SonicDoor also senses user behaviors such as wearing a backpack or holding a phone. Both of these techniques use reliable power or batteries and high-powered sensors (ultrasonic range finder), where on the other hand Waldo uses energy harvesting and passive detection techniques to detect people walking through a doorway, providing room-level occupancy detection.

Energy as Data Sensing: Waldo uses solar panels as both the energy source and as a sensor at the same time. This technique has been used in other systems for applications other than occupancy monitoring. Monjolo [9] measures the AC loads consumption based on the harvested power from the AC load. Trinity [30] is designed to measure the airflow speed of air-conditioning based on the harvested power from piezoelectricity that generated from the impact of air flow. DoubleDip [21] is another system that adapted this technique to monitor the water flow through a pipe using thermoelectric generator as a harvester and sensor. Along with these, KEH-Gait [31] is designed for healthcare authentication and providing activity tracking. It does this by sensing the voltage level produced by two types of kinetic harvesters (piezoelectric and electromagnetic), which simultaneously also power the system. There has been another attempt to design a battery-free pedometer [17] by placing a piezoelectric harvester inside a shoe and estimating the number of steps based on the amount of harvested energy.

Despite the fact that there is an indoor-sensing architecture that uses indoor solar-harvested power [4], this architecture does not implement the idea of using the energy harvesting source as the data sensor, as used in Waldo. Waldo is the first batteryless energy harvesting occupancy monitoring platform, that gathers both signal as well as energy from solar panels.

Batteryless, Transiently Powered Sensing: Recent work like HarvOS [2], Mayfly [14], and Ratchet [29] have explored operating system and language-level support for developing applications easily on batteryless devices with frequent power failures. Other efforts have focused on energy management and storage techniques to improve uptime and responsiveness of these systems: such as Federated Energy [13]. Each of these systems inform our work, however, none have tackled the problem of batteryless occupancy monitoring.

7 DISCUSSION & FUTURE WORK

In this paper, we demonstrated that we can monitor how people use buildings without running wires, without structural renovations, and without batteries. Our evaluation has presented the performance of Waldo as a batteryless occupancy sensor and we also have identified corner cases that might confound the current version of the system. This section describes our future plans in terms of making Waldo more robust and reliable. We also present some ideas for expansion of this project.

Improving robustness and reliability: Waldo in its current version depends on sudden changes in the solar panel outputs in a fairly binary manner. It triggers when there's change and doesn't when there isn't. This allows it to detect people walking through with high accuracy. However, it becomes susceptible to false positives as other events might also cause a sudden change in the solar panel, for example when someone walks by the side of the door. As discussed in Section 5, there is a visible difference between someone walking through a doorway and a false positive. One of our goals for future work is to add direct signal processing on the microcontroller so that it will be able to access the whole shape of the waveform, and will not be reliant on the binary nature of the detector interrupts. This will enable Waldo to be more successful in identifying people walking through the doorway with minimal false positives.

User perceptions of privacy: Occupancy monitoring is often privacy violating—cameras, audio, and other methods being examples. Privacy rights in the workspace have long been debated [22], with some workers reporting productivity suffered because of the perception of loss of privacy [26]. Even though Waldo is privacy preserving, and incapable of gathering video, audio, or other personal information, we have not yet surveyed people who live and work with Waldo in their room or office. We believe user perceptions of their privacy could inform both the design of future Waldo prototypes and provide insight into this tension between privacy and real time occupancy monitoring. We plan to explore this in future work.

Adaptability: We plan to make the system more dynamic and flexible by providing adjustable thresholds to the detector circuit. This will equip Waldo with the ability to tune its sensitivity to problematic cases, such as darker lighting conditions. Another way we aim to improve the performance and adaptibility of Waldo would be to make use of learning algorithms. Our goal is to use learning for identifying different events and separating the true positives from false ones, subsequently improving accuracy and precision. We will introduce confidence indicators so that, even in cases where it is comparatively tougher to distinguish between those events, Waldo will be able to attach a confidence level to its prediction, broadening the range of events it can identify. This is a feasible goal considering the evident difference between those events.

Network of Waldos: Waldo is not meant to be a standalone system in that its true potential is realized as a part of a wider network of similar sensors. Different Waldos could exchange information to monitor occupancy on a larger scale and also to improve individual performance. For example, if one sensor detects a large amount of traffic heading into a hallway, but none of the other sensors detect activity, it is likely that there might be some other factor that is confounding the first sensor and this knowledge could be used to refine the learning model. Having a network of such batteryless sensors could also enable the deployment of a more sophisticated, energy-efficient communication model than simply broadcasting information opportunistically.

Additional sensors: We also plan to expand the system in terms of sensing abilities by adding more sensors. These sensors could provide various types of information such as RGB data, which could be used to semi-identify the person walking through. This would help assign some uniqueness to each individual so that we can better track their travel through rooms in a building without gathering identifiable information that would require additional security considerations to be added to the system. We could also opportunistically use an ultrasonic range finder in moments of high illumination to detect the height of the person passing through.

Waldo can be expanded in many different ways, as demonstrated by these ideas.

8 CONCLUSIONS

This paper has presented Waldo, a batteryless, energy-harvesting doorway-mounted sensor system for room level occupancy monitoring. Waldo uses its energy source—generated from an array of solar cells—as data signal for detecting doorway movement, as well as the energy that powers all activities. Waldo uses a novel, tunable, detection circuit that watches the energy harvesting signal with the processor asleep, and it is the first batteryless occupancy-monitoring system in existence. We deployed Waldo on 6 doorways and found that it can detect single persons moving through the doorways with a high overall detection accuracy of 97.38%. Our results show that Waldo can differentiate between entry and exit of persons walking through the doorway for 95.42% of the detected events. We also evaluated different factors that affect the performance of Waldo. There are some events that confound the current version of Waldo into generating false positives, but we have demonstrated inherent differences from the true positives *i.e.,*someone walking through the door. This makes us confident that we can further improve the Waldo system to make it robust to such events. We evaluated Waldo microbenchmarks that demonstrate Waldo is low power, and efficient, able to harvest enough energy to power all activities, intermittently, while providing quality of application. Waldo represents a first step towards robust and reliable occupancy-monitoring systems without batteries, using energy harvesting.

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