Waldo: Batteryless Occupancy Monitoring with Reflected Ambient Light

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ABSTRACT

The buildings of our science fiction dreams have always adapted to the needs of their occupants. Today, "smart buildings" are poised to become reality, enabled by advances in sensors that monitor room-level occupancy and movement. Unfortunately, existing occupancy-tracking systems are plagued by large size, high energy consumption, and, unsurprisingly, short battery lifetimes.

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. Like previous systems, Waldo is mountable at the top of a doorframe, allowing for detection and tracking of a person at the entry and exit point of a room. We evaluated the Waldo sensor in an office-style setting using both ambient and traditional fluorescent lighting sources on both sides of the doorway with subjects exhibiting varying physical characteristics such as height, hair color, gait, and clothing. While challenges remain, this work 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*;

KEYWORDS

Occupancy, Batteryless, Intermittent, Energy harvesting

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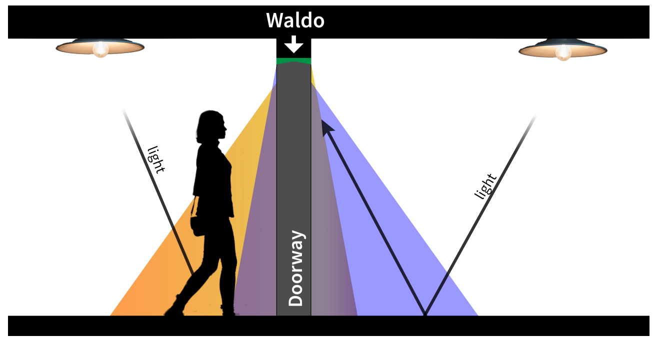


Figure 1: The overall system concept of Waldo, a batteryless, energy-harvesting, doorjamb mounted occupancy tracking and person detection enabling system. This system uses reflective indoor lighting to both power the system and detect person entry and exit activity to a room.

1 INTRODUCTION

Understanding how occupants move, work, and live within a workplace or residence is essential for enabling health, efficiency, and security applications in smart buildings. Appliances, computers, lighting, and 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, generating data that can be used to further understand how people interact with buildings and the different spaces within them. These benefits are dependent on the data that sensors collect as they observe people moving through a building and their interactions within the space.

Unfortunately, current occupancy-tracking systems are too large and costly to be considered for large-scale deployment, and are too high-maintenance for long-term monitoring. There are also privacy concerns for occupancy tracking systems that can identify people's daily habits within a building, possibly without their knowledge. Existing systems use ultrasound[13], images[20, 21], wearables[8], instrumented objects[3], structural vibrations[17], and opportunistic data leaked from existing meters and security systems[24]. Some of these solutions (like imaging) 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 our sensors (which is usually expensive), or use batteries which increase cost, environmental impact, and fire risk, not to mention required replacement 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 [13], Waldo is attached to a doorjamb 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 and florescent 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.

Contributions

The contributions of this paper include:

(1) A novel system design for unobtrusive, long-term, low-cost, zero-maintenance occupancy tracking.
(2) An in-depth analysis of the design considerations for batteryless, intermittently powered continuous sensing systems that have computation and data with high temporal locality 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.

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 less impact on the environment.

However, batteryless sensing is challenging. Energy is stored in one or more small, cheap capacitors to improve efficiency and responsiveness [10]. 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, 18], consistent execution [5, 15], timekeeping [12], energy management [10], testing [9], and debugging [6] address key challenges, and have enabled new and interesting applications: tracking building and appliance energy consumption [4, 7] and monitoring greenhouses [10].

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 makes it difficult or impossible to gather streams of uninterrupted data, and provide high quality of service to the user. This has led to avoidance of some sensing applications that work best with uninterrupted sensing; such as occupancy monitoring.

Occupancy monitoring applications instrument buildings, people, or other technology, 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 [13, 14]. In this paper, we investigate the challenges of occupancy monitoring using intermittently powered devices mounted in doorways. We recognize three major challenges to implementing a successful system:

Intermittent operation: The effect of small energy storage, unpredictable energy harvesting means that occupancy sensing devices must be careful to (1) manage energy to reduce power failures (so as not to miss people walking through the door), (2) use ultra low power sensing techniques and passive methods to gather signal and support the applications, and

[1] Actual lifetimes depend on environmental conditions, enclosure quality, and rates of decay for silicon and other circuit materials. The point is that the usual bottleneck (the battery) is not there. Lifetimes of 10–50 years are realistic but not guaranteed.

(3) be failure resistant, gracefully handling power failures and returning to deterministic states.

Signal from Energy harvesting noise: Door-mounted occupancy sensors can harvest energy from indoor and ambient lighting using solar panels pointed towards the floor or other reflective surfaces. This energy is readily available in typical residential, industrial, and commercial buildings. This energy can be harvested, stored, and used to power sensing tasks. Importantly, 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. This correspondence between the energy that powers the sensor and the data that makes the application work can be leveraged to enable occuapcny 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, as the solar panels themselves are free sensors. However, this signal is noisy, and the resolution and magnitude of signal depends on the behavior of the sensor [9]. Processing useful signal from energy harvesting noise under a constrained computational and energy situation poses challenges at the hardware and firmware level for batteryless occupancy monitoring.

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. Peoples clothing, hair color, skin color, walking speed, and height will all affect the amount of occluded or reflected light and potentially change the readings on the solar panel. Any system that promises robust occupancy monitoring using energy harvesting must be able to handle with these many confounding factors.

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

3 WALDO

Waldo is a slim, batteryless, occupancy monitoring enabling sensor platform mounted to the top of a doorframe that 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 the **energy** needed for computation, sensing, and signaling while also providing the **signal** that Waldo uses to detect when a person walks through the doorway. Waldo records the time and direction—entry or exit—of each doorway event and stores this information in non-volatile memory for later processing.

Design Goals: Intermittent power supplies coupled with confounding factors of human based sensing combine to 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) **Variable lighting conditions:** Indoor lighting conditions change throughout the day, due to human behavior and the movement of the sun. We have designed Waldo to work in a range of different lighting conditions by using detection circuits that respond to change in light level, independent of the absolute amount of light, as well as tuning mechanisms built into the prototype.
(3) **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 can be robust to these human variations.
(4) **Form factor:** We want Waldo to be easy to deploy, to fit unobtrusively inside any 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 changing the aesthetics of the doorway.

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

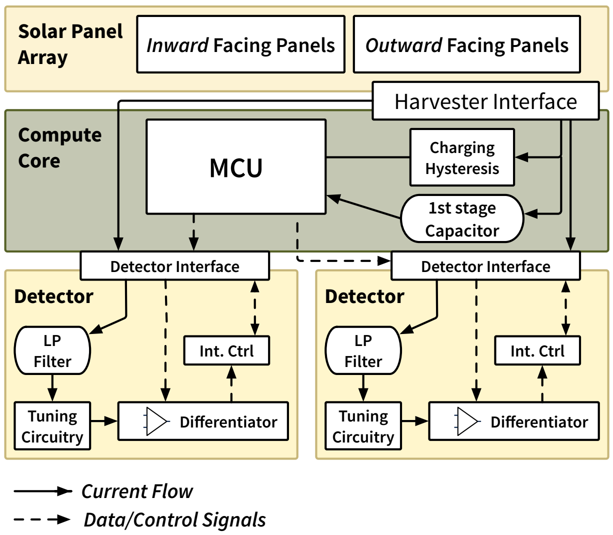


Figure 2: The Waldo architecture overview. Waldo uses the energy and signal from two sets of solar panels to both power the sensor and detect people passing into and out of a doorway. Two detector circuits each monitor half of the solar panels mounted in series that face inward, and outward in the doorway.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

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 spread across the top of the door frame in a custom 3D printed case, pointing down at the floor. Pointing the panels downward is not ideal for energy harvesting, but it is ideal for detecting doorway events and provides a slim, easy-to-deploy form factor.

Waldo uses federated energy storage [10]. Energy harvested from all of the solar panels is fed into a common first-stage storage capacitor and then automatically federated to its peripherals. Waldo currently supports slots for two peripherals, a Texas Instruments CC1101 radio and an ultrasonic rangefinder. We plan to add additional sensors to our design in the near future. These sensors are not used in the evaluation of our prototype. 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 of the microcontroller losing power.

3.2 Detection

When someone walks under Waldo, he or she blocks some of the reflected light hitting the solar panels. In Figure 3, the “solar” trace on top shows how the voltage from the solar panels changes during a doorway event. Doorway events have a characteristic “W” shape because the person passing through the doorway first breaks the light reflected from the origin room and then breaks the light coming from the destination room. The voltage increases when the person is directly under Waldo, and light from both sides is momentarily able to reach the panels.

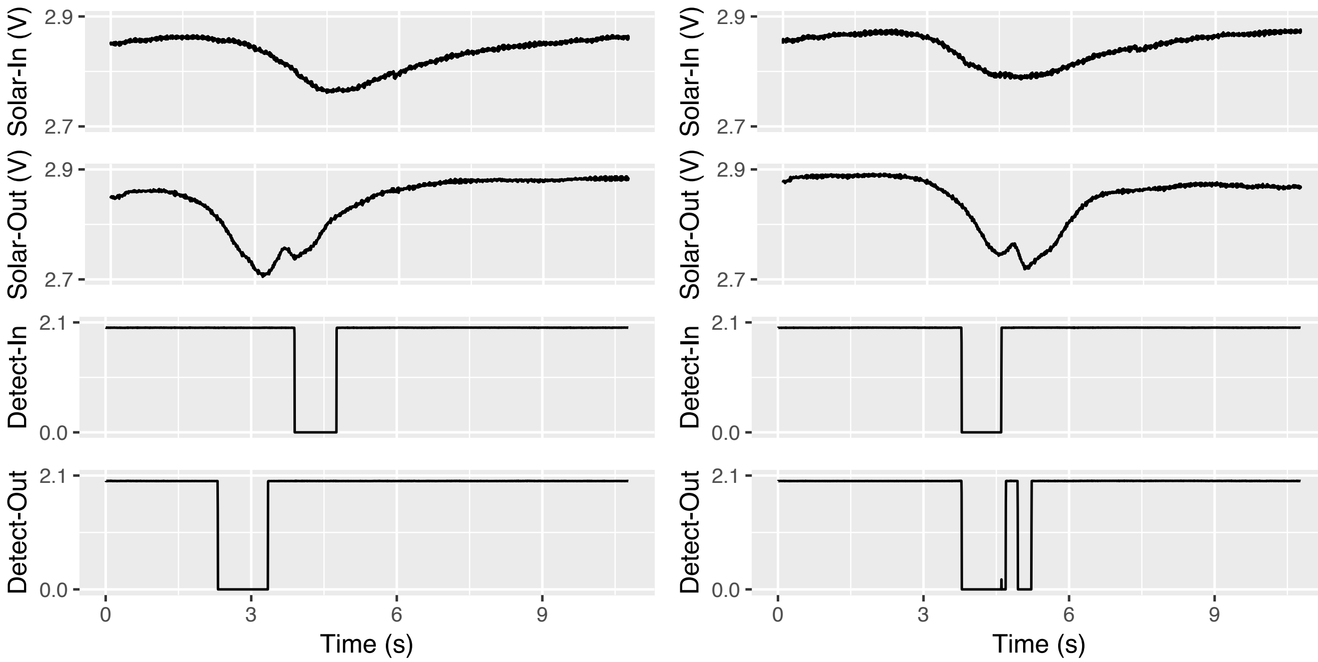
In order to detect a doorway event, we could use an ADC to continuously measure the solar panel voltage over time and analyze those readings to detect the appropriate “W” shape. Voltage levels and waveform shapes vary with lighting conditions, especially when one side of the doorway has more natural light, and 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 differentiator circuit[2] with its output fed into a comparator. This combination produces a square wave with transitions that occur when the solar voltage either increases or decreases faster than a set rate. Figure 3 shows example traces from both a high-to-low detection circuit (detects rapid decrease) and a low-to-high detection circuit (detects rapid increase). In practice we use high-to-low detection circuits exclusively to detect the beginning of a doorway event.

Removing light flicker. Many fluorescent indoor lights flicker at either 60 Hz or higher. These fluctuations are a much higher frequency than those we want to detect, and they can confuse the detection circuit and produce many false positives unless they are filtered out. We add a low-pass filter to remove noise above 10 Hz from the solar panel signal. Figure 4 shows the impact of the noise to the light signal both before and after filtering out the higher frequencies from the signal.

Isolating harvesting from sensing. If connected directly, Waldo’s harvesting and event detection circuits conflict in

[2] A passive differentiator is essentially a first-order capacitive high-pass filter with the cut-off frequency set well above the highest frequencies in the signal.



(a) Walking in.

(b) Walking out.

Figure 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.

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, which 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 differentiatior circuit power draw.

Detecting movement direction. In order to detect the direction that the person is moving, Waldo's solar panels are divided into two groups—one group angled slightly inward and the other group angled outward. Every other panel is angled facing outward, with the other facing inward. Each group of panels has its own detection circuit (differentiator, comparator, and low pass filter) and can wake up the microcontroller independent of the other group.

Ideally, when a person walks into a room, the panels tilted outward will react before the inward facing panels and vice versa. In practice, this is not always the case, due to uneven lighting that can make one detector circuit more sensitive than its counterpart; however, tilting the panels does consistently effect the timing of the interrupts, which we use to determine in what direction the person was moving.

Detection algorithm: During normal operation, when Waldo is not in a doorway event, the MCU remains in deep sleep (or if there is not enough energy stored, is in brown-out). While in deep sleep, the MCU is only triggered awake by the differentiator circuits going from low to high—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 differentiators status change (from LOW to

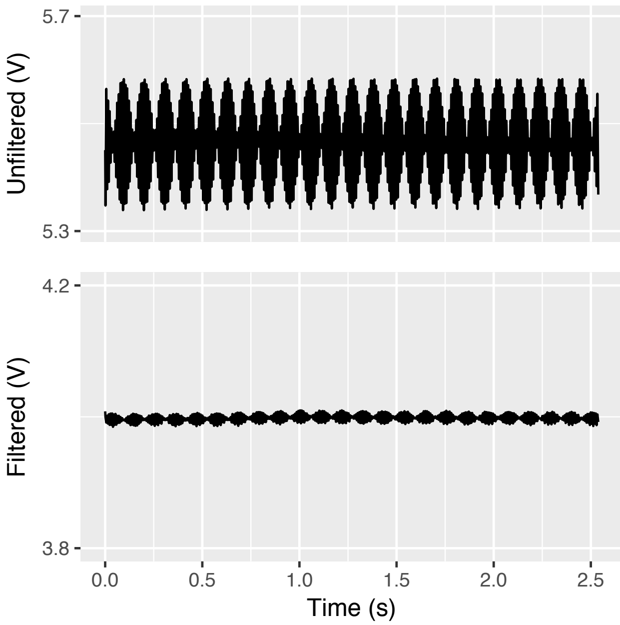
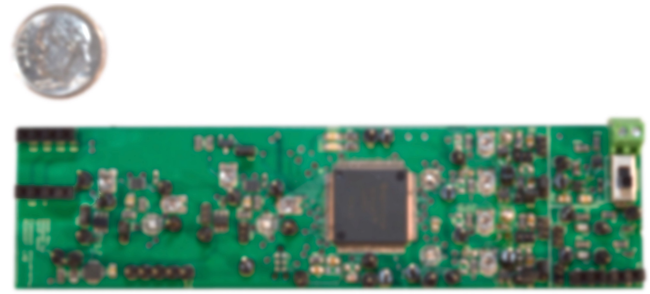
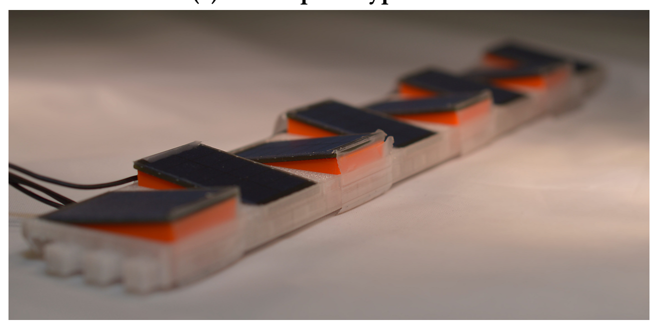


Figure 4: These plots show the impact of the solar signal to Waldo both before and after it the system filters the signal by passing it through the differentiator and the harvestor.



(a) Waldo prototype PCB.



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

Figure 5: Waldo implementation (some details obscured for anonymization).

HIGH and vice-versa). Multiple interrupts often fire during a single doorway event, and the timer defines the boundaries for what will be considered part of the event.

Times are recorded for the first falling edge interrupt and last recorded rising edge for both solar panel groups. When the timer fires, both solar panel groups' end times are compared to determine the direction of the event and start and end times are compared to determine the duration of the event, and then determine whether the doorway event was an entry or exit.

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

4 IMPLEMENTATION

We have implemented a prototype Waldo sensor for use in evaluating our approach, including custom hardware in the form of a Printed Circuit Board (PCB) (shown in Figure 5a, 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 5b.

Hardware: Our prototype hardware integrates eight (8) 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 MSP430's have several advantages over previous models: lower sleep-mode currents, shorter wake-up latencies, and faster nonvolatile 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 series to increase the harvesting voltage, allowing for greater volatility in voltage which makes it easier to recognize features of the signal. This comes at the cost of increased harvesting current. The differentiator circuitry is made using nano-power TI TLV3691 comparators 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 5a, is not prohibitively expensive or obtrusive. The total cost of the current prototype, including all PCB, parts, assembly costs, and solar panels is $33.37 per unit if ordered in quantities of 1000.

Firmware: The Waldo firmware implements the detection algorithm discussed in Section 3. Monitoring the interrupts from the detectors, and analyzing the waveform once triggered are the main tasks. 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 differentiator 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 multi-programming operating systems.

Mechanical Design: The 3D printed mounting system (shown in Figure 5b) 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.

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 examine the overall accuracy of the system in detecting doorway events, as well as the direction of the person's movement. We investigate the systems robustness to multiple human factors, such as height, walking speed, and clothing / hair color. We also evaluate the Waldo on two doorways with different lighting settings. We conducted a study, involving human test subjects, to verify the efficacy of our approach.[3] Our experiments are conducted with the Waldo prototype described in Section 4, with 12 test subjects and 124 individual doorway events.

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 percent of time it caught doorway events (and the number of doorway events missed) for each doorway test. We explore variable lighting conditions (Goal 2) by testing the device under two different lighting conditions. We address variable human characteristics (Goal 3) to a large extent by evaluating different walking speeds and the effect of different clothing and hair color on detection patterns. We claim that (Goal 4), concerning form factor, is addressed by our prototype and slim mechanical design, described in Section 4. We note that these experiments are best effort, and cannot hope to cover all variability and confounding factors of tracking of diverse persons and buildings.

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 and a recording duration of ten (10) seconds. The analyzer has high impedance ADC's allowing for unobtrusive monitoring of all signals. This sampling rate is slow, but sufficient to determine the detection events on the doorway, as we are measuring human recognizable events. We manually recorded the direction of each doorway event as ground truth to verify the accuracy of Waldo in event detection, compared with the results measured by the logic analyzer.

5.2 Detection Accuracy

This section seeks to understand how well Waldo can perform occupancy monitoring. We define occupancy monitoring in this context very narrowly; detecting doorway events caused by people walking under Waldo, and further detecting the direction of these people using solar energy harvesting traces. In this experiment, we affixed the Waldo prototype to the doorjamb of a reasonably well lit (inside and out) doorway. This doorway was lit with existing fluorescent office lighting on both sides, with minimal amounts of natural light from windows. The door was kept open all through the experiments and the flooring was light colored tiles. This doorway had nearly equal amounts of light (measured in lux) on both sides.

We had ten (10) participants walk through the doorway at different speeds. Each participant walked in and out of the room six times in each direction. We evaluated results at three different walking speeds (normal, fast, and slow). In order to calculate the speed of each participant, we marked a fixed length path through the door and recorded the time they took to cover it. Results indicated average speeds for all participants as follows: 3.7 foot per second (1.12 m/s) for normal, 2.6 foot per second (0.79 m/s) for slow, and 5.36 foot per second (1.6 m/s) fast. Furthermore, participants wore different colored clothing (ranging from light to dark) and had different heights that ranged from 5ft 3in (1.6m) to 6ft 1in (1.85m). We also considered the hairstyle or headgear of the participants as a factor in the recruitment process.

Results: The results of this experiment are shown in Table 1. We list the height, hair / hat color, and light levels alongside

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

[4] https://www.saleae.com

Subject	Height	Hair/Clothes	Light (Lux)	Detected Direction	
				In (%)	Out (%)
1	6'1"	Black/Orange	75	100%	100%
2	6'1"	Bald/Lt. Blue	74	100%	100%
3	5'11"	Brown/Green	70	100%	100%
4	5'6"	Pink/Black	75	100%	100%
5	6'0"	Brown/Black	71	100%	100%
6	6'0"	Tan/Black	73	100%	100%
7	6'1"	Brown/Orange	72	100%	100%
8	5'10"	Black/Grey	70	100%	100%
9	5'3"	Brown/Lt. Blue	70	100%	100%
10	6'0"	Bald/Blue	70	100%	100%

Table 1: Results from 10 test subjects with variable heights, walking speed, hair color, and clothing, walking through a doorway with even artificial lighting on entrance and exit over a reflective floor in the late afternoon. These results show that a tuned, well-lit Waldo occupancy monitor is very accurate at detecting doorway events and direction.

detection. Waldo was very successful in detecting both doorway events, and the direction people were traveling through the doorway. This success was the same irrespective of human variability such as height, hair / hat / clothing color, and speed. For all subject, the doorway event, and direction was detected correctly.

Conclusions: When properly tuned, and reasonably well lit (at 70 lux or above) with artificial light, Waldo very accurately detects people walking under the sensor and their direction, enabling room level occupancy monitoring. We note that confounding cases such as lingering in a doorway, poking a head or other body part in for a brief moment, or passing close by the doorway were not tested, and could cause false positives.

5.3 Low Light Detection

Waldo performs well with above 70 lux, typically found in reasonably well lit office buildings. In this next experiment, we sought to evaluate how well Waldo does in a less well lit room, and with lighting mismatched between entry and exit. We placed our Waldo prototype on a doorway with 30 lux brightness on one side, and 45 lux brightness on the other side; so half the brightness of the previous experiment documented in Table 1. This doorways was lit with existing fluorescent office lighting on either sides, with minimal amount of natural light. The door was kept open all through the experiments and the flooring was light colored tiles. Two subjects were asked to pass through the door walking normally; one subject passed through three times, the other one time.

Results: Waldo detected each doorway event when subjects passed through, however, Waldo was not able to detect the *direction* of the person walking under the door way. This is because of the low light levels on the side of the door with only 30 lux brightness. The amount of light (specifically the amount of light occluded by the person) was not enough to actuate the solar cell to cause the differentiator circuit to register a change. The differentiator circuit on the 45 lux side recognized the person walking, but this is not enough to get a direction. We anticipate that a solar panel tuned to indoor light, made with an amorphous material (versus the mono-crystalline used) would more easily register these slight changes in harvested energy.

Conclusions: While Waldo is robust to human variability factors we tested (as demonstrated in the previous experiment) such as walking speed, hair / hat color, and clothing. Waldo has trouble in it's current implementation accounting for low light levels when detecting direction.

The current design of the Waldo circuit that the two channels representing either side of the doorway are kept separate in signaling and combined in harvesting. In order to isolate the harvesting from signaling, we added diodes to the path so that no reverse voltage will flow from one set of panels to the other. In this case, however, the light levels on either sides of the door had a steep difference between them, resulting in one channel reverse biasing the diode for the other channel. This effectively shut down the harvesting contribution of one channel. As a result, during wakeup operation, the circuit drew current from only one channel dampening it much more than it would usually have been. This would cause the dampened channel to react extremely slowly to changes in light levels and made it unable to detect someone walking through. The second channel, on the other hand, was free from harvesting responsibilities and would detect a

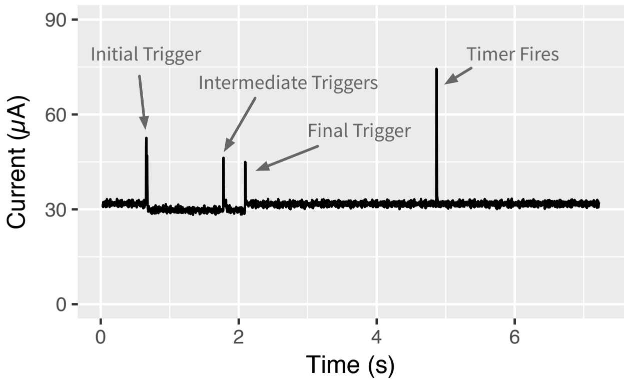


Figure 6: Waldo current draw profile showing differentiators triggering and subsequent current draw spikes during active mode processing by MCU.

person walking through with sufficient ease even when the lighting on it's side was very poor. This limited the ability of the device to detect the direction of motion however it was still able to identify that an event had occurred.

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. We gathered current draw traces of our Waldo prototype conducting a detection event, this is shown in Figure 6. The figure shows that triggers, caused by people passing under the sensor, cause bursts of precessing to understand the direction of the event. These active mode processing bursts are short, with the device spending the majority of its time (even when detecting) in idle mode between differentiator triggers. Microbenchmarks for the power draw of the Waldo prototype device are shown in Table 2. The most relevant statistic; idle draw of 30 μA shows that Waldo can survive in a doorway with minimal light and energy harvesting. Together these benchmarks demonstrate the ultra low power passive sensing abilities of Waldo, enabling long availability despite unpredictable energy harvesting.

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 as energy and data signal; deriving application information from the energy source. We detail the related work to Waldo below.

Occupancy Monitoring Systems: Many exotic methods for occupancy detection, and movement between rooms have

Event/State	Current	Duration
Idle	30uA	N/A
Port Interrupt	60uA	4ms
Timer Interrupt	90uA	8ms
Power On Reset	300uA	50ms

Table 2: Waldo microbenchmarks showing current draw and duration of system level events. When not in power failure, idle current is the passive draw of the differentiator detector circuits.

been explored. Existing occupancy monitoring systems use ultrasound[13], imaging[20, 21], wearables[8], instrumented objects[3], structural vibrations[17], and opportunistic data leaked from existing meters and security systems[24]. Each of these systems proved accurate in 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. These monitoring systems did not address the issue of the power source, as it is supposed to eliminate the power load of the building and laborious work of replacing the battery for that type of device. AURES [19] 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. Unlike Waldo, AURES is not installed on the doorjamb and is not a batteryless and maintenance free device.

Doorway Occupancy Monitoring: Closely related to Waldo are doorway occupancy monitoring systems; the UVa Doorjamb sensor being the first significant work [13]. UVa Doorjamb enabled room level tracking of people as they moved through a house, by way of ultra sonic 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 [14]—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 like the ultra sonic range finder, Waldo uses energy harvesting and batteryless, passive detection techniques to detect people walking through a doorway, informing occupancy detection.

Energy as Data Sensing: Waldo uses solar panels as the energy source and a sensor at the same time. This technique has been used in other systems rather than occupancy monitoring. Monjolo [7] measures the AC loads consumption based on the harvested power from the AC load. Also, Trinity [23]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 [16] is another monitoring system that adapted this technique to monitor the water flow through a pipe using thermoelectric generator as a harvester and sensor. Despite the fact that there is an indoor-sensing architecture that uses indoor solar-harvested power [4], this architecture does not support 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 builds on other works by gathering energy and data from the harvester.

Batteryless, Transiently Powered Sensing: Waldo is not the first batteryless, transiently powered sensing system. Recent work like HarvOS [2], Mayfly [11], and Ratchet [22] have explored operating system and language level support for developing applications easily on batteryless devices with frequent power failures. Other work has focused on energy management and storage techniques to improve uptime and responsiveness of these systems: such as Federated Energy [10]. 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 demonstrate that we can monitor how people use buildings without running wires, requiring structural renovations, and without batteries. Our results are, to date, both promising and limited. This section describes both our current limitations and our future plans.

7.1 Limitations

Limitations of Waldo are exhibited because of variability of people, and rooms in buildings. We will never be able to test every combination of these variables; however, in the coming months, we plan to expand our experiments to include more participants, a wider range of environments, and lighting conditions. We list confounding factors below:

Lighting Conditions: Ambient and florescent light reflections provide convenient information and energy sources; however, the lighting conditions that Waldo will face when deployed is difficult to predict at design time. Our experiments have explored a typical florescent lighting scenario encountered in an office setting but this does not account for the impact of additional lighting sources such as windows and multiple lighting sources in a room or lack of lighting sources (such as a home with no overhead lighting). With rooms that include windows, time of day could have a great impact on the energy available to the system and light available to detect individuals.

Flooring: Waldo was tested in an environment with a semi-reflective tile floor. In an office building or home, there maybe many different types of flooring encountered by the sensor. The diffuse and reflective attributes of materials would help or hinder the signal and amount of energy harvested by Waldo. Some doorways may also experience a mix of flooring types like those between a transition from a carpeted room to a laminate floored kitchen.

Human variation: Differences in skin/clothing color, height, gait, and body size did not noticeably affect Waldo's accuracy for our well-lit doorway. However, it is not know how much these factors influenced the detection of direction in the second doorway, that was not as well lite on one side. Additionally, readings from a single individual walking through the doorway will produce a different signal than a group of people walking through a doorway together or in rapid succession as would happen when a meeting lets out.

Problematic cases: Fortunately, doorways tend to be used for their intended purpose and Waldo can improve its accuracy from anticipating those typical actions. However, there are some problematic cases for this system that happen from time-to-time by human users. These include actions such as lingering in a doorway, poking a head in for a brief moment, or passing close by the doorway of interest. These problematic cases can produce false positives in the system as they may still impact the readings from the sensor.

7.2 Future Work

For occupancy sensing, it is observed that it is much better to enable longer streams of uninterrupted sensing at a lower application quality or application accuracy than to gather short, intermittent bursts at a higher quality, requiring more energy, and constraining execution to only a certain level of available energy. To support nearly continuous sensing, approximate computing can be leveraged, trading accuracy and quality of services for uninterrupted operation. The following are required for this to work: 1) identifying the levels of service that can be supported by the application, and 2) knowing when to switch between these levels of service. Approximate computing applied to batteryless systems makes intuitive sense when sensor data exhibits high temporal locality, meaning that a data point gathered immediately after another may be worthless, as nothing has changed (for example when monitoring an empty doorway). Knowing when to reduce the level of service is a key challenge that we plan to explore in future work. This approximation approach could also benefit from integrating other sensors; such as RGB color sensors or ultra sonic range finders. These sensors could help differentiate or identify persons walking through the doorway (using either height or relative color).

8 CONCLUSIONS

This paper has presented Waldo, a batteryless, energy harvesting doorjamb 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 in a laboratory doorway and found that it can detect single persons moving through the doorway in reasonably lit office / lab settings. Our results show that Waldo can differentiate between entry and exit of persons walking through the doorway with high accuracy. 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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