Lights Out

Authors: Diva-Oriane Marty, Malavika Krishnamurthy, Ryan Gess: Electrical and Computer Engineering, Carnegie Mellon University

***Abstract*—Lights Out is a system capable of reducing energy consumption of lights in shared work spaces and labs. It does so by dividing up large work spaces into individually lit work areas and automatically turning lights on and off based on human activity. It is a more advance motion detection automatic light system. Our system uses sound and motion detection to detect human presence. Other affordable automatic light systems rely only on motion detection and fail to stay on in common cases, such as when there is a group of people talking, but not moving.**

***Index Terms*—Energy Consumption, Lighting, Motion Detection, Occupation Sensing, Open Work Space**

1 INTRODUCTION

According to the Commercial Building Energy Consumption Survey, commercial buildings consume 2.5 kWh per square foot [1]. Often open work space and labs don't require the whole room to be lit up. These spaces are broken up into cubicles, desks, or lab benches. When only a specific delimited space(s) is being used, turning on the whole room is a waste of energy. According a Meta-Analysis conducted by the Lawrence Berkeley National Laboratory [2] the average energy saving potential of occupancy detection controlled lighting systems is 24% for Commercial Buildings. Motion detection lights are often used to ensure that only the necessary lights stay on. However, a primary problem with current motion detection lights is that they shut off when people are working and not actively moving around the room triggering the motion detectors. This can often cause the lights to turn off at inappropriate times. The most simple solution is just to keep the lights on for a relatively long period of time, (i.e. 20 minutes), however this can be very wasteful and is not an efficient solution.

Lights Out is a solution that aims to reduce energy consumption due to lights in open work spaces such as labs or open offices. Lights Out is an enhanced automatic lights system that uses motion detection sensors and microphones to only have the lights on in specific occupied section(s). This solution targets classrooms/labs/office spaces as it caters to spaces with predefined and delimited work areas. This solution also is limited to using only motion detection sensors and microphones, which are relatively low cost sensors when compared to alternatives such as thermal cameras. These sensors also collect relatively autonomous data when compared to cameras. Another goal of this product is to provide an inexpensive solution that allows for relative anonymity to be maintained.

2 DESIGN REQUIREMENTS

Our requirements are broken up into several parts, to best fit our use cases, namely: correctness, accuracy, latency, scalability, cost effectiveness, and privacy. Since one of our primary goals is to improve the correctness of a motion detection light system, i.e. more correctly identify human presence, it is imperative that we attain better correctness than current motion detection light systems. Since we are breaking up the room into work areas it is not only necessary to correctly detection presence, but accurately locate which work area(s) people are occupying. In order for our solution to be useful and user friendly, the latency for human presence to be detect or not detected must be reasonable. A goal of our product is to cater to different open work spaces. Each work space has slightly different needs so it is imperative that our product is scalable. To make this solution attractive for these kinds of spaces it must be cost effective, not much more expensive that current motion detection light systems. Lastly, since we are recording human behavior it is important to keep in mind privacy concerns.

A *Correctness*

The goal is to reduce energy consumption by the proportion of unoccupied space in the room (50% of room is occupied = 50% energy consumption). In order to achieve this goal we must ensure a certain level of correctness. Perfect correctness would mean that the lights are only on and remain on when a given area is being occupied. We want to achieve better correctness than what is already attained with simple motion detection lights. For this we must achieve correctness in the simplest case, anytime there is continued noticeable movement. In addition to this basic case, we need to achieve correctness when there is noticeable sound. Noticeable sound would be approximately 60db, which is the average noise level of a conversation. [3] However, it is import to note that in these spaces it is common to have people working at desks, so we want to be able to detect common work noises such as typing. We want to be able to detect these work noises the majority of the time. Hence, for this low movement and low noise case we want at least 50% accuracy. In these work environments it is relatively rare for a person to be completely still and making no noise for extended periods of time. Hence, we acknowledge that we may not always be able to account for the no noise no movement case, but don't feel like it is detrimental for our use case. We are most concerned with cases where lack of correctness causes users to be interrupted from their tasks and have to manually turn back on the lights.

B *Accuracy*
We want to be able to detect individual within a 1 meter radius and turn on the lights around them. A 1meter radius is reasonable for our use test case where each work area is 4meters wide, also based on the placement of the lights in our lab it is a reasonable assumption that this requirement would provide adequate lighting to work. Accuracy is important in order to correctly locate human presence and not turn on unnecessary lights. Correctness and accuracy differ in that correctness is related to when the lights are on and accuracy is related to which lights are on.

C *Latency*
Latency is in regards to how fast the system recognizes that a person has entered an area and turns on the lights. We want to at least maintain the latency of a simple motion detection light system. From our own use cases 2 seconds is a reasonable expectation for localizing and communicating that a person has entered an area, and to turn on the lights accordingly.

D *Scalability*
The solution should be easily adaptable for different room sizes and different number of work areas. The solution should be modular and the sensor setup should be specific to a certain square footage.

E *Cost Effectiveness*
We cannot directly compare the cost of our prototype to that of motion detection light system as we are using low cost LEDs and very simple fixtures to mimic the lighting setup of the lab. However, since our primary additional costs come from the additional sensors and the Raspeberry Pi, we can determine our cost effectiveness by insure that they remain under the a certain threshold. With the cost of microphones being under $7 for our MVP, and potentially cheaper microphones could be used, we find that our additional sensors produce negligible additional cost.

F *Privacy*
In order to ensure privacy we want to keep our data offline. The system should not store raw sensor data, but rather the resulting behavior based on a given type of feedback from the sensors. Feedback from the microphones should not get saved as sound waves, but rather a binary signal, that shows whether or not it is meeting the sound threshold to be equate to potential human presence.

3 ARCHITECTURE OVERVIEW

3.1 Sensor Setup: Guide

The system uses two types of sensors: PIRs (Passive Infrared Sensors), which are standard in motion detection light systems, and microphones. The setup is depended on the shape and size of the room. Figure 1.b shows an example setup of a lab. The following properties must be taken into account.

- No/Minimum overlap between PIRs
  (1m < PIR radius < 6m)
  angle down in order to reduce overlap
- All desk areas are covered by a PIR
- Each desk area is covered by a microphone

Each work area is associated to a minimum of 1 PIR and 1 microphone, more if the size/ formation of the space requires it. Each sensor communicates back to the Raspberry Pi base station through a Node MCU micro controller, which sends data over WiFi. In locations such as open offices and labs, plugs are available so we are generally not concerned with finding a power source or battery life.

3.2 Sensor Setup: Lab Test Case

The particular lab we are using for our test case has 4 general work areas that cover the two sides of the room. The room is 8x4 meters. Each work area is about about 4meters long, and < 2meters wide. The width is a not a precise measurement as people move around when in the work area, i.e. chairs can be pushed further out. In order to ensure the work areas are covered, we positioned 3 PIR sensors per side of the room. Each work area has 1 PIR sensor that is unique to them and another one that is shared with its neighboring work area(s). We want to ensure that we cover the 4meter diameter along the sides, without interacting with the PIR sensors on the opposite side. In order to do so we attached our PIR sensors above the desks at a 60degree angle from the horizon. Our PIR's sensing radius is approximately 1.5 meters. We also ensure that there is one microphone positioned in the middle of each work area. Each work area has its own LED strip positioned directly above it. See figure b for a birds eye view of our lab test case.

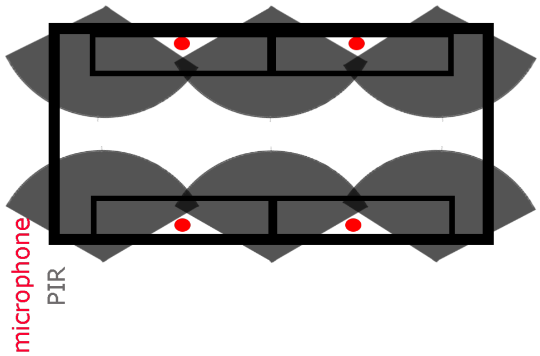

Figure 1: Sensor Setup in Lab Test Case

3.3 Sensor Data Translation

The Raspberry Pi recognizes what work area the sensor is related to and what kind of sensor it is. Our software estimates the likelihood that a person is in the area and turns the light on, keeps the light on, or turns the light off in the work area. The system is also controllable through a web application, which allows the user to overwrite the program if they have a particular need to modify the behavior of the lights such that they do not follow human activity.

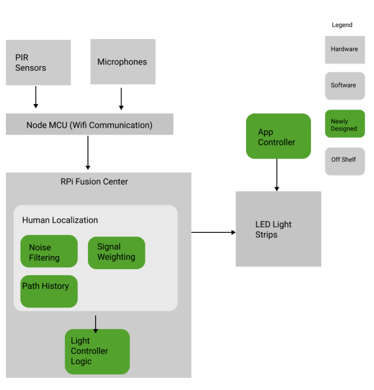

Figure 2: System picture: Overall system

3.4 Work Area

A work area is defined as a desk or lab bench and its surrounding typical use space. When defining a work area, we try to ensure that its area does not overlap with another work area. However, in the case were sensor data is unclear, the light in multiple work areas could be turned on. The algorithm detects human presence in a given work areas as an independent process. Previous work shows that detecting a person's path with PIR sensors become highly unreliable once there are 4 people in a room [5]. In addition, in our particular case we are not concerned with how many people are at each work area, nor do we care exactly how they moved around the room. We are just concerned with whether or not at least one person is in a given work space. Additionally, human presence in a given work space is often independent from human presence in another work space. Only case were path tracking could be potentially useful is when a person moves from one space to another, or leaves all together and we can guarantee that no other people entered the space as they were leaving. With the types of sensors and the data we are collecting from them, we cannot tell if one or more people are triggering them. Hence, path tracking is not beneficial.

3.5 Web Application

Sometimes the needs of a work area may vary from the default system, so the web application allows users to modify the lighting system based on their needs.

- Low Sensitive / High Sensitive Mode
- Force on by work area
- Timer turn on / off

4 DESIGN TRADE STUDIES

A few options were considered for the design of our project.

A *Communication - Wifi*
For communication between sensors and the Raspberry Pi computation hub, three frameworks were considered: bluetooth, wifi and wires. Because of their ease of setup and all of our application areas will be rooms with a wifi network, it was decided to use Node MCU D1 mini's equipped with an ESP8266 microcontroller which can connect and send messages over a wifi network. While wires are also simple to setup and cheap, their usability is not great as long wires typically get tangled up and it is best to prevent our users from dealing with this. While we can also accomplish our wireless requirement with Bluetooth modules, wifi is more cost effective and the simplicity of setup is comparable. It is important to note however, there are some current complications connecting to CMU's wifi network in the lab so this design may need to be adjusted.

B *Computation - Raspberry Pi*
The Raspberry Pi was chosen as the computation hub because of its CPU specifications and its compatibility with our wifi communication modules. Some NVDIA Jetson models were also considered however our algorithm does not require a GPU, the 4 core Raspberry Pi will suffice.

C *Infrared Sensors*
Passive Infared Sensors (PIR) were chosen as they are the existing technology and the goal of this project is to improve the existing technology. The number of sensors in the room is being increase to allow a greater

coverage of the room and these sensors are cheap so this fits under the design requirements. While a video camera could meet the accuracy requirements of the system in terms of localizing people, video cameras are more expensive and added hardware complexity. PIR is a simple hardware and allows a novel algorithm to be developed for human localization.

D *Microphones*
Microphones were added as a supplement to PIR sensors. They are also cost effective which again is why they were chosen over a video camera. These were added to increase functionality of the system in addition to the accuracy. For the improved system, it is required to localize individuals in a low movement environment. It is expected in these situations there may be some sound (conversation, typing at a desk) that even when individuals are very still, thier relative location can still be determined. wifi communication / raspberry pi hub / PIR and microphone vs video

E *Lights - LED Strips*
LED Light strips were chosen to simulate classroom/lab or conference room lights. These allow for prototyping and customization of different room configurations without being constrained to existing classrooms and modifying the existing circuitry or dealing with high amperage.

F *Power*
Since the use case is a classroom/lab or conference room there is typically access to wall outlets throughout the room so it was decided to plug components into the wall instead of using some other power source such as a battery.

G *Human Localization*
Various localization techniques were iterated, including multiple human tracking using PIR, audio beamforming, and the chosen novel solution which combines principles from each of the former techniques and in addition, includes principles from statistics and sensor fusion.

Audio Beamforming
Beamforming is a technique that uses filtering of microphone signals and constructively combining them together in order to determine the spatial location. Often, delay of signal input is used as an influential feature in determining location [4]. The microphones used in this project are not sensitive enough to detect delay so rather we plan to rely on signal amplitude. Microphone arrays can be purchased for beamforming and localization however these are much more expensive than setting up our own around the room. We expect for our case we can localize within our accuracy requirements by using amplitude and a threshold to distinguish between humans in various locations of the room.

Human Tracking using PIR
This approach uses many PIR sensors to track paths of multiple humans in a room. The algorithm relies on two main processing steps and location estimation for path estimation. It also maintains path history. The algorithm performed very well for tracking one persons path in a room. Unfortunately, as the number of individuals increases in the room, the accuracy greatly decreased [5]. Therefore, it was decided to not rely fully on path tracking and this technique to localize in a room as we would like to scale to multiple people in the room.

Lights Out
Our approach combines a few principles from microphone beamforming, path tracking as well as signal weighting to localize humans in the room. This is algorithmically complex and requires multiple threads however it can be performed on a Raspberry Pi. In addition, we are not constrained to determining location by path, however we can use the last location detected as a signal and weight this in our combination of signals.

5 SYSTEM DESCRIPTION

5.1 Sensor and Software Interface: General Setup

Based on our preliminary testing, false positives for PIRs are relatively rare, while false negative are more common. False positives are due to detecting movement outside of the intended area, while false negatives are due to being outside of the expected desk space, or having too little movements. Standalone microphone feedback is less reliable, primarily because it is hard to distinguish between soft noises near the mic and stronger noises far away from the mic. PIR sensors provide a straight forward digital feedback. As previously mentioned in the part 3.4, for our use case determining human presence per work area is the best fitted solution. Due to the independent nature of the work areas' states, our design has one thread per work area. There is a queue that takes in the sensor data, and sends it to the thread(s) (work area(s)) concerned.

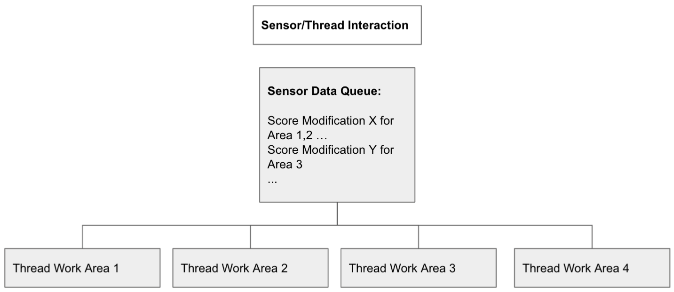

Figure 3: Sensor/Thread Interaction

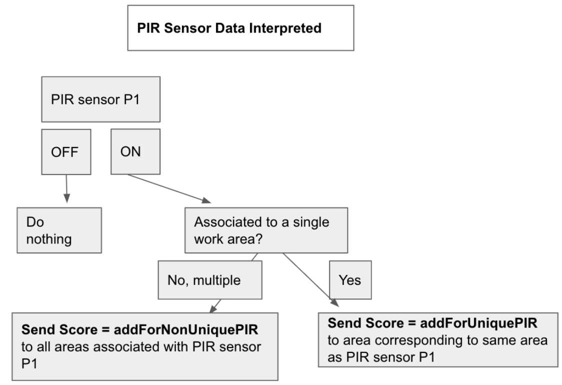

Figure 4: PIR Sensor Detection to Score Translation

5.2 Constants

A maxScore = 100 (the max score that a client can have)

B thresholdOnOff (the score at which the light switches between on and off)

C addForUniquePIR (increase score by this value when a PIR that is specific to a work area is set off)

D addForNonUniquePIR(increase score by this value when a PIR that is shared between work areas is set off)

E soundDBThreshold (level in dB that constitutes the sound as significant enough)

F addForSound (increase score by this value when a microphone, always specific to a work area, is above soundDbThreshold)

G maxTimeWithoutActivity (the time in seconds that can go by before the lights turn off)

H removeByTime = maxTimeWithoutActivity/(maxScore-thresholdOnOff) (decrease score by this value every second)

5.3 PIR Sensor Detection

A PIR sensor is either on or off. If it is on, then we determine which work areas it is associated with. In the case of a unique area being detected with a PIR, the sensor tells a specific area to bring up their score by addForUniquePIR. If the sensor is associated to multiple areas, we are not sure exactly which area the person is located in. In the case of multiples areas being detected with a PIR, the sensor tells all those areas to bring up their scores by addForNonUniquePIR. $addForNonUniquePIR < addForUniquePIR$ as we are less certain of the location of the person.

5.4 Microphone Sensor Detection

A microphone sensor is not used to detect initial presence in an area. It is used to determine if a person is still there if the light is already on but there is minimal movement. Microphones are always unique to a work area. The microphone sensor considers sound input that is $\geq soundDBThreshold$. When entering a work area, you are sure to set a PIR sensor on. We only consider microphone sensor inputs in the case were the work area's score is already $\geq thresholdOnOff$. This is in order to avoid the case where there is a loud noise in one work area that is detected by the microphones in other non-occupied work areas. We are using this coupling of information to minimize expected false positives from microphone sensors. For each feedback from the microphone sensors that meet these criterion we increment the score of the associated work area by addForSound, unless the score is already at the maxScore.

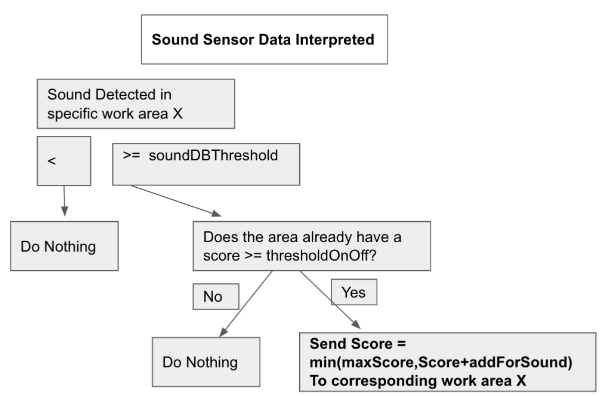

Figure 5: Microphone Sensor Detection to Score Translation

5.5 Work Area Thread

Each work area is associated to a thread that handles the incrementation and decrementation of its score, and the consequential turning on or off of its light(s). First we check if a score modification is received from the sensor data queue. If it is we do the appropriate incrementation of the score. Simulatenously if the score > 0 every second we decrement the score by removeByTime. After these modification we check that the score is still above the threshodlOnOff, if it is we turn on or keep the light(s) on, or turn off or keep off the lights(s).

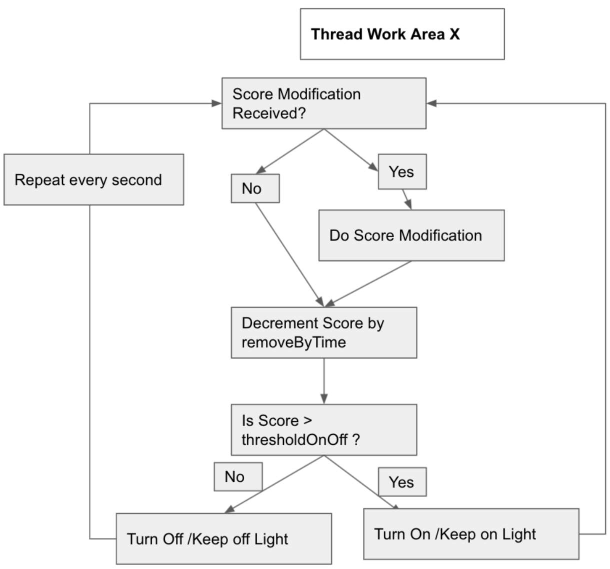

Figure 6: Functionality of a Thread handling a Given Work Area

6 TEST & VALIDATION

Testing was conducted in order to evaluate the performance of the PIR sensors in order to revise our design. The objective is to maximize the coverage of the room while minimizing overlap, and in order to so we need to determine the optimal range and angle of the motion detecting sensors. This allowed us to reevaluate our design specification and sensor logic. Our team ultimately decided that it would be optimal to place sensors on a shelf above each work bench at a downward angle of 60 degrees with the range of each sensor having a radius of 1 meter. We were unable to test the microphones as they were not compatible with the Raspberry Pi and were intended for printed circuit boards.

6.1 Results for Angling the PIR sensors

We initially intended to set the PIR sensors directly flat on top of the shelf, but when testing this configuration, we were getting many false positive measurements. Although the range was set to the minimum setting, the sensor would register movement coming from across the room from the opposite bench even when there were no individuals in the vicinity of its own designated station. We then angled the sensor downwards so that the field of view would not reach all the way across the room and would intersect with the floor halfway through the room. Design limitations include only having a 120 degree field of view from the sensor and not being able to decrease the range to less than a radius of 1 meter.

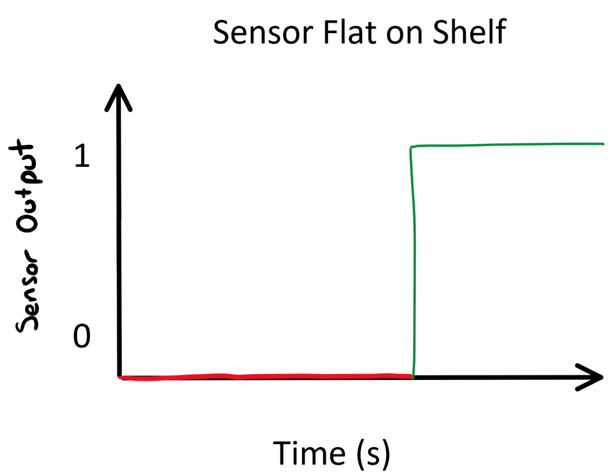

Figure 7: Sensor output when placed flat on shelf

As seen above in figure 7, when placed flatly on the shelf, the sensor provides false positives when individuals are seated across the room. When the sensor output is 0, the state of movement in the room is a below on the left in figure 8. It is evident that there are no individuals in the room, so this is the result we expect. However, when there are individuals (and movement) in the adjacent work station, the sensor output is 1 when we only want to sensor to register movements in its designated zone.

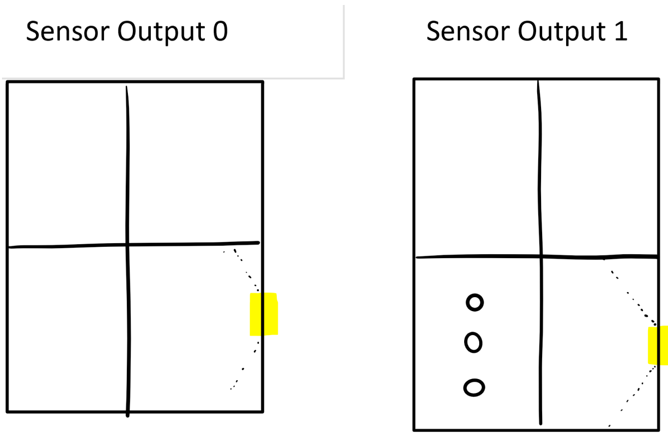

Figure 8: Room diagrams when sensor output from above trial is 0 (on left) and when sensor output is 1 (on right)

Using the same configuration of the room in figure 8, we ran the trial again with the PIR sensor angled down 60 degrees so that the opposite side of the room was not in its field of view. This was the sensor output for the given conditions, which matched our prediction.

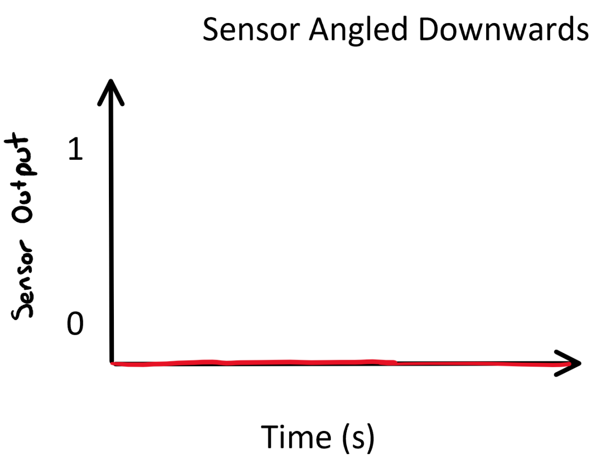

Figure 9: Sensor output when device is angled downwards by 60 degrees and there is movement in the adjacent work station

6.2 Results for Determining Range of PIR Sensors

After continued testing with angling the PIR sensors, our team determined that a range of 1 meter for each sensor would be most ideal for maximizing the coverage and minimizing the overlap of the motion detecting sensors. While we initially ran trials with the range being 2 meters (so that we would only need to designate 1 sensor per work station), there were apparent blind spots in the field of view. We then adjusted the range to be 1 meter and ran tests again, providing the sensor output as specified below by figure 10.

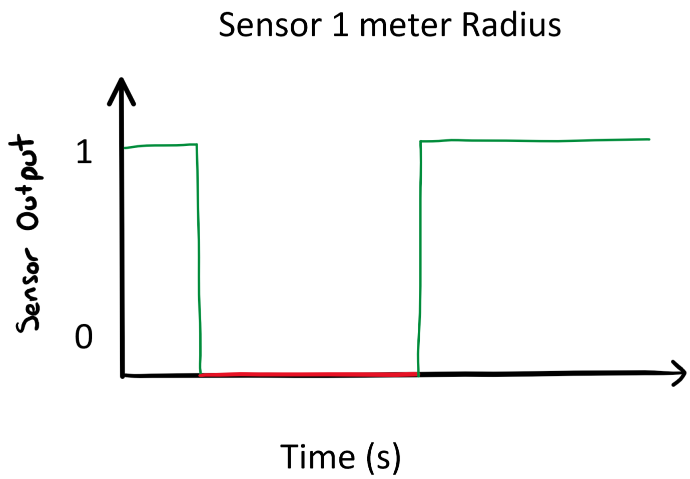

Figure 10: Sensor output when device is angled downwards by 60 degrees and range is adjusted to be 1 meter

The sensor output seen above in figure 10 follows with the room layout and movement as seen below. The entire square represents one specific work zone.

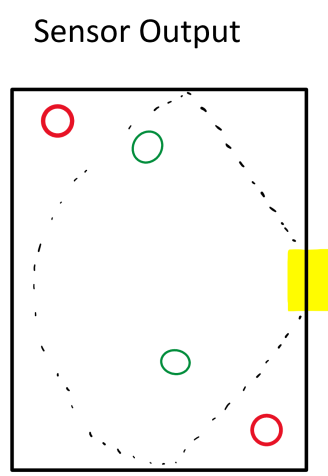

Figure 11: Room layout for results in figure 10

The results we obtained in these test runs match our predictions and helped revise our design specification and layout for the use case area.

7 PROJECT MANAGEMENT

7.1 Schedule

A full Gantt chart of our team's schedule is available at the end of the design review document on page 12. From the proposal review until now, we have had to make changes to the schedule by allotting more time for sensor testing and waiting to receive all the sensors. While we have received the microphones, we placed another order for microphones that are compatible with out system components last week. We accordingly adjusted our schedule to reflect this change in the timeline. However, we still have a full 2 weeks at the end of the semester to fully integrate and test our system.

7.2 Team Member Responsibilities

Team member responsibilities have not dramatically changed since the proposal presentation. Ryan and Diva are both still in charge of testing and integrating the microphone and PIR sensors. Ryan and Diva both set up the Raspberry Pi and circuit board to test the PIR sensor configuration. All team members were involved with the logic of the sensors and how the weights would be assigned to each measurement to produce one final output for where the individual is located in the room. Malavika is still in charge of developing the website for the breadboard and is deploying a basic version of the website using AWS credits. She is currently working on using Node.js and websockets to allow the buttons to interface with the GPIO pins. During the last two weeks of the semester, all team members are responsible for testing the final project.

7.3 Budget

The budget is as seen in Table 1 on the page 10. We did not account for the extra set of microphones that needed to be ordered.

7.4 AWC Credit Usage

We plan on using our allotted AWS credits to host our website which will control the GPIO pins of the Raspberry Pi to override our system logic at the user's discretion. We are grateful for these credits so that we may expand upon and develop pur project to a further extent and design new features to continually iterate upon our ideas. We would like to thank Amazon for enabling us to bring our ideas to life!

7.5 Risk Management

There were several potential risks that our group had to account for and mitigate throughout the past 2 months. From the standpoint of design, we needed to establish a method for determining whether there were individuals at each work station and accordingly decide to turn on the corresponding light. We redesigned our logic with the help of our TA, Edwared Lucero, as well as our Professor Byron Yu. As for scheduling risks, we incorporated buffer weeks into our Gantt chart to account for unforeseen delays. This was need when we realized our microphones were not compatible with our Raspberry Pi. Since our budget is currently onle at about 25 percent of our maximum allotted budget, we are not too worried about potential risks from a financial outlook. When ordering new microphones, we did not want to wait the full two weeks for our order to arrive, so while our team placed the order through the ECE lab to receive the parts, we all bought one unit from Amazon through our personal spending so that it would arrive earlier, allowing us to get started on testing before we desing and integrate the entire system.

8 ETHICAL ISSUES

Our primary ethical issue is privacy, which we addressed in the design requirements section. Privacy is an ever present issue when dealing with IoT devices. However, this product is catered towards work environments so privacy issues could be seen as less sever than if this were a Home IoT device. We primarily address this issue by not collecting any identifiable data on the people using spaces in which our product is installed. We do acknowledge however that the time at which the lights are turned on and off could be used to keep track of general patterns that could be associated to all people that often use the space. We do keep the system offline, so those that could access the data, would probably also be able to physically see if people are in the room or not. We don't believe our system significantly increases privacy concerns for people using a space.

References

[1] Independent Statistics Analysis U.S. Energy Information Administration. "Table E6. Electricity consumption intensities (kWh) by end use, 2012". In: *COMMERCIAL BUILDINGS ENERGY CONSUMPTION SURVEY (CBECS)* (May 2016).

[2] Karina Garbesi Alison Williams Barbara Atkinson and Francis Rubinstein. "A Meta-Analysis of Energy Savings from Lighting Controls in Commercial Buildings". In: *Energy Analysis Department Lawrence Berkeley National Laboratory* (Sept. 2011), p. 13.

[3] Centers for Disease Control and Prevention. *What Noises Cause Hearing Loss?* URL: `https://www.cdc.gov/nceh/hearing_loss/what_noises_cause_hearing_loss.html`.

[4] Abdulqadir Alaqeeli Amiri Hamid Hidri Adel Meddeb Souad. "Beamforming Techniques for Multichannel Audio Signal Separation". In: ().

[5] Yuki Kasama Toshiaki Miyazaki. "Multiple Human Tracking Using Binary Infrared Sensors". In: *Sensors (Basel, Switzerland)* (June 2015).

Table 1: Bill of materials

Description	Model #	Manufacturer	Quantity	Cost @	Total
PIR Sensor	1528-1991	AdaFruit	10	$9.95	$99.50
Microphone	SPH0641LU4H-1	Knowles	8	$2.14	$17.12
Raspberry Pi	1690-1028	Raspberry Pi	1	$25.00 $Free	
LED Lights		KWZM	2	$11.99	$23.98
Node MCU	ESP8266	AITRIP	6	$2.66	$15.99
Microphone	SPW2430	AdaFruit	1	$8.58	$8.58
					$165.17

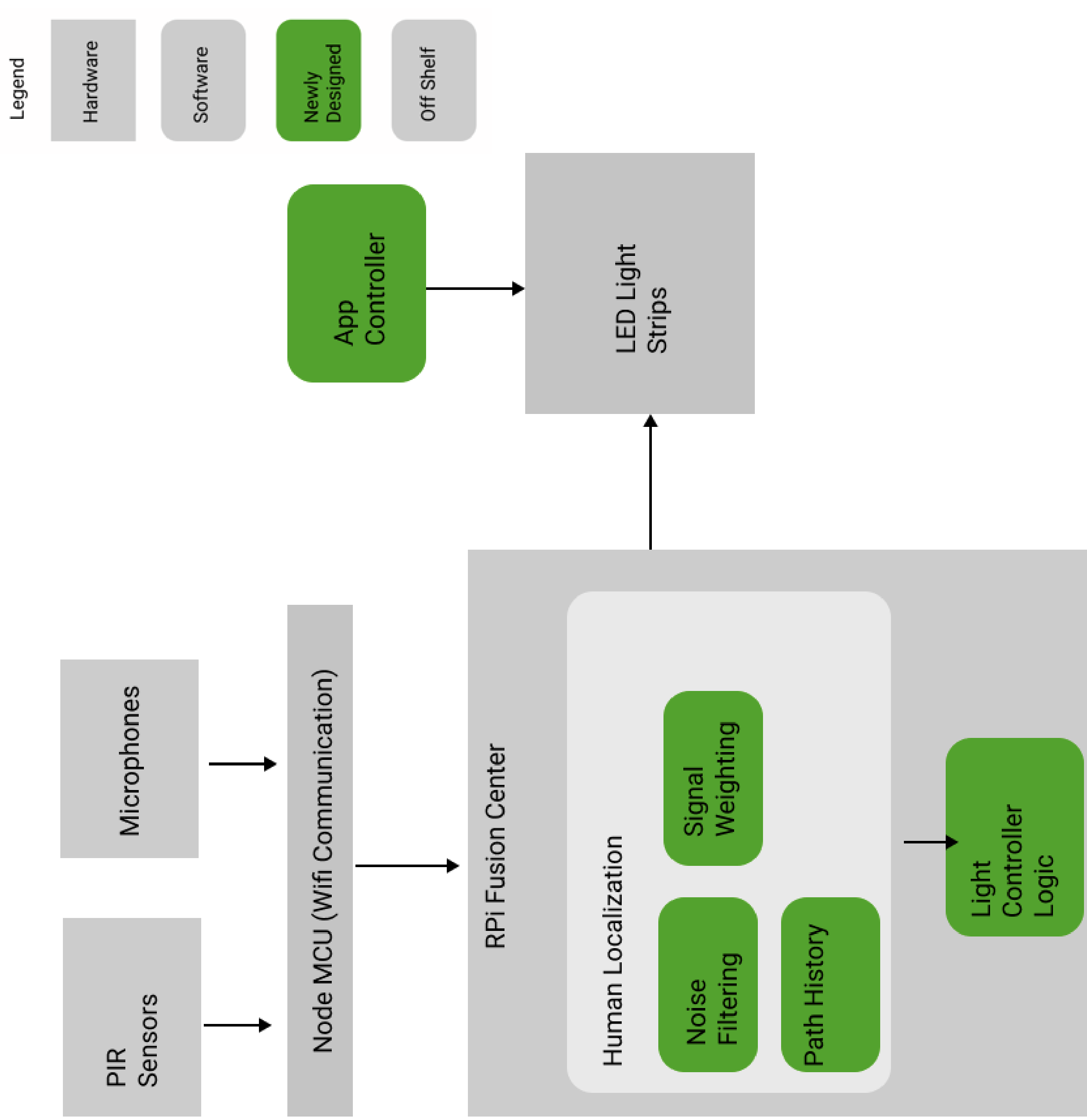

Figure 12: A full-page version of the same system block diagram as depicted earlier.

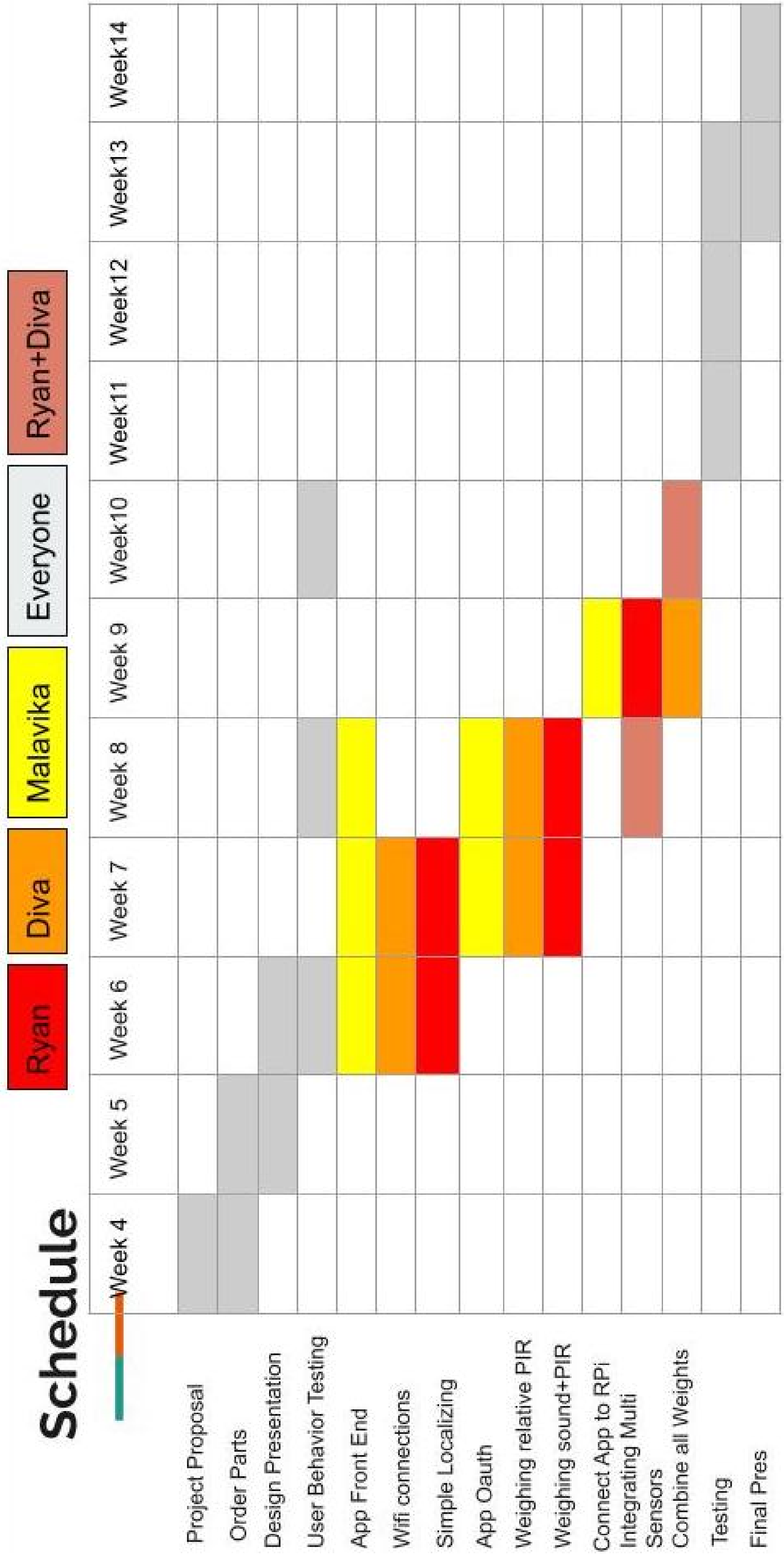

Figure 13: Gantt Chart