

# **Developing a robust system for occupancy detection in the household**

Ash Tyndall

*This report is submitted as partial fulfilment  
of the requirements for the Honours Programme of the  
School of Computer Science and Software Engineering,  
The University of Western Australia,  
2015*

# Abstract

This is the abstract.

**Keywords:** keyword, keyword

**CR Categories:** category, category



© 2014–15 Ashley Ben Tyndall

This document is released under a Creative Commons Attribution-ShareAlike 4.0 International License. A copy of this license can be found at <http://creativecommons.org/licenses/by-sa/4.0/>.

A digital copy of this document and supporting files can be found at <http://github.com/atyndall/honours>.

The following text can be used to satisfy attribution requirements:

“This work is based on the honours research project of Ash Tyndall, developed with the help of the School of Computer Science and Software Engineering at The University of Western Australia. A copy of this project can be found at <http://github.com/atyndall/honours>.”

Code and code excerpts included in this document are instead released under the GNU General Public License v3, and can be found in their entirety at <https://github.com/atyndall/thing>.

# Acknowledgements

These are the acknowledgements.

# Contents

<b>Abstract</b>	<b>ii</b>
<b>Acknowledgements</b>	<b>iv</b>
<b>1 Introduction</b>	<b>1</b>
<b>2 Literature Review</b>	<b>3</b>
2.1 Intrinsic traits . . . . .	4
2.1.1 Static traits . . . . .	4
2.1.2 Dynamic traits . . . . .	6
2.2 Extrinsic traits . . . . .	6
2.2.1 Instrumented traits . . . . .	6
2.2.2 Correlative traits . . . . .	8
2.3 Analysis . . . . .	8
2.4 Thermal sensors . . . . .	10
2.5 Research Gap . . . . .	11
2.6 Conclusion . . . . .	12
<b>3 Prototype Design</b>	<b>13</b>
3.1 Hardware . . . . .	14
3.2 Software . . . . .	16
3.3 Sensor Properties . . . . .	18
3.3.1 Bias . . . . .	20
3.3.2 Noise . . . . .	22
3.3.3 Sensitivity . . . . .	22
<b>4 Methods</b>	<b>26</b>
4.1 Classifier Experiment Set 1 Setup . . . . .	26

<b>5</b>	<b>Results</b>	<b>28</b>
5.1	Classifier Experiment Set 1 . . . . .	28
<b>6</b>	<b>Discussion and Conclusion</b>	<b>30</b>
6.1	Future Directions . . . . .	30
<b>A</b>	<b>Original Honours Proposal</b>	<b>31</b>
A.1	Background . . . . .	31
A.2	Aim . . . . .	32
A.3	Method . . . . .	33
A.3.1	Hardware . . . . .	33
A.3.2	Classification . . . . .	33
A.3.3	Robustness / API . . . . .	34
A.4	Timeline . . . . .	34
A.5	Software and Hardware Requirements . . . . .	35
A.6	Proposal References . . . . .	36
<b>B</b>	<b>Ideal System Architecture</b>	<b>38</b>
B.1	Protocols . . . . .	38
B.2	Devices . . . . .	40
<b>C</b>	<b>Code Listings</b>	<b>42</b>
C.1	ThingLib . . . . .	42
C.1.1	cam.py . . . . .	42
C.1.2	pxdisplay.py . . . . .	60
C.1.3	features.py . . . . .	63
C.2	Arduino Sketch . . . . .	70
<b>D</b>	<b>Full Results</b>	<b>92</b>
D.1	Classifier Experiment Set 1 . . . . .	92
D.1.1	Nominal Results . . . . .	92
D.1.1.1	Multilayer Perceptron . . . . .	92

D.1.1.2	IBk . . . . .	95
D.1.1.3	Naive Bayes . . . . .	97
D.1.1.4	SMO . . . . .	99
D.1.1.5	J48 . . . . .	102
D.1.2	Numeric Results . . . . .	104
D.1.2.1	Multilayer Perceptron . . . . .	104
D.1.2.2	IBk . . . . .	106
D.1.2.3	Linear Regression . . . . .	107
D.1.2.4	Decision Stump . . . . .	108
<b>E</b>	<b>Physical Form</b>	<b>109</b>
	<b>Bibliography</b>	<b>111</b>

# List of Tables

2.1	Comparison of different sensors and project requirements . . . . .	9
3.1	Hardware tiers . . . . .	14
3.2	Mean and standard deviations for each pixel at rest . . . . .	21
5.1	Classifier Experiment Set 1 Nominal Results . . . . .	28
5.2	Classifier Experiment Set 1 Numeric Results . . . . .	29
B.1	Proposed protocol stack . . . . .	38



# List of Figures

2.1	Taxonomy of occupancy sensors . . . . .	4
3.1	MLX90620, PIR and Arduino integration circuit . . . . .	15
3.2	Prototype system architecture . . . . .	17
3.3	Initialisation sequence and thermal packet . . . . .	18
3.4	Experiment setup to determine sensor properties . . . . .	19
3.5	Comparison of noise levels at the Melexis MLX90620 ( <i>Melexis</i> )' various sampling speeds . . . . .	23
3.6	Block diagram for the <i>Melexis</i> taken from datasheet [20] . . . . .	24
3.7	Different <i>Melexis</i> pixel temperature values as hot object moves across row . . . . .	24
3.8	Variation in temperature detected for hot object at 1Hz sampling ration . . . . .	25
4.1	Classifier Experiment Set 1 Setup . . . . .	27
B.1	Proposed system architecture . . . . .	40
E.1	Prototype in action . . . . .	109
E.2	Prototype Physical Form . . . . .	110

## CHAPTER 1

# Introduction

The proportion of elderly and mobility-impaired people is predicted to grow dramatically over the next century, leaving a large proportion of the population unable to care for themselves, and also reducing the number of human carers available [8]. With this issue looming, investments are being made in technologies that can provide the support these groups need to live independent of human assistance.

With recent advance in low cost embedded computing, such as the Arduino and Raspberry Pi, the ability to provide a set of interconnected sensors, actuators and interfaces to enable a low-cost ‘smart home for the disabled’ that takes advantage of the Internet of Things (IoT) is becoming increasingly achievable.

Sensing techniques to determine occupancy, the detection of the presence and number of people in an area, are of particular use to the elderly and disabled. Detection can be used to inform various devices that change state depending on the user’s location, including the better regulation energy hungry devices to help reduce financial burden. Household climate control, which in some regions of Australia accounts for up to 40% of energy usage [5] is one area in which occupancy detection can reduce costs, as efficiency can be increased with annual energy savings of up to 25% found in some cases [7].

While many of the above solutions achieve excellent accuracies, in many cases they suffer from problems of installation logistics, difficult assembly, assumptions on user’s technology ownership and component cost. In a smart home for the disabled, accuracy is important, but accessibility is paramount.

The goal of this research project is to devise an occupancy detection system that forms part of a larger ‘smart home for the disabled’, and integrates into the IoT, that meets the following qualitative accessibility criteria;

- *Low Cost*: The set of components required should aim to minimise cost, as these devices are intended to be deployed in situations where the serviced user may be financially restricted.

- *Non-Invasive*: The sensors used in the system should gather as little information as necessary to achieve the detection goal; there are privacy concerns with the use of high-definition sensors.
- *Energy Efficient*: The system may be placed in a location where there is no access to mains power (e.g. roof), and the retrofitting of appropriate power can be difficult; the ability to survive for long periods on only battery power is advantageous.
- *Reliable*: The system should be able to operate without user intervention or frequent maintenance, and should be able to perform its occupancy detection goal with a high degree of accuracy.

To create a picture of what options there are in this sensing area, a literature review of the available sensor types and wireless sensor architectures is needed. From this list, proposed solutions will be compared against the aforementioned accessibility criteria to determine their suitability.

## CHAPTER 2

# Literature Review

To achieve the accessibility criteria, a wide variety of sensing approaches must be considered. It can be difficult to approach the board variety of sensor types in the field, so a structure must be developed through which to evaluate them. Teixeira, Dublon and Savvides [24] propose a 5-element human-sensing criteria which provides a structure through which we may define the broad quantitative requirements of different sensors.

These quantitative requirements can be used to exclude sensing options that clearly cannot meet the requirements before the more specific qualitative accessibility criteria will be considered for those remaining sensors.

The quantitative criteria elements are;

1. *Presence*: Is there any occupant present in the sensed area?
2. *Count*: How many occupants are there in the sensed area?
3. *Location*: Where are the occupants in the sensed area?
4. *Track*: Where do the occupants move in the sensed area? (local identification)
5. *Identity*: Who are the occupants in the sensed area? (global identification)

At a fundamental level, this research project requires a sensor system that provides both Presence and Count information. To assist with the reduction of privacy concerns, excluding systems that permit Identity will generally result in a less invasive system also. The presence of Location or Track are irrelevant to our project's goals, but overall, minimising these elements should in most cases help to maximise the energy efficiency of the system also.

Teixeira, Dublon and Savvides [24] also propose a measurable occupancy sensor taxonomy (see Figure 2.1 on the following page), which categorises different

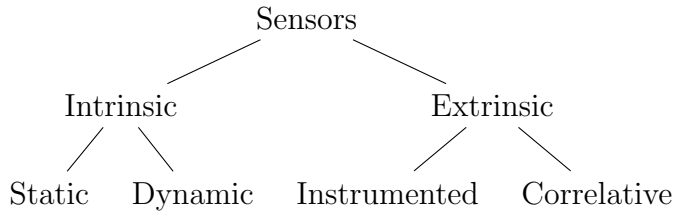


Figure 2.1: Taxonomy of occupancy sensors

sensing systems in terms of what information they use as a proxy for human-sensing. We use this taxonomy here as a structure through which we group and discuss different sensor types.

## 2.1 Intrinsic traits

Intrinsic traits are those which can be sensed that are a direct property of being a human occupant. Intrinsic traits are particularly useful, as in many situations they are guaranteed to be present if an occupant is present. However, they do have varying degrees of detectability and differentiation between occupants. Two main subcategories of these sensor types are static and dynamic traits.

### 2.1.1 Static traits

Static traits are physiologically derived, and are present with most (living) occupants. One key static trait that can be used for occupant sensing is that of thermal emissions. All human occupants emit distinctive thermal radiation in both resting and active states. The heat signatures of these emissions could potentially be measured with some apparatus, counted, and used to provide Presence and Count information to a sensor system, without providing Identity information.

Beltran, Erickson and Cerpa [7] propose Thermosense, a system that uses a type of thermal sensor known as an Infrared Array Sensor (IAR). This sensor is much like a camera, in that it has a field of view which is divided into “pixels”; in this case an  $8 \times 8$  grid of detected temperatures. This sensor is mounted on an embedded device on the ceiling, along with a Passive Infrared Sensor (PIR), and uses a variety of classification algorithms to detect human heat signatures within the raw thermal and motion data it collects. Thermosense achieves Root Mean Squared Error  $\approx 0.35$  persons, meaning the standard deviation between Thermosense’s occupancy predictions and the actual occupancy number was  $\approx$

0.35.

Another static trait is that of CO<sub>2</sub> emissions, which, like thermal emissions, are emitted by human occupants in both resting and active states. By measuring the buildup of CO<sub>2</sub> within a given area, one can use a variety of mathematical models of human CO<sub>2</sub> production to determine the likely number of occupants present. Hailemariam et al. [14] trialled this as part of a sensor fusion within the context of an office environment, achieving a  $\approx 94\%$  accuracy. Such a sensing system could provide both the Presence and Count information, and exclude the Identity information as required. However, a CO<sub>2</sub> based detection mechanism has serious drawbacks, discussed by Fisk, Faulkner and Sullivan [10]: The CO<sub>2</sub> feedback mechanism is very slow, taking hours of continuous occupancy to correctly identify the presence of people. In a residential environment, occupants are more likely to be moving between rooms than an office, so the system may have a more difficult time detecting in that situation. Similarly, such systems can be interfered with by other elements that control the CO<sub>2</sub> buildup in a space, like air conditioners, open windows, etc. This is also much more of a concern in a residential environment compared to the studied office space, as the average residence can have numerous such confounding factors that cannot easily be controlled for.

Visual identification can be, achieved through the use of video or still-image cameras and advanced image processing algorithms. Video can be used in occupancy detection in several different ways, achieving different levels of accuracy and requiring different configurations. The first use of video, POEM, proposed by Erickson, Achleitner and Cerpa [9] is the use of video as a “optical turnstile”; the video system detects potential occupants and the direction they are moving in at each entrance and exit to an area, and uses that information to extrapolate the number of occupants within the turnstiled area; this system has up to a 94% accuracy. However, the main issue with such a system applied to a residential environment is the system assumes that there will be wide enough “turnstile areas”, corridors of a fairly large area that connect different sections of a building, to use as detection zones. While such corridors exist in office environments, they are less likely to exist in residential ones.

Another video sensor system is proposed by Serrano-Cuerda et al. [22], that uses ceiling-based cameras and advanced image processing algorithms to count the number of people in the captured area. This system achieves a specificity of  $TP/(TP + FP) \approx 97\%$  and a sensitivity  $TP/(TP + FN) \approx 96\%$  (TP = true positives, FP = false positives, FN = false negatives). Such a system could be successfully applied to the residential environment, as both it and the “optical turnstile” model provide Presence and Count information. However, these

systems also allow Identity to be determined, and thus are perceived as privacy-invasive. This perception leads to adoption and acceptance issues, which work against the ideal system’s goals.

### 2.1.2 Dynamic traits

Dynamic traits are usually products of human occupant activity, and thus can generally only be detected when a human occupant is physically active or in motion.

Ultrasonic systems, such as Doorjamb proposed by Hnat et al. [15], use clusters of such sensors above doorframes to detect the height and direction of potential occupants travelling between rooms. This acts as a turnstile based system, much like POEM [9], but augments this with an understanding of the model of the building to error correct for invalid and impossible movements brought about from sensing errors. This system provides an overall room-level tracking accuracy of 90%, however to achieve this accuracy, potential occupants are intended to be tracked using their heights, which has privacy implications. The system can also suffer from problems with error propagation, as there are possibilities of “phantom” occupants entering a room due to sensing errors.

Solely PIR based systems, like those used by Hailemariam et al. [14], involve the motion of the sensor being averaged over several different time intervals, and fed into a decision tree classifier. This PIR system alone produced a  $\approx 98\%$  accuracy. However, such a system, due to only motion detection capabilities, can only provide Presence information, and is unable to provide Count information, nor detect motionless occupants.

## 2.2 Extrinsic traits

Extrinsic traits are those which are actually other environmental changes that are caused by or correlated with human occupant presence. These traits generally present a less accurate picture, or require the sensed occupants to be in some way “tagged”, but they are generally also easier to sense in of themselves. The sensors in this category have been divided into two subcategories.

### 2.2.1 Instrumented traits

One extrinsic trait category is instrumented approaches; these require that detectable occupants carry with them some device that is detected as a proxy for

the occupant themselves.

The most obvious of these approaches is a specially designed device. Li et al. [19] use RFID tags placed on building occupant’s persons and a set of transmitters to triangulate the tags and place them within different thermal zones for the use of the HVAC system. For stationary occupants, there was a detection accuracy of  $\approx 88\%$ , and for occupants who were mobile, the accuracy was  $\approx 62\%$ . Such a system could be re-purposed for the residence, however, these systems raise issues in a residential environment as it requires occupants to be constantly carrying their sensors, which is less likely in such an environment. Additionally, the accuracy for this system is not necessarily high enough for a residential environment, where much smaller rooms are used.

To make extrinsic detection more reliable, Li, Calis and Becerik-Gerber [16] leverage a common consumer device; wifi enabled smart phones. They propose the *homeset* algorithm, which uses the phones to scan the visible wifi networks, and from that information estimate if the occupants are at home or out and about by “triangulating” their position from the visible wifi networks. This solution does not provide the fine-grained Presence data that we need, as it is only able to triangulate the phone’s position very roughly with the wireless network detection information.

Balaji et al. [6] also leverage smart phones to determine occupancy, but in a more broad enterprise environment: Wireless association logs are analysed to determine which access points in a building a given occupant is connected to. If this access point falls within the radio range of their designated “personal space”, they are considered to be occupying that personal space. This technique cannot be applied to a residential environment, as there are usually not multiple wireless hotspots.

Finally, Gupta, Intille and Larson [13] use specifically the GPS functions of the smartphone to perform optimisation on heating and cooling systems by calculating the “travel-to-home” time of occupants at all times and ensuring at every distance the house is minimally heated such that if the potential occupant were to travel home, the house would be at the correct temperature when they arrived. While this system does achieve similar potential air-conditioning energy savings, it is not room-level modular, and also presupposes an occupant whose primary energy costs are from incorrect heating when away from home, which isn’t necessarily the case for this demographic.



### 2.2.2 Correlative traits

The second of these subcategories are correlative approaches. These approaches analyse data that is correlated with human occupant activity, but does not require a specific device to be present on each occupant that is tracked with the system.

The primary approach in this area is work done by Kleiminger et al. [17], which attempts to measure electricity consumption and use such data to determine Presence. Electricity data was measured at two different levels of granularity; the whole house level with a smart meter, and the consumption of specific appliances through smart plugs. This data was then processed by a variety of classifiers to achieve a classification accuracy of more than 80%. Such a system presents a low-cost solution to occupancy, however it is not sufficiently granular in either the detection of multiple occupants, or the detection of occupants in a specific room.

## 2.3 Analysis

From these various sensor options, there are a few candidates that provide the necessary quantitative criteria (Presence and Count); these are thermal, CO<sub>2</sub>, Video, Ultrasonic, RFID and WiFi association and triangulation based methods. All sensing options are compared on Table 2.1 on the next page.

In the context of our four qualitative accessibility criteria, CO<sub>2</sub> sensing has several reliability drawbacks, the predominant ones being a large lag time to receive accurate occupancy information and interference from a variety of air conditioning sources which can modify the CO<sub>2</sub> concentration in the room in unexpected ways.

Video-based sensing methods suffer from invasiveness concerns, as they by design must have a constant video feed of all detected areas.

Ultrasonic methods suffer from reliability concerns when a user falls outside the prescribed height bounds of normal humans. Wheelchair bound occupants, a core demographic of our proposed sensing system, are not discussed in the Door-jamb paper. Their wheelchair may also interfere with height measurement results. Ultrasonic methods also provide weak Identity information through height detection.

RFID sensing also has several drawbacks; it is difficult value proposition to get residential occupants to carry RFID tags with them continuously. Another drawback is that the triangulation methods discussed are too unreliable to place occupants in specific rooms in many cases.

	Requires		Excludes	Irrelevant	
	Presence	Count	Identity	Location	Track
<u>Intrinsic</u>					
<i>Static</i>					
Thermal	✓	✓	✓	✓	
CO <sub>2</sub>	✓	✓	✓		
Video	✓	✓	✗	✓	✓
<i>Dynamic</i>					
Ultrasonic	✓	✓	✗		✓
PIR	✓	✗	✓		
<u>Extrinsic</u>					
<i>Instrumented</i>					
RFID	✓ <sup>1</sup>	✓	✓	✓	
WiFi assoc. <sup>2</sup>	✓ <sup>1</sup>	✓	✗	✓	
WiFi triang. <sup>2</sup>	✓ <sup>1</sup>	✓	✗		
GPS <sup>2</sup>	✓ <sup>1</sup>	✗	✓	✓	
<i>Correlative</i>					
Electricity	✓ <sup>1</sup>	✗	✓		

<sup>1</sup>Doesn't provide data at required level of accuracy for home use.

<sup>2</sup>Uses smartphone as detector.

Table 2.1: Comparison of different sensors and project requirements

WiFi association is not granular enough for residential use, as the original enterprise use case presupposed a much larger area, as well as multiple wireless access points, neither of which a typical residential environment have.

WiFi triangulation is a good candidate for residential use, as there are most likely neighbouring wireless networks that can be used as virtual landmarks. However, it suffers from the same granularity problems as WiFi association, as these signals are not specific enough to pinpoint an occupant to a specific room.

For approaches presupposing smartphones being present on each occupant, it is more difficult to ensure that occupants are carrying their smartphones with them at all times in a residential environment. Another issue with smart phones is that they represent an expense that the target markets of the elderly and the disabled may not be able to afford.

Finally, we have thermal sensing. It provides both Presence and Count information, as it uses occupants' thermal signatures to determine the presence of people in a room. It does not however provide Identity information, as thermal signatures are not sufficiently unique with the technologies used to distinguish between occupants. Such a sensor system is presented as low-cost and energy efficient within Thermosense [7], is non-invasive by design and can reliably detect occupants with a very low root mean squared error. For our specific accessibility criteria, thermal sensing appears to be the best option available.

## 2.4 Thermal sensors

Our analysis (Subsection 2.3 on page 8) concluded that thermal sensors are the best candidates for this project. In this section we discuss the thermal sensing field in more detail.

A primary static/dynamic sensor fusion system in this field is the Thermosense system [7], a Passive Infrared Sensor (PIR) and Infrared Array Sensor (IAR) used to subdivide an area into an  $8 \times 8$  grid of sections from which temperatures can be derived. This sensor system is attached to the roof on a small embedded controller which is responsible for collecting the data and transmitting it back to a larger computer via low powered wireless protocols.

The Thermosense system develops a thermal background map of the room using an Exponential Weighted Moving Average (EMWA) over a 15 minute time window (if no motion is detected). If the room remains occupied for a long period, a more complex scaling algorithm is used which considers the coldest points in the room empty, and averages them against the new background, then performs EMWA with a lower weighting.

This background map is used as a baseline to calculate standard deviations of each grid area, which are then used to determine several characteristics to be used as feature vectors for a variety of classification approaches. The determination of the feature vectors was subject to experimentation, since the differences at each grid element too susceptible to individual room conditions to be used as feature vectors. Instead, a set of three different features was designed; the number of temperature anomalies in the space, the number of groups of temperature anomalies, and the size of the largest anomaly in the space. These feature vectors were compared against three classification approaches; K-Nearest Neighbors, Linear Regression and an a feed-forward Artificial Neural Network of one hidden layer and 5 perceptions. All three classifiers achieved a Root Mean Squared Error (RMSE) within  $0.38 \pm 0.04$ . This final classification is subject to a final averaging process over a 4 minute window to remove the presence of independent errors from the raw classification data.

The Thermosense approach presents the state of the art in the field of sensing with IAR technology. Using a similar IAR system along with those types of classification algorithms should yield useful sensing results which can be then integrated into the broader sensor system.

## 2.5 Research Gap

Throughout this review of the area of wireless occupancy sensors within the Internet of Things (IoT) it can be seen that there is a clear research gap within the area of occupancy. No group could be found who has assembled an occupancy sensor that optimises these areas of Low Cost, Non-Invasiveness, Energy Efficiency and Reliability into a architected software and hardware package that can be integrated like any other Thing into the IoT.

This is a key research area, because, as we have previously mentioned, the true “disruptive level of innovation” [4] the IoT provides can only be realised once a novel idea has been properly packaged as a Thing, rather than as a research curiosity. Packaging something as a Thing requires careful consideration of the best sensing systems, the best hardware to run those systems on, the best protocols to allow these Things to communicate, and the best device architecture to enable that communication. The state of the art in all these areas have been discussed throughout this literature review.

## 2.6 Conclusion

Several criteria were identified through which the spectrum of occupancy sensing could be examined; a quantitative criteria by Teixeira, Dublon and Savvides [24] to examine the different functionality offerings of sensor systems and a qualitative criteria derived from the aims of the project to examine how those sensors fit within the project's parameters.

Occupancy research performed with different sensor types was examined methodically through a set of taxonomic categories also originally proposed by Teixeira, Dublon and Savvides [24], but modified to better suit the specifics of occupancy sensors. These sensor types included Thermal, CO<sub>2</sub>, Video, Ultrasonic, Passive Infrared Sensor (PIR), RFID, various WiFi based methods, GPS and electricity consumption. Through an examination of these sensing systems quantitative and qualitative characteristics, it was determined that the Thermosense Infrared Array Sensor (IAR) system [7] was the most suitable to the project's aims.

A key part of enabling the "smart home for the disabled" is creating a set of Things that can improve quality of life for those people. We believe our proposed Thing has clearly demonstrated this potential.

## CHAPTER 3

# Prototype Design

As discussed in the Literature Review, using an Infrared Array Sensor (IAR) appear to be the most viable way to achieve the high-level goals of this project. Thermosense [7], the primary occupancy sensor in the IAR space, used the low-cost Panasonic Grid-EYE sensor for this task. This sensor, costing around \$30USD, appears to be a prime candidate for use in this project, as it satisfied low-cost criteria, as well as being proven by Thermosense to be effective in this space. However, while still available for sale in the United States, we were unable to order the sensor for shipping to Australia due to export restrictions outside of our control. While such restrictions would be circumventable with sufficient effort, using a sensor with such restrictions in place goes against an implicit criteria of the parts used in the project being relatively easy to acquire.

This forced us to search for alternative sensors in the space that fulfill similar criteria but were more broadly available. The sensor we settled on was the Melexis MLX90620 (*Melexis*) [20], an IAR with similar overall qualities that differed in several important ways; it provides a  $16 \times 4$  grid of thermal information, it has an overall narrower field of view and it sells for approximately \$80USD. Like the Grid-EYE, the *Melexis* sensor communicates over the 2-wire I<sup>2</sup>C bus, a low-level bi-directional communication bus widely used and supported in embedded systems.

In an idealized version of this occupancy system, much like Thermosense this system would include wireless networking and a very small form factor. However, due to time and resource constraints, the scope of this project has been limited to a minimum viable implementation. Appendix Chapter B on page 38 discusses in detail how the introduction of new open standards in the Wireless Personal Area Network space could be used in future systems to provide robust, decentralized networking of future occupancy sensors. This prototype architecture has been designed such that a clear path to the idea system architecture discussed therein is available.

<b>Analysis Tier</b>	Raspberry Pi B+
<b>Preprocessing Tier</b>	Arduino Uno R3
<b>Sensing Tier</b>	Melexis MLX90620 & PIR

Table 3.1: Hardware tiers

### 3.1 Hardware

As reliability and future extensibility are core concerns of the project, a three-tiered system is employed with regards to the hardware involved in the system (Table 3.1). At the bottom, the Sensing Tier, we have the raw sensor, the Melexis MLX90620 (*Melexis*), which communicate over I<sup>2</sup>C . Connected to these devices via those respective protocols is the Preprocessing Tier, run an embedded system. The embedded device polls the data from these sensors, performs necessary calculations to turn raw information into suitable data, and communicates this via Serial over USB to the third tier. The third tier, the Analysis Tier, is run on a fully fledged computer. In our prototype, it captures and stores both video data, and the Temperature and Motion data it receives over Serial over USB.

While at a glance this system may seem overly complicated, it ensures that a sensible upgrade path to a more feature-rich sensing system is available. In the current prototype, the Analysis Tier merely stores captured data for offline analysis, in future prototypes this analysis can be done live and served to interested parties over a RESTful API. In the current prototype, the Analysis and Sensing Tiers are connected by Serial over USB, in future prototypes, this can be replaced by a wireless mesh network, with many Preprocessing/Sensing Tier nodes communicating with one Analysis Tier node.

Due to low cost and ease of use, the Arduino platform was selected as the host for the Preprocessing Tier, and thus the low-level I<sup>2</sup>C interface for communication to the *Melexis*. Initially, this presented some challenges, as the *Melexis* recommends a power and communication voltage of 2.6V, while the Arduino is only able to output 3.3V and 5V as power, and 5V as communication. Due to this, it was not possible to directly connect the Arduino to the *Melexis*, and similarly due to the two-way nature of the I<sup>2</sup>C 2-wire communication protocol, it was also not possible to simply lower the Arduino voltage using simple electrical techniques, as such techniques would interfere with two-way communication.

A solution was found in the form of a I<sup>2</sup>C level-shifter, the Adafruit “4-channel I2C-safe Bi-directional Logic Level Converter” [1], which provided a cheap method to bi-directionally communicate between the two devices at their own preferred voltages. The layout of the circuit necessary to link the Arduino

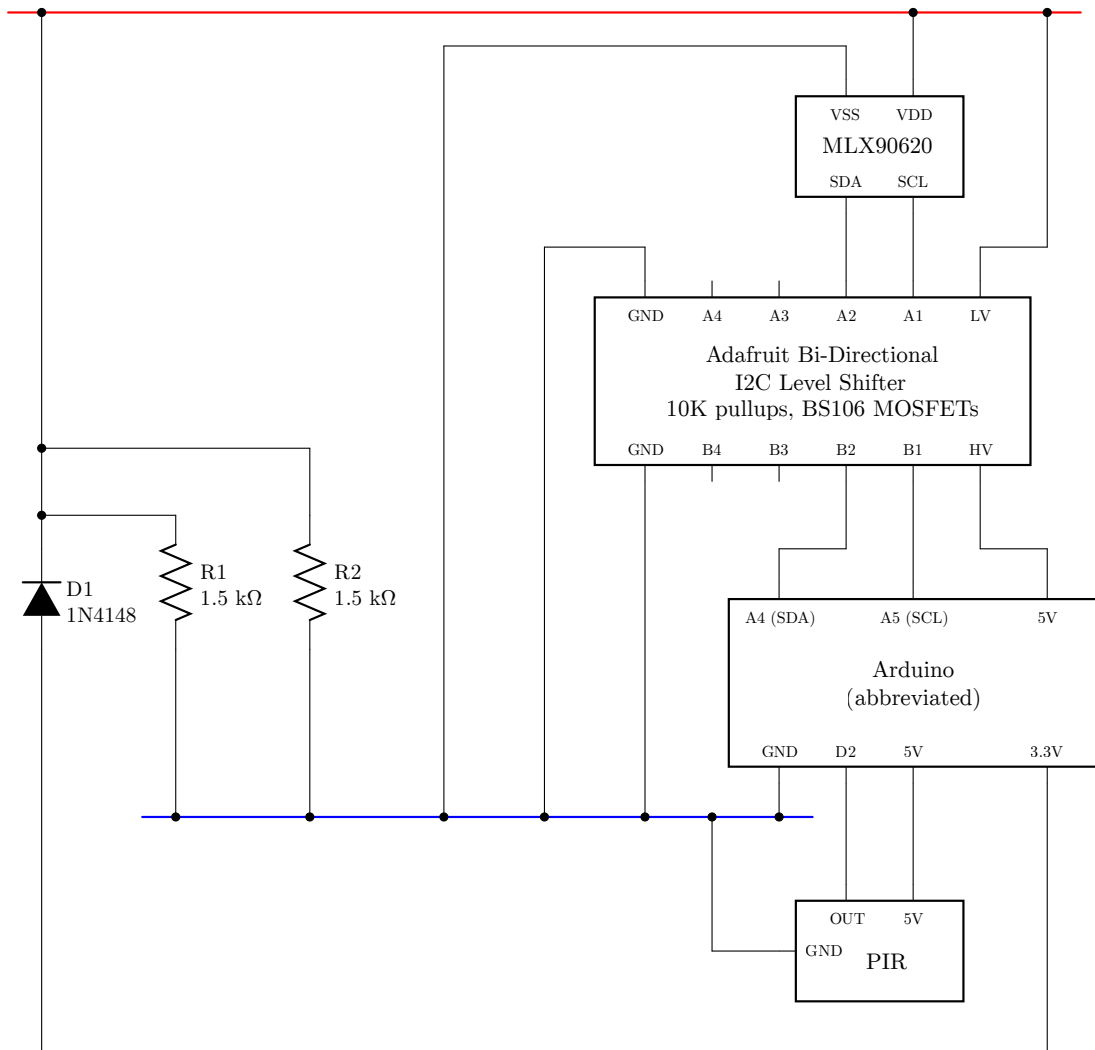


Figure 3.1: MLX90620, PIR and Arduino integration circuit



and the *Melexis* using this converter can be seen in Figure 3.1 on the previous page.

Additionally, as used in the Thermosense paper, a Passive Infrared Sensor (PIR) motion sensor [2] was also connected to the Arduino . This sensor, operating at 5V natively, did not require any complex circuitry to interface with the Arduino . It is connected to digital pin 2 on the Arduino , where it provides a rising signal in the event that motion is detected, which can be configured to cause an interrupt on the Arduino . In the configuration used in this project, the sensor’s sensitivity was set to the highest value and the timeout for re-triggering was set to the lowest value (approximately 2.5 seconds). Additionally, the continuous re-triggering feature (whereby the sensor produces continuous rising and falling signals for the duration of motion) was disabled using the provided jumpers.

For the Analysis Tier, the Raspberry Pi B+ was chosen, as it is a powerful computer capable of running Linux available for an extraordinarily low price. The Arduino is connected to the Raspberry Pi over USB, which provides it both power and the capacity to transfer data. In turn, the Raspberry Pi is connected to a simple micro-USB rechargeable battery pack, which provides it with power, and subsequently the Arduino and sensors.

## 3.2 Software

To calculate the final temperature values that the Melexis MLX90620 (*Melexis*) offers, a complex initialisation and computational process must be followed, which is specified in the sensor’s datasheet [20]. This process involves initialising the sensor with values attained from a separate on-board I<sup>2</sup>C EEPROM, then retrieving a variety of normalisation and adjustment values, along with the raw sensor data, to compute the final temperature result.

The basic algorithm to perform this normalisation was based upon code by users “maxbot”, “IIBaboomba”, “nseidle” and others on the Arduino Forums [3] and was modified to operate with the newer Arduino “Wire” I<sup>2</sup>C libraries released since the authors’ posts. In pursuit of the project’s aims to create a more approachable thermal sensor, the code was also restructured and rewritten to be both more readable, and to introduce a set of features to make the management of the sensor data easier for the user, and for the information to be more human readable.

The first of the features introduced was the human-readable format for serial transmission. This allows the user to both easily write code that can parse the serial to acquire the serial data, as well as examine the serial data directly with

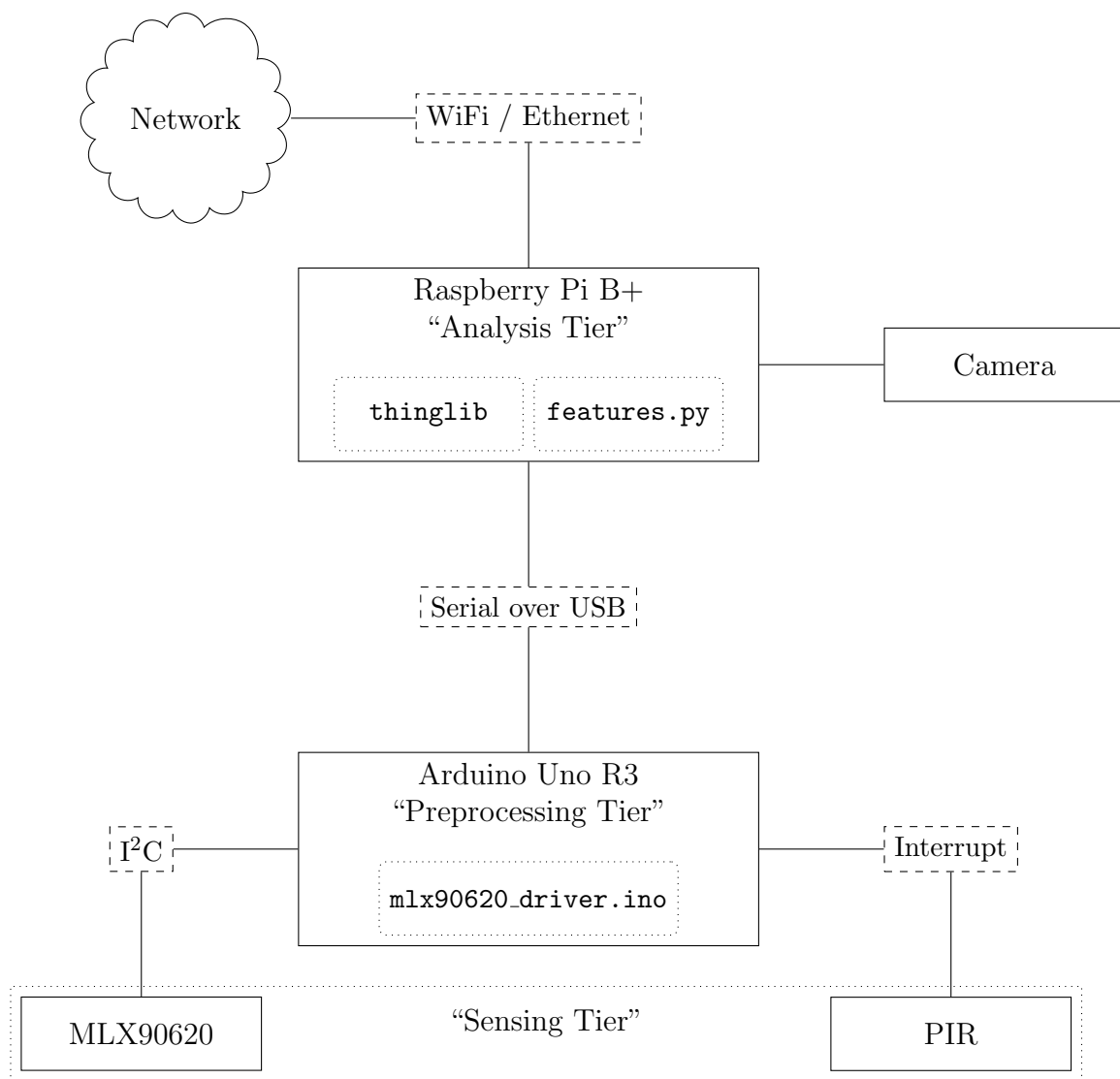


Figure 3.2: Prototype system architecture

```

INIT 0
INFO START
DRIVER MLX90620
BUILD Feb  1 2015 00:00:00
IRHZ 1
INFO STOP
ACTIVE 33

START 34
MOVEMENT 0
1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0
1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0
1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0
1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0
STOP 97

```

Figure 3.3: Initialisation sequence and thermal packet

ease. When the Arduino first boots running the software, the output in Figure 3.3 is output. This specifies several things that are useful to the user; the attached sensor (“DRIVER”), the build of the software (“BUILD”) and the refresh rate of the sensor (“IRHZ”). Several different headers, such as “ACTIVE” and “INIT” specify the current millisecond time of the processor, thus indicating how long the execution of the initialisation process took (33 milliseconds).

Once booted, the user is able to send several one-character commands to the sensor to configure operation, which are described in Table ?? on page ??. Depending on the sensor configuration, IR data may be periodically output automatically, or otherwise manually triggered. This IR data is produced in the packet format described in Figure 3.3. This is a simple, human readable format that includes the millisecond time of the processor at the start and end of the calculation, if the Passive Infrared Sensor (PIR) has seen any motion for the duration of the calculation, and the 16x4 grid of calculated temperature values.

### 3.3 Sensor Properties

In order to best utilize the Melexis MLX90620 (*Melexis*), we must first understand the properties it exhibits, and their potential affects on our ability to perform person related measurements. These properties can be broadly separated into three different categories; bias, noise and sensitivity. A broad range of data was collected with the sensor in a horizontal orientation using various sources of heat and cold to determine these properties. This experimental setup is described in Figure 3.4 on the next page.

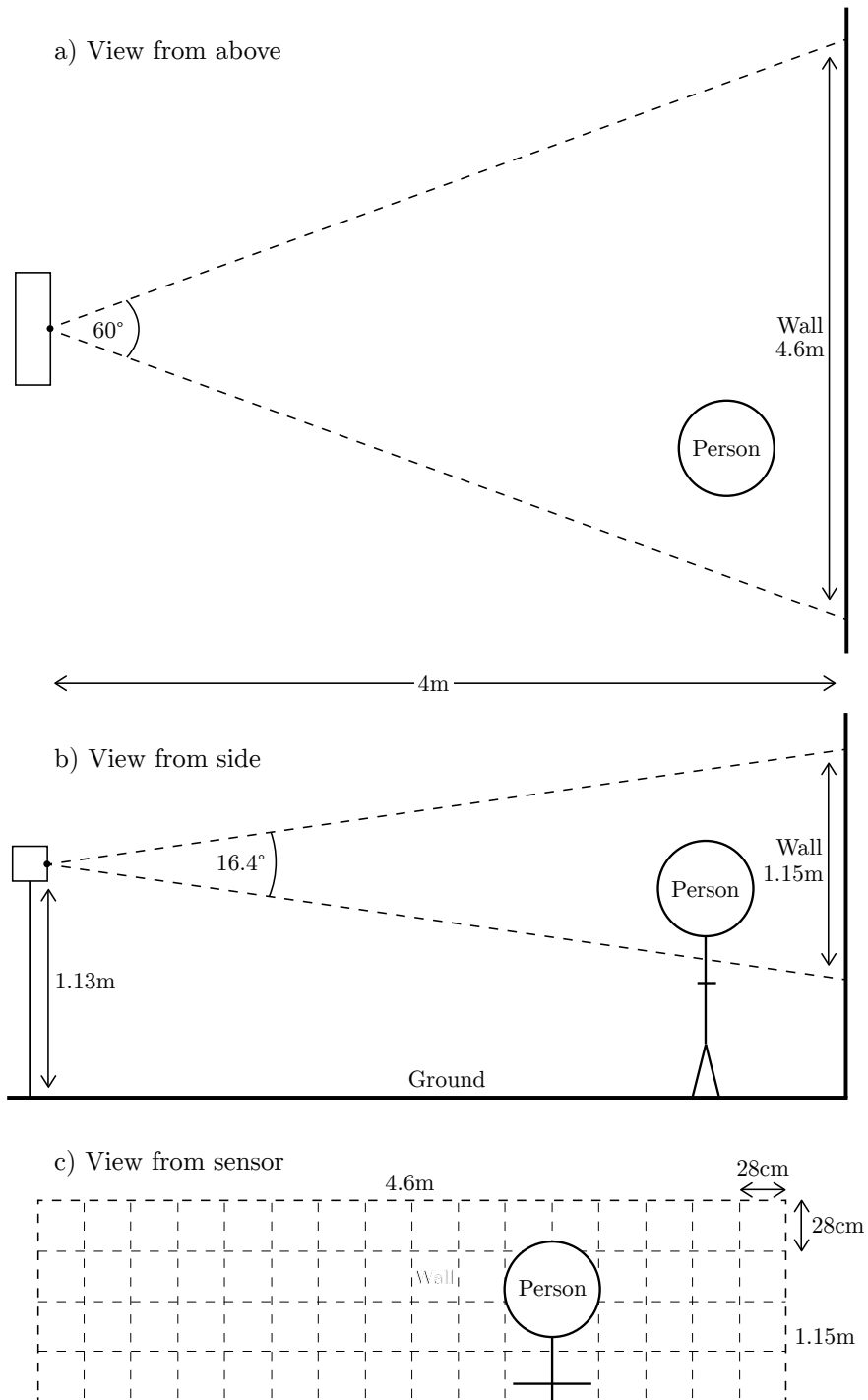


Figure 3.4: Experiment setup to determine sensor properties

### 3.3.1 Bias

When receiving no infrared radiation, the sensor should indicate a near-zero temperature. If in such conditions it does not, that indicates that the sensor has some level of bias in its measurement values. We attempted to investigate this bias by performing thermal captures of the night sky. While this does not completely remove the infrared radiation, it does remove a significant proportion of it.

In Table 3.2 on the following page the thermal sensor was exposed to the night sky at a capture rate of 1Hz for 4 minutes, with the sensing results combined to create a set of means and standard deviations to indicate the pixels at “rest”. The average temperature detected was 11.78°C, with the standard deviation remaining less than 0.51°C over the entire exposure period. The resultant thermal map shows that pixels centered around the four “primary” pixels in the centre maintain a similar temperature around 9°C, with temperatures beginning to deviate as they became further from the center.

14.95 0.51	14.33 0.27	12.34 0.27	8.77 0.33	8.15 0.31	10.84 0.38	9.02 0.26	7.79 0.37	6.67 0.27	9.63 0.29	9.29 0.26	8.24 0.27	9.84 0.25	14.28 0.33	14.92 0.3	13.16 0.25
14.54 0.34	15.62 0.31	12.73 0.23	11.51 0.27	11.79 0.26	11.47 0.27	11.43 0.29	9.02 0.35	8.57 0.23	11.15 0.23	10.64 0.22	10.3 0.24	12.09 0.22	14.49 0.26	14.88 0.31	14.71 0.36
18.25 0.45	16.62 0.31	14.15 0.24	11.97 0.34	13.11 0.3	12.64 0.22	10.66 0.23	9.15 0.24	9.58 0.28	11.95 0.28	11.22 0.24	11.52 0.36	11.11 0.23	12.59 0.25	14.44 0.31	13.35 0.28
16.02 0.28	16.81 0.36	15.0 0.25	11.53 0.28	10.18 0.29	12.2 0.25	11.78 0.29	8.36 0.31	8.15 0.33	10.36 0.32	10.74 0.31	8.25 0.36	9.99 0.35	12.42 0.38	11.39 0.4	11.06 0.34

Table 3.2: Mean and standard deviations for each pixel at rest

3.3.2 Noise

3.3.3 Sensitivity

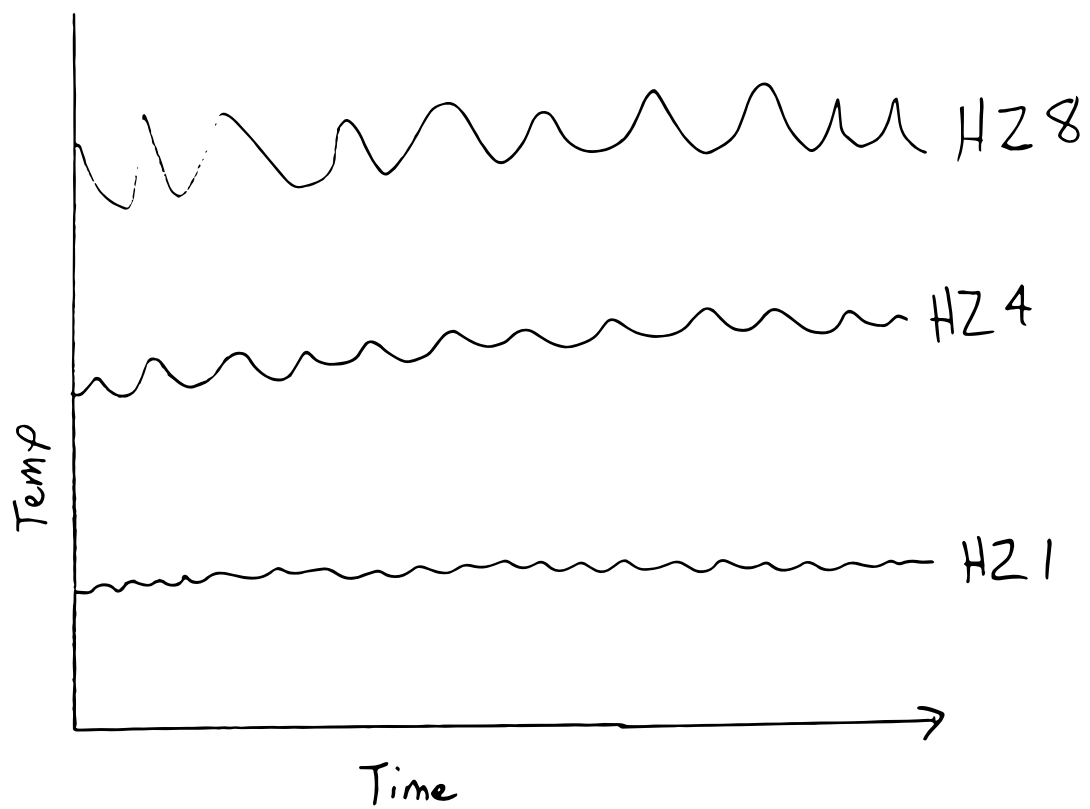


Figure 3.5: Comparison of noise levels at the *Melexis*' various sampling speeds



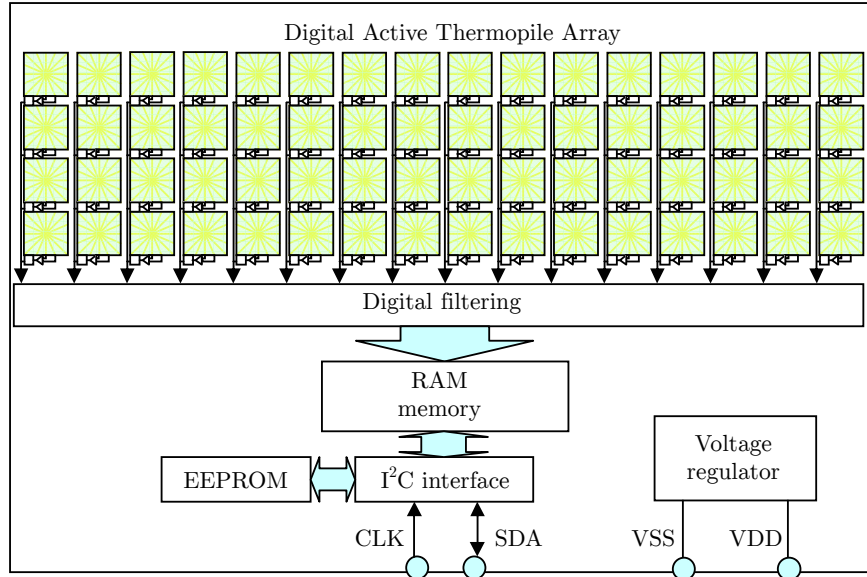


Figure 3.6: Block diagram for the *Melexis* taken from datasheet [20]

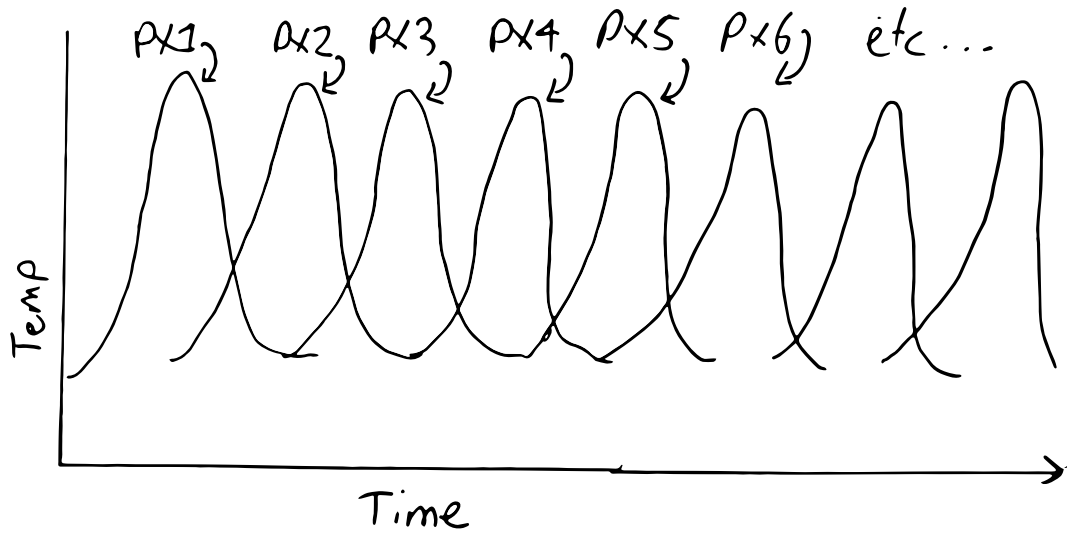


Figure 3.7: Different *Melexis* pixel temperature values as hot object moves across row

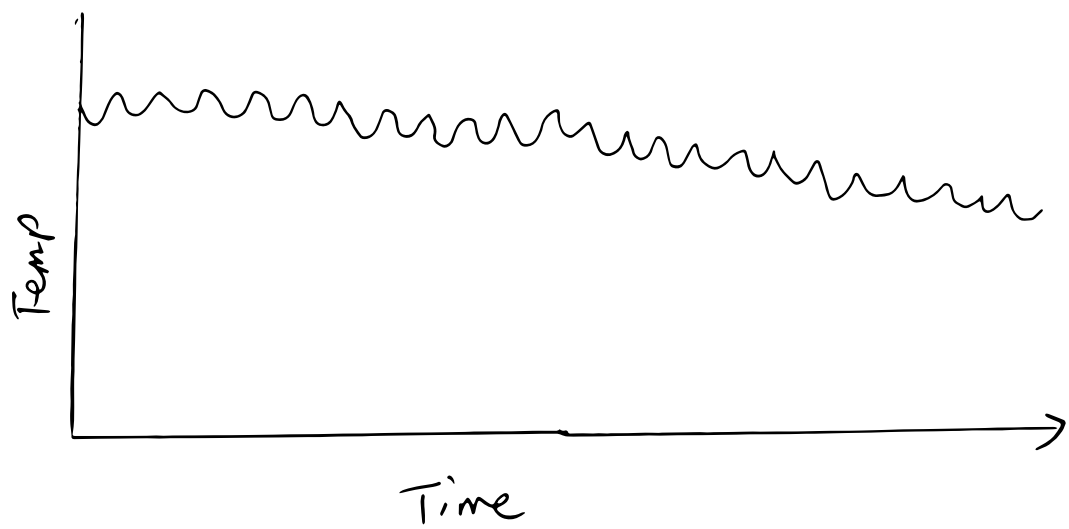


Figure 3.8: Variation in temperature detected for hot object at 1Hz sampling ration

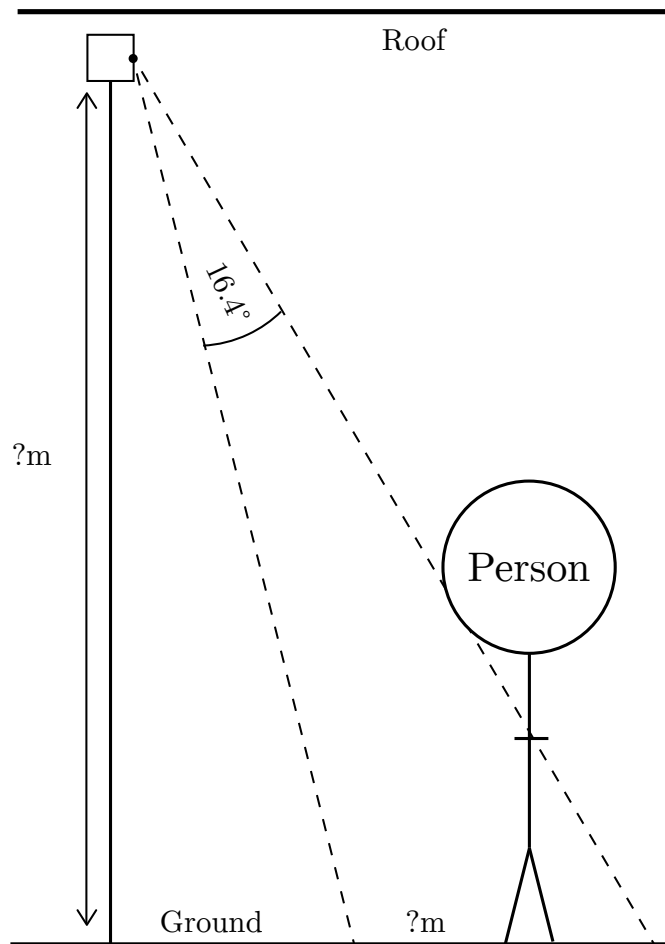
## CHAPTER 4

# Methods

### 4.1 Classifier Experiment Set 1 Setup

See Figure 4.1 on the next page.

a) View from side



b) View from above

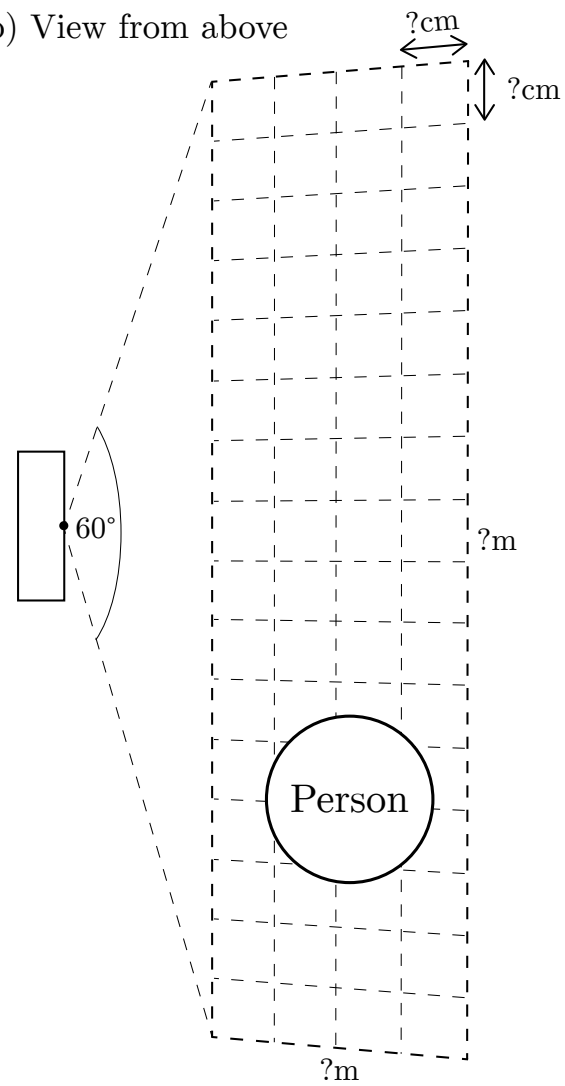


Figure 4.1: Classifier Experiment Set 1 Setup

## CHAPTER 5

# Results

### 5.1 Classifier Experiment Set 1

See Section D.1 on page 92.

<b>Classifier</b>	<b>Correctly Classified</b>	<b>RMS Error</b>	<b>F-Measure</b>
<i>J48</i>	82.9%	0.2878	0.824
<i>MLP</i>	78.5%	0.2936	0.777
<i>Naive Bayes</i>	66.2%	0.3516	0.644
<i>IBk</i>	57.6%	0.4245	0.563
<i>SMO</i>	57.5%	0.3795	0.554

Table 5.1: Classifier Experiment Set 1 Nominal Results

<b>Numeric</b>	<b>Correctly Classified</b>	<b>RMS Error</b>
<i>Linear Regression</i>	63.4%	0.6589
<i>IBk</i>	55.8%	1.1947
<i>Multilayer Perceptron</i>	50.2%	0.7768

Table 5.2: Classifier Experiment Set 1 Numeric Results

## CHAPTER 6

# Discussion and Conclusion

### 6.1 Future Directions

- Wireless mesh networking
- Convert into circuit board
- MLX90621
- Lenses
- Rotating the sensor to see wider FOV
- Subpixel localisation (see prev graphs bell curves)

## APPENDIX A

# Original Honours Proposal

**Title:** Developing a robust system for occupancy detection in the household  
**Author:** Ash Tyndall  
**Supervisor:** Professor Rachel Cardell-Oliver  
**Degree:** BCompSci (24 point project)  
**Date:** October 8, 2014

## A.1 Background

The proportion of elderly and mobility-impaired people is predicted to grow dramatically over the next century, leaving a large proportion of the population unable to care for themselves, and consequently less people able care for these groups. [6] With this issue looming, investments are being made into a variety of technologies that can provide the support these groups need to live independent of human assistance.

With recent advancements in low cost embedded computing, such as the Arduino [1] and Raspberry Pi, [2] the ability to provide a set of interconnected sensors, actuators and interfaces to enable a low-cost ‘smart home for the disabled’ is becoming increasingly achievable.

Sensing techniques to determine occupancy, the detection of the presence and number of people in an area, are of particular use to the elderly and disabled. Detection can be used to inform various devices that change state depending on the user’s location, including the better regulation energy hungry devices to help reduce financial burden. Household climate control, which in some regions of Australia accounts for up to 40% of energy usage [3] is one particular area



in which occupancy detection can reduce costs, as efficiency can be increased dramatically with annual energy savings of up to 25% found in some cases. [8]

Significant research has been performed into the occupancy field, with a focus on improving the energy efficiency of both office buildings and households. This is achieved through a variety of sensing means, including thermal arrays, [5] ultrasonic sensors, [11] smart phone tracking, [12][4] electricity consumption, [13] network traffic analysis, [15] sound, [10] CO<sub>2</sub>, [10] passive infrared, [10] video cameras, [7] and various fusions of the above. [16][15]

## A.2 Aim

While many of the above solutions achieve excellent accuracies, in many cases they suffer from problems of installation logistics, difficult assembly, assumptions on user's technology ownership and component cost. In a smart home for the disabled, accuracy is important, but accessibility is paramount.

The goal of this research project is to devise an occupancy detection system that forms part of a larger 'smart home for the disabled' that meets the following accessibility criteria;

- *Low Cost*: The set of components required should aim to minimise cost, as these devices are intended to be deployed in situations where the serviced user may be financially restricted.
- *Non-Invasive*: The sensors used in the system should gather as little information as necessary to achieve the detection goal; there are privacy concerns with the use of high-definition sensors.
- *Energy Efficient*: The system may be placed in a location where there is no access to mains power (i.e. roof), and the retrofitting of appropriate power can be difficult; the ability to survive for long periods on only battery power is advantageous.
- *Reliable*: The system should be able to operate without user intervention or frequent maintenance, and should be able to perform its occupancy detection goal with a high degree of accuracy.

Success in this project would involve both

1. Devising a bill of materials that can be purchased off-the-shelf, assembled without difficulty, on which a software platform can be installed that performs analysis of the sensor data and provides a simple answer to the occupancy question, and
2. Using those materials and softwares to create a final demonstration prototype whose success can be tested in controlled and real-world conditions.

This system would be extensible, based on open standards such as REST or CoAP, [9][14] and could easily fit into a larger ‘smart home for the disabled’ or internet-of-things system.

## A.3 Method

Achieving these aims involves performing research and development in several discrete phases.

### A.3.1 Hardware

A list of possible sensor candidates will be developed, and these candidates will be ranked according to their adherence to the four accessibility criteria outlined above. Primarily the sensor ranking will consider the cost, invasiveness and reliability of detection, as the sensors themselves do not form a large part of the power requirement.

Similarly, a list of possible embedded boards to act as the sensor’s host and data analysis platform will be created. Primarily, they will be ranked on cost, energy efficiency and reliability of programming/system stability.

Low-powered wireless protocols will also be investigated, to determine which is most suitable for the device; providing enough range at low power consumption to allow easy and reliable communication with the hardware.

Once promising candidates have been identified, components will be purchased and analysed to determine how well they can integrate.

### A.3.2 Classification

Depending on the final sensor choice, relevant experiments will be performed to determine the classification algorithm with the best occupancy determina-

tion accuracy. This will involve the deployment of a prototype to perform data gathering, as well as another device/person to assess ground truth.

### A.3.3 Robustness / API

Once the classification algorithm and hardware are finalised, an easy to use API will be developed to allow the data the device collects to be integrated into a broader system.

The finalised product will be architected into a easy-to-install software solution that will allow someone without domain knowledge to use the software and corresponding hardware in their own environment.

## A.4 Timeline

Date	Task
Fri 15 August	<i>Project proposal and project summary due to Coordinator</i>
August	Hardware shortlisting / testing
25–29 August	<i>Project proposal talk presented to research group</i>
September	Literature review
Fri 19 September	<i>Draft literature review due to supervisor(s)</i>
October - November	Core Hardware / Software development
Fri 24 October	<i>Literature Review and Revised Project Proposal due to Coordinator</i>
November - February	<i>End of year break</i>
February	Write dissertation
Thu 16 April	<i>Draft dissertation due to supervisor</i>
April - May	Improve robustness and API
Thu 30 April	<i>Draft dissertation available for collection from supervisor</i>
Fri 8 May	<i>Seminar title and abstract due to Coordinator</i>
Mon 25 May	<i>Final dissertation due to Coordinator</i>
25–29 May	<i>Seminar Presented to Seminar Marking Panel</i>
Thu 28 May	<i>Poster Due</i>
Mon 22 June	<i>Corrected Dissertation Due to Coordinator</i>

## A.5 Software and Hardware Requirements

A large part of this research project is determining the specific hardware and software that best fit the accessibility criteria. Because of this, an exhaustive list of software and hardware requirements are not given in this proposal.

A budget of up to \$300 has been allocated by my supervisor for project purchases. Some technologies with promise that will be investigated include;

**Raspberry Pi Model B+** Small form-factor Linux computer

Available from <http://arduino.cc/en/Guide/Introduction>; \$38

**Arduino Uno** Small form-factor microcontroller

Available from <http://arduino.cc/en/Main/arduinoBoardUno>; \$36

**Panasonic Grid-EYE** Infrared Array Sensor

Available from <http://www3.panasonic.biz/ac/e/control/sensor/infrared/grid-eye/index.jsp>; approx. \$33

**Passive Infrared Sensor**

Available from various places; \$10–\$20

## A.6 Proposal References

- [1] Arduino. <http://arduino.cc/en/Guide/Introduction>. Accessed: 2014-08-09.
- [2] Raspberry pi. <http://www.raspberrypi.org/>. Accessed: 2014-08-09.
- [3] AUSTRALIAN BUREAU OF STATISTICS. 4602.2 - household water and energy use, victoria: Heating and cooling. Tech. rep., October 2011.
- [4] BALAJI, B., XU, J., NWOKAFOR, A., GUPTA, R., AND AGARWAL, Y. Sentinel: occupancy based hvac actuation using existing wifi infrastructure within commercial buildings. In *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems* (2013), ACM, p. 17.
- [5] BELTRAN, A., ERICKSON, V. L., AND CERPA, A. E. Thermosense: Occupancy thermal based sensing for hvac control. In *Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings* (2013), ACM, pp. 1–8.
- [6] CHAN, M., CAMPO, E., ESTÈVE, D., AND FOURNIOLS, J.-Y. Smart homescurrent features and future perspectives. *Maturitas* 64, 2 (2009), 90–97.
- [7] ERICKSON, V. L., ACHLEITNER, S., AND CERPA, A. E. Poem: Power-efficient occupancy-based energy management system. In *Proceedings of the 12th international conference on Information processing in sensor networks* (2013), ACM, pp. 203–216.
- [8] ERICKSON, V. L., BELTRAN, A., WINKLER, D. A., ESFAHANI, N. P., LUSBY, J. R., AND CERPA, A. E. Thermosense: thermal array sensor networks in building management. In *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems* (2013), ACM, p. 87.
- [9] GUINARD, D., ION, I., AND MAYER, S. In search of an internet of things service architecture: Rest or ws-\*? a developers perspective. In *Mobile and Ubiquitous Systems: Computing, Networking, and Services*. Springer, 2012, pp. 326–337.

- [10] HAILEMARIAM, E., GOLDSTEIN, R., ATTAR, R., AND KHAN, A. Real-time occupancy detection using decision trees with multiple sensor types. In *Proceedings of the 2011 Symposium on Simulation for Architecture and Urban Design* (2011), Society for Computer Simulation International, pp. 141–148.
- [11] HNAT, T. W., GRIFFITHS, E., DAWSON, R., AND WHITEHOUSE, K. Doorjamb: unobtrusive room-level tracking of people in homes using doorway sensors. In *Proceedings of the 10th ACM Conference on Embedded Network Sensor Systems* (2012), ACM, pp. 309–322.
- [12] KLEIMINGER, W., BECKEL, C., DEY, A., AND SANTINI, S. Using unlabeled wi-fi scan data to discover occupancy patterns of private households. In *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems* (2013), ACM, p. 47.
- [13] KLEIMINGER, W., BECKEL, C., STAAKE, T., AND SANTINI, S. Occupancy detection from electricity consumption data. In *Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings* (2013), ACM, pp. 1–8.
- [14] KOVATSCH, M. Coap for the web of things: from tiny resource-constrained devices to the web browser. In *Proceedings of the 2013 ACM conference on Pervasive and ubiquitous computing adjunct publication* (2013), ACM, pp. 1495–1504.
- [15] TING, K., YU, R., AND SRIVASTAVA, M. Occupancy inferencing from non-intrusive data sources. In *Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings* (2013), ACM, pp. 1–2.
- [16] YANG, Z., LI, N., BECERIK-GERBER, B., AND OROSZ, M. A multi-sensor based occupancy estimation model for supporting demand driven hvac operations. In *Proceedings of the 2012 Symposium on Simulation for Architecture and Urban Design* (2012), Society for Computer Simulation International, p. 2.

## APPENDIX B

# Ideal System Architecture

Beyond specific sensor design and occupancy detection algorithms, a core goal of this project is to create a system that is designed to operate as a useful Thing in a real-world Internet of Things (IoT) environment, as the key advantage of Things is the “disruptive level of innovation”[4] brought about by their ability to be combined in ways unforeseen (yet still enabled) by their creators. This architecture involves careful consideration of the embedded hardware that will drive the system, as well as the communications protocols utilised between the sensor and devices interested in the sensor’s information.

## B.1 Protocols

In an ideal smart-home environment, the sensor systems used will communicate with each other wirelessly. As the complete sensor system has low power requirements to enable battery operation, it is important to prioritise those protocols and architectures that minimise power usage while still enabling the necessary wireless communication. The system will also ideally exist in a system with other identical sensors (one for each room in a residence), thus it is important to prioritise those protocols which allow multiple identical sensor systems to coexist on the same network without conflict, and to be uniquely addressable and iden-

REST	
<b>Application</b>	CoAP
<b>Transport</b>	UDP
<b>IP / Routing</b>	IETF RPL
<b>Adaptation</b>	IETF 6LoWPAN
<b>Medium Access</b>	IEEE 802.15.4e
<b>Physical</b>	IEEE 802.15.4-2006

Table B.1: Proposed protocol stack

tifiable. In recent years, many developments have been made in the Internet of Things (IoT) arena, with standards emerging specifically designed for low-power embedded devices to communicate between themselves and bigger systems that address these and other unique needs, across the entire protocol stack.

Palattella et al. [21] propose a protocol stack that aligns with the above requirements, with the key advantage being a wholly standardized implementation of the stack exists. This implementation is based on TCP/IP, uses the latest IEEE and IETF IoT standards, and is free from proprietary protocol restrictions (unlike ZigBee 1.0 devices, for instance). Table B.1 on the previous page shows the full stack proposed. The key components of this proposal are the introduction of CoAP at the application layer, RPL at the IP / Routing layer and 6LoWPAN at the Adaptation layer.

Above the application layer, Guinard et al. [11] propose the use of Representational state transfer (REST) over Web Services Descriptive Language / Simple Object Access Protocol (WS-\*) as a method of exchanging information between sensor systems. Their data suggests that REST is easier to use than WS-\*, and the key advantage of a WS-\* based approach is its ability to represent much more complex data and abstractions, which are unnecessary in this project’s situation.

Constrained Application Protocol (CoAP) [18] is an application layer protocol designed to replace HTTP as a way of transmitting RESTful information between clients. The chief advantage of CoAP over HTTP is it compresses the broad-strokes of the HTTP feature set into a binary language that is much more suitable for transmission over low-bandwidth and low-power links, such as those discussed here.

IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) [25] is a routing protocol designed for low power environments, allowing low power nodes to create and maintain a mesh network between themselves, allowing, among other things, the routing of packets to a “root” node and back again. RPL is particularly suited to the routing situation of our proposed architecture, as individual sensors do not need to communicate with one another, but rather report back to a larger node (further discussed in Subsection B.2 on the following page).

IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) [23] is a compression and formatting specification to allow IPv6 packets to be sent over an 802.15.4 based network. Optimisations are found in the reduction of the size of 6LoWPAN packets, IPv6 addresses as well as redesigning core Internet Protocol algorithms so that they can run with low power consumption on participating devices.



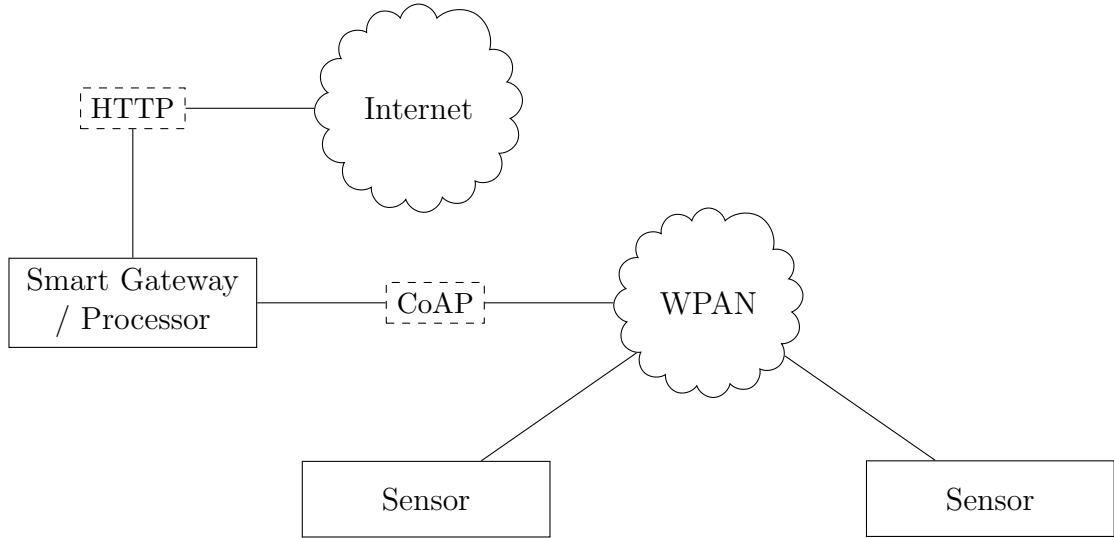


Figure B.1: Proposed system architecture

## B.2 Devices

In addition to the protocol stack used, how these nodes relate to each other is also an important consideration. Part of what will inform these decisions are the requisite processing power and internet connectivity required to successfully execute all elements of the sensing system. Kovatsch [18] provides a constructive classification system to consider this, by describing three classes of resource constrained devices that would benefit from Constrained Application Protocol (CoAP), and each can provide different levels of security for an IP stack;

- *Class 0*: “not capable of running an RFC-compliant IP stack in a secure manner. They require application-level gateways to connect to the Internet.”
- *Class 1*: Able to connect to the internet with some “integrated security mechanisms”. Are unable to employ full HTTP with TLS.
- *Class 2*: Normal Internet nodes, able to use the full HTTP stack with TLS.

The devices that we propose the sensors will connect to are the likes of the Arduino, which can be classified as class 0 or possibly class 1 devices. Due to their insecurity and difficulty running a fully fledged IP stack, Guinard et al. [12] propose the use of a “Smart Gateway” system to bridge the wider internet

and these sensor systems. This gateway would be able to communicate with the sensor systems over CoAP and 802.15.4 , as well as receive API requests via HTTP from a traditional TCP/IP network to forward on to these sensors.

The Thermosense paper [7] proposes several different algorithms to process the raw sensing data into the occupancy estimates (further discussed in Section 2.4 on page 10), all of which are fairly computationally expensive. Because of this, it would be non-trivial to implement these algorithms on the embedded sensing devices themselves. This problem is already resolved in our proposed system, as the aforementioned “Smart Gateway” can easily also take on the task of processing the raw sensor data into estimates which it can relay to interested parties over its HTTP-based API. A visualisation of this proposed system is shown in Figure B.1 on the preceding page.

## APPENDIX C

# Code Listings

### C.1 ThingLib

#### C.1.1 cam.py

42

```
from __future__ import division 1
from __future__ import print_function 2

import serial 3
import copy 4
import Queue as queue 5
import time 6
from collections import deque 7
import threading 8
import pygame 9
import colorsys 10
import datetime 11
from PIL import Image, ImageDraw, ImageFont 12
import subprocess 13
import tempfile 14
import os 15
16
```

```
import os.path 17
import fractions 18
import pxdisplay 19
import multiprocessing 20
import numpy as np 21
import io 22
23
24
25
class BaseManager(object): 26
    driver = None 27
    build = None 28
    irhz = None 29
30
    tty = None 31
    baud = None 32
33
    hflip = True 34
    vflip = True 35
36
    _temps = None 37
    _serial_obj = None 38
    _queues = [] 39
40
    def __init__(self, tty, hz=8, baud=115200): 41
        self.tty = tty 42
        self.baud = baud 43
        self.irhz = hz 44
45
        self._serial_obj = serial.Serial(port=self.tty, baudrate=self.baud, rtscts=True, dsrdtr=True) 46
47
    def __del__(self): 48
        self.close() 49
50
```

```

def _reset_and_conf(self, timers=True):
    self._serial_obj.write('r\n') # Reset the sensor
    self._serial_obj.flush()

    time.sleep(2)

    if timers:
        self._serial_obj.write('t\n') # Turn on timers
    else:
        self._serial_obj.write('o\n') # Turn on timers

    self._serial_obj.flush()

def _decode_packet(self, packet):
    decoded_packet = {}
    ir = []

    for line in packet:
        parted = line.partition(" ")
        cmd = parted[0]
        val = parted[2]

        try:
            if cmd == "START":
                decoded_packet['start_millis'] = long(val)
            elif cmd == "STOP":
                decoded_packet['stop_millis'] = long(val)
            elif cmd == "MOVEMENT":
                if val == "0":
                    decoded_packet['movement'] = False
                elif val == "1":
                    decoded_packet['movement'] = True
            else:
                ir.append(tuple(float(x) for x in line.split("\t")))

```

```

        except ValueError:
            print(packet)
            print("WARNING: Could not decode corrupted packet")
            return {}

    if self.hflip:
        ir = map(tuple, np.fliplr(ir))

    if self.vflip:
        ir = map(tuple, np.flipud(ir))

    decoded_packet['ir'] = tuple(ir)

    return decoded_packet

def _decode_info(self, packet):
    decoded_packet = {}
    ir = []

    for line in packet:
        parted = line.partition(" ")
        cmd = parted[0]
        val = parted[2]

        if cmd == "INFO":
            pass
        elif cmd == "DRIVER":
            decoded_packet['driver'] = val
        elif cmd == "BUILD":
            decoded_packet['build'] = val
        elif cmd == "IRHZ":
            decoded_packet['irhz'] = int(val) if int(val) != 0 else 0.5

    return decoded_packet

```

```
def _update_info(self):
    ser = self._serial_obj

    ser.write('i')
    ser.flush()
    imsg = []

    line = ser.readline().decode("ascii", "ignore").strip()

    # Capture a whole packet
    while not line == "INFO START":
        line = ser.readline().decode("ascii", "ignore").strip()

    while not line == "INFO STOP":
        imsg.append(line)
        line = ser.readline().decode("ascii", "ignore").strip()

    imsg.append(line)

    packet = self._decode_info(imsg)

    self.driver = packet['driver']
    self.build = packet['build']

    if packet['irhz'] != self.irhz:
        ser.write('f{}'.format(self.irhz))
        self._update_info()

def _wait_read_packet(self):
    ser = self._serial_obj
    line = ser.readline().decode("ascii", "ignore").strip()
    msg = []
```

```
# Capture a whole packet
while not line.startswith("START"):
    line = ser.readline().decode("ascii", "ignore").strip()

while not line.startswith("STOP"):
    msg.append(line)
    line = ser.readline().decode("ascii", "ignore").strip()

msg.append(line)

return msg

def close(self):
    return

def get_temps(self):
    if self._temps is None:
        return False
    else:
        return copy.deepcopy(self._temps)

def subscribe(self):
    q = queue.Queue()
    self._queues.append(q)
    return q

def subscribe_multiprocess(self):
    q = multiprocessing.Queue()
    self._queues.append(q)
    return q

def subscribe_lifo(self):
    q = queue.LifoQueue()
    self._queues.append(q)
```



```

        return q
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220

class Manager(BaseManager):
    _serial_thread = None
    _serial_stop = False
    _serial_ready = False

    _decode_thread = None

    _read_decode_queue = None

    def __init__(self, tty, hz=8, baud=115200):
        super(self.__class__, self).__init__(tty, hz, baud)

        self._serial_thread = threading.Thread(group=None, target=self._read_thread_run)
        self._serial_thread.daemon = True

        self._decode_thread = threading.Thread(group=None, target=self._decode_thread_run)
        self._decode_thread.daemon = True

        self._reset_and_conf(timers=True)

        self._read_decode_queue = queue.Queue()

        self._decode_thread.start()
        self._serial_thread.start()

        while not self._serial_ready: # Wait until we've populated data before continuing
            pass

    def close(self):
        self._serial_stop = True

```

```

if self._serial_thread is not None:
    while self._serial_thread.is_alive(): # Wait for thread to terminate
        pass

def _read_thread_run(self):
    ser = self._serial_obj
    q = self._read_decode_queue
    self._update_info()

    while True:
        msg = self._wait_read_packet()

        q.put(msg)
        self._serial_ready = True

        if self._serial_stop:
            ser.close()
            return

def _decode_thread_run(self):
    dq = self._read_decode_queue
    while True:
        msg = dq.get(block=True)

        dpct = self._decode_packet(msg)

        if 'ir' in dpct:
            self._temps = dpct

            for q in self._queues:
                q.put(self.get_temps())

    if self._serial_stop:

```

```

        return
255
256
257
class OnDemandManager(BaseManager):
258
    def __init__(self, tty, hz=8, baud=115200):
259
        super(self.__class__, self).__init__(tty, hz, baud)
260
261
        self._reset_and_conf(timers=False)
262
263
        self._update_info()
264
265
    def close(self):
266
        self._serial_obj.close()
267
268
    def capture(self):
269
        self._serial_obj.write('p') # Capture frame manually
270
        self._serial_obj.flush()
271
272
        msg = self._wait_read_packet()
273
        dpct = self._decode_packet(msg)
274
275
        if 'ir' in dpct:
276
            self._temps = dpct
277
278
            for q in self._queues:
279
                q.put(self.get_temps())
280
281
        return dpct
282
283
284
285
class ManagerPlaybackEmulator(BaseManager):
286
    _playback_data = None
287
288

```

```

_pb_thread = None
_pb_stop = False
_pb_len = 0

_i = 0

def __init__(self, playback_data=None):
    if playback_data is not None:
        self.irhz, self._playback_data = playback_data
        self._pb_len = len(self._playback_data)

        self.driver = "Playback"
        self.build = "1"

def set_playback_data(self, playback_data):
    self.stop()
    self.irhz, self._playback_data = playback_data
    self._pb_len = len(self._playback_data)

def close(self):
    return

def start(self):
    if self._pb_thread is None:
        self._pb_stop = False
        self._pb_thread = threading.Thread(group=None, target=self._pb_thread_run)
        self._pb_thread.daemon = True
        self._pb_thread.start()

def pause(self):
    self._pb_stop = True

    while self._pb_thread is not None and self._pb_thread.is_alive():
        pass

```

```
        self._pb_thread = None

    def stop(self):
        self._pb_stop = True

        while self._pb_thread is not None and self._pb_thread.is_alive():
            pass

        self._pb_thread = None
        self._i = 0

    def get_temps(self):
        return self._playback_data[self._i]

    def _pb_thread_run(self):
        while True:
            if self._pb_stop:
                return

            for q in self._queues:
                q.put(self._playback_data[self._i])

            time.sleep(1.0/float(self.irhz))

            self._i += 1

            if self._i >= self._pb_len:
                return

class Visualizer(object):
    _display_thread = None
```

323  
324  
325  
326  
327  
328  
329  
330  
331  
332  
333  
334  
335  
336  
337  
338  
339  
340  
341  
342  
343  
344  
345  
346  
347  
348  
349  
350  
351  
352  
353  
354  
355  
356



```

start = datetime.datetime.now()
offset = playdata[0]['start_millis']

for n, frame in enumerate(playdata):
    frame['text'] = 'T+%.3f' % ((frame['start_millis'] - offset)/ 1000.0)
    q.put(frame)

def display_close(self):
    if self._display_thread is None:
        return

    self._display_stop = True
    self._display_thread = None

def close(self):
    self.display_close()

def capture_to_file(self, capture, hz, filen):
    with open(filen + '_thermal.hcap', 'w') as f:
        f.write(str(hz) + "\n")

        for frame in capture:
            t = frame['start_millis']
            motion = frame['movement']
            arr = frame['ir']
            f.write(str(t) + "\n")
            f.write(str(motion) + "\n")
            for l in arr:
                f.write('\t'.join([str(x) for x in l]) + "\n")
            f.write("\n")

def capture_to_img_sequence(self, capture, directory, tmin=15, tmax=45, text=True):
    hz, frames = capture

```

```

pxwidth = 120
print(directory)

for i, frame in enumerate(frames):
    im = Image.new("RGB", (1920, 480))
    draw = ImageDraw.Draw(im)
    font = ImageFont.truetype("arial.ttf", 35)

    for k, row in enumerate(frame['ir']):
        for j, px in enumerate(row):
            rgb = pxdisplay.temp_to_rgb(px, tmin, tmax)

            x = k*pxwidth
            y = j*pxwidth

            coords = (y, x, y+pxwidth+1, x+pxwidth+1)

            draw.rectangle(coords, fill=rgb)

            if text:
                draw.text([y+20,x+(pxwidth/2-20)], str(px), fill=(255,255,255), font=font)

        im.save(os.path.join(directory, '{:09d}.png'.format(i)))

def capture_to_movie(self, capture, filename, width=1920, height=480, tmin=15, tmax=45):
    hz, frames = capture
    tdir = tempfile.mkdtemp()

    self.capture_to_img_sequence(capture, tdir, tmin=tmin, tmax=tmax)

    args = [self._ffmpeg_loc,
            "-y",
            "-r", str(fractions.Fraction(hz)),
            "-i", os.path.join(tdir, "%09d.png"),

```



```

        "-s", "{}x{}".format(width, height),
        "-sws_flags", "neighbor",
        "-sws_dither", "none",
        "-vcodec", 'qtrle', '-pix_fmt', 'rgb24',
        filename + '_thermal.mov'
    ]

    subprocess.call(args)

def file_to_capture(self, filen):
    capture = []
    hz = None
    with open(filen + '_thermal.hcap', 'r') as f:
        frame = {'ir': []}

        for i, line in enumerate(f):
            if i == 0:
                hz = float(line)
                continue

            j = (i-1) % 7
            if j == 0:
                frame['start_millis'] = int(line)
            elif j == 1:
                frame['movement'] = bool(line)
            elif 1 < j < 6:
                frame['ir'].append(tuple([float(x) for x in line.split("\t")]))
            elif j == 6:
                capture.append(frame)
                frame = {'ir': []}

        return (hz, capture)

def capture(self, seconds, name=None, hcap=False, video=False):

```

```

buff = []
q = self._tcam.subscribe()
hz = self._tcam.irhz
tdir = tempfile.mkdtemp()

camera = None
visfile = name + '_visual.h264' #os.path.join(tdir, name + '_visual.h264')

if video and self._camera is not None:
    self._camera.resolution = (1920, 1080)
    self._camera.framerate = hz
    self._camera.start_recording(visfile)

start = time.time()
elapsed = 0

while elapsed <= seconds:
    elapsed = time.time() - start
    buff.append( q.get() )

if video and self._camera is not None:
    self._camera.stop_recording()

    #args = [self._ffmpeg_loc,
    # "-y",
    # "-r", str(fractions.Fraction(hz)),
    # "-i", visfile,
    # "-vcodec", "copy",
    # name + '_visual.mp4'
    # ]

    #subprocess.call(args)

    #os.remove(visfile)

```

```

if hcap:
    self.capture_to_file(buff, hz, name)

return (hz, buff)

def capture_synced(self, seconds, name, hz=2):
    cap_method = getattr(self._tcam, "capture", None)
    if not callable(cap_method):
        raise "Provided tcam class must support the capture method"

    if self._camera is None:
        raise "No picamera object provided, cannot proceed"

    camera = self._camera
    camera.resolution = (1920, 1080)

    # TODO: Currently produces black images. Need to fix.
    # Wait for analog gain to settle on a higher value than 1
    #while camera.analog_gain <= 1 or camera.digital_gain <= 1:
    #    time.sleep(1)

    # Now fix the values
    #camera.shutter_speed = camera.exposure_speed
    #camera.exposure_mode = 'off'
    #g = camera.awb_gains
    #camera.awb_mode = 'off'
    #camera.awb_gains = g

import datetime, threading, time

dir_name = name
frames = seconds * hz
```

```

buff = []
imgbuff = [io.BytesIO() for _ in range(frames + 1)]
fps_avg = []
lag_avg = []

try:
    os.mkdir(dir_name)
except OSError:
    pass

def trigger(next_call, i):
    if i % (hz * 3) == 0:
        print('{} / {} seconds'.format(i/hz, seconds))

    t1_start = time.time()
    camera.capture(imgbuff[i], 'jpeg', use_video_port=True)
    t1_t2 = time.time()
    buff.append(self._tcam.capture())
    t2_stop = time.time()

    sec = t2_stop - t1_start
    fps_avg.append(sec)
    lag_avg.append(t2_stop - t1_t2)

    if sec > (1.0/float(hz)):
        print('Cannot keep up with frame rate!')

    if frames == i:
        return

    th = threading.Timer( next_call - time.time(), trigger,
        args=[next_call+(1.0/float(hz)), i + 1] )
    th.start()

```

```

        th.join()
595
596
trigger(time.time(), 0)
597
598
print('Average time for frame capture = {} seconds'.format(sum(fps_avg)/len(fps_avg)))
599
print('Average lag between camera and thermal capture = {} seconds'.format(sum(lag_avg)/len(lag_avg)))
600
601
self.capture_to_file(buff, hz, os.path.join(dir_name, 'output'))
602
603
for i, b in enumerate(imgbuff):
604
    img_name = os.path.join(dir_name, 'video-{:09d}.jpg'.format(i))
605
    with open(img_name, 'wb') as f:
606
        f.write(b.getvalue())
607
608
return (hz, buff)
609

```

8

## C.1.2 pxdisplay.py

```

from __future__ import division
1
from __future__ import print_function
2
3
from multiprocessing import Process, Queue
4
import colorsys
5
import time
6
7
def millis_diff(a, b):
8
    diff = b - a
9
    return (diff.days * 24 * 60 * 60 + diff.seconds) * 1000 + diff.microseconds / 1000.0
10
11
def temp_to_rgb(temp, tmin, tmax):
12
    OLD_MIN = tmin
13
    OLD_MAX = tmax
14

```

```

    if temp < OLD_MIN:
        temp = OLD_MIN

    if temp > OLD_MAX:
        temp = OLD_MAX

    v = (temp - OLD_MIN) / (OLD_MAX - OLD_MIN)

    rgb = colorsys.hsv_to_rgb((1-v), 1, v * 0.5)

    return tuple(int(c * 255) for c in rgb)

def create(q=None, limit=0, width=100, tmin=15, tmax=45, caption="Display"):
    if q is None:
        q = Queue()

    p = Process(target=_display_process, args=(q, caption, tmin, tmax, limit, width))
    p.daemon = True
    p.start()

    return (q, p)

def _display_process(q, caption, tmin, tmax, limit, pxwidth):
    import pygame
    pygame.init()
    pygame.display.set_caption(caption)

    size = (16 * pxwidth, 4 * pxwidth)
    screen = pygame.display.set_mode(size)

    background = pygame.Surface(screen.get_size())
    background = background.convert_alpha()

```

```

font = pygame.font.Font(None, 36)
49
50
while True:
51
    for event in pygame.event.get():
52
        if event.type == pygame.QUIT:
53
            pygame.quit()
54
            return
55
56
    # Keep the event loop running so the windows don't freeze without data
57
    try:
58
        qg = q.get(True, 0.3)
59
    except:
60
        continue
61
62
    px = qg['ir']
63
64
    #lag = q.qsize()
65
    #if lag > 0:
66
    #    print("WARNING: Dropped " + str(lag) + " frames")
67
68
    for i, row in enumerate(px):
69
        for j, v in enumerate(row):
70
            rgb = temp_to_rgb(v, tmin, tmax)
71
72
            x = i*pxwidth
73
            y = j*pxwidth
74
75
            screen.fill(rgb, (y, x, pxwidth, pxwidth))
76
77
if 'text' in qg:
78
    background.fill((0, 0, 0, 0))
79
    text = font.render(qg['text'], 1, (255,255,255))
80
    background.blit(text, (0,0))
81
82

```

<i># Blit everything to the screen</i>	83
screen.blit(background, (0, 0))	84
	85
pygame.display.flip()	86
	87
if limit != 0:	88
time.sleep(1.0/float(limit))	89

### C.1.3 features.py

83

from __future__ import division	1
from __future__ import print_function	2
	3
import threading	4
import pxdisplay	5
import time	6
import math	7
import copy	8
import networkx as nx	9
import itertools	10
import collections	11
<i>#import matplotlib.pyplot as plt</i>	12
	13
def tuple_to_list(l):	14
new = []	15
	16
for r in l:	17
new.append(list(r))	18
	19
return new	20
	21
def min_temps(l, n):	22



```

flat = []
for i, r in enumerate(l):
    for j, v in enumerate(r):
        flat.append(((i,j), v))
flat.sort(key=lambda x: x[1])

ret = [x[0] for x in flat]
return ret[:n]

def init_arr(val=None):
    return [[val for x in range(16)] for x in range(4)]

class Features(object):
    _q = None
    _thread = None

    _background = None
    _means = None
    _stds = None
    _stds_post = None
    _active = None

    _num_active = None
    _connected_graph = None
    _num_connected = None
    _size_connected = None

    _lock = None

    _rows = None
    _columns = None

    motion_weight = None

```

23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56

```

nomotion_weight = None
57
58
motion_window = None
59
60
hz = None
61
62
display = None
63
64
_exit = False
65
66
def __init__(self, q, hz, motion_window=10, motion_weight=0.1, nomotion_weight=0.01, display=True, rows=4,
67
↳ columns=16):
    self._q = q
    68
    self.hz = hz
    69
    self.motion_weight = motion_weight
    70
    self.nomotion_weight = nomotion_weight
    71
    self.display = display
    72
    self.motion_window = motion_window
    73
    74
    self._active = []
    75
    76
    self._rows = rows
    77
    self._columns = columns
    78
    79
    self._thread = threading.Thread(group=None, target=self._monitor_thread)
    80
    self._thread.daemon = True
    81
    82
    self._lock = threading.Lock()
    83
    84
    self._thread.start()
    85
    86
def get_background(self):
    87
    self._lock.acquire()
    88
    background = copy.deepcopy(self._background)
    89

```

```

        self._lock.release()
        return background

def get_means(self):
    self._lock.acquire()
    means = copy.deepcopy(self._means)
    self._lock.release()
    return means

def get_stds(self):
    self._lock.acquire()
    stds = copy.deepcopy(self._stds_post)
    self._lock.release()
    return stds

def get_active(self):
    self._lock.acquire()
    active = copy.deepcopy(self._active)
    self._lock.release()
    return active

def get_features(self):
    self._lock.acquire()
    num_active = self._num_active
    num_connected = self._num_connected
    size_connected = self._size_connected
    self._lock.release()
    return (num_active, num_connected, size_connected)

def close(self):
    self._exit = True

    if self._thread is not None:
        while self._thread.is_alive(): # Wait for thread to terminate

```

```

        pass
124
125
def __del__(self):
126
    self.close()
127
128
def _monitor_thread(self):
129
    bdisp = None
130
    ddisp = None
131
132
    freq = self.hz * self.motion_window
133
    mwin = collections.deque([False] * freq)
134
135
    n = 1
136
    while True:
137
        fdata = None
138
139
        if self._exit:
140
            return
141
142
        try:
143
            fdata = self._q.get(True, 0.3)
144
        except:
145
            continue
146
147
        if self.display and bdisp is None:
148
            bdisp, _ = pxdisplay.create(caption="Background", width=80)
149
            ddisp, _ = pxdisplay.create(caption="Deviation", width=80)
150
151
        frame = fdata['ir']
152
153
        mwin.popleft()
154
        mwin.append(fdata['movement'])
155
        motion = any(mwin)
156
157

```

```

self._lock.acquire()
158

self._active = []
159
160
161
g = nx.Graph()
162
163
if n == 1:
164
    self._background = tuple_to_list(frame)
165
    self._means = tuple_to_list(frame)
166
    self._stds = init_arr(0)
167
    self._stds_post = init_arr()
168
else:
169
    weight = self.nomotion_weight
170
    use_frame = frame
171
172
    # Not currently working
173
    #if motion:
174
    # indeces = min_temps(frame, 5)
175
    # scalepx = []
176
    #
177
    # for i, j in indeces:
178
    #     scalepx.append(self._background[i][j] / frame[i][j])
179
    #
180
    # scale = sum(scalepx) / len(scalepx)
181
    # scaled_bg = [[x * scale for x in r] for r in frame]
182
    #
183
    # weight = self.motion_weight
184
    # use_frame = scaled_bg
185
186
for i in range(self._rows):
187
    for j in range(self._columns):
188
        prev = self._background[i][j]
189
        cur = use_frame[i][j]
190
191

```

```

cur_mean = self._means[i][j]
cur_std = self._stds[i][j]

if not motion: # TODO: temp fix
    self._background[i][j] = weight * cur + (1 - weight) * prev

    # maybe exclude these from motion calculations?
    # n doesn't change when in motion, so it'll cause all sort of corrupted results, as they use n?
    self._means[i][j] = cur_mean + (cur - cur_mean) / n
    self._stds[i][j] = cur_std + (cur - cur_mean) * (cur - self._means[i][j])
    self._stds_post[i][j] = math.sqrt(self._stds[i][j] / (n-1))

if (cur - self._background[i][j]) > (3 * self._stds_post[i][j]):
    self._active.append((i,j))

    g.add_node((i,j))

    x = [(-1, -1), (-1, 0), (-1, 1), (0, -1)] # Nodes that have already been computed as active
    for ix, jx in x:
        if (i+ix, j+jx) in self._active:
            g.add_edge((i,j), (i+ix,j+jx))

active = self._active

self._num_active = len(self._active)

components = list(nx.connected_components(g))

self._connected_graph = g
self._num_connected = nx.number_connected_components(g)
self._size_connected = max(len(component) for component in components) if len(components) > 0 else None

self._lock.release()

```

```

if self.display:
    bdisp.put({'ir': self._background})

    if n >= 2:
        std = {'ir': init_arr(0)}

        for i, j in active:
            std['ir'][i][j] = frame[i][j]

        ddisp.put(std)

    #print(n)
    #if n > 30:
    #    nx.draw(g)
    #    plt.show()

if not motion:
    n += 1

```

## C.2 Arduino Sketch

```

/**
 * MLX90260 Arduino Interface
 * Based on code from http://forum.arduino.cc/index.php/topic,126244.0.html
 */
//#define __ASSERT_USE_STDERR

//#include <assert.h>
#include <math.h>
#include <Wire.h>
#include <EEPROM.h>

```

```

#include "SimpleTimer.h" // http://playground.arduino.cc/Code/SimpleTimer
11
12
// Configurable options
13
const int POR_CHECK_FREQ    = 2000; // Time in milliseconds to check if MLX reset has occurred
14
const int PIR_INTERRUPT_PIN = 0;    // D2 on the Arduino Uno
15
16
// Configuration constants
17
#define PIXEL_LINES    4
18
#define PIXEL_COLUMNS  16
19
#define BYTES_PER_PIXEL 2
20
#define EEPROM_SIZE    255
21
#define NUM_PIXELS      (PIXEL_LINES * PIXEL_COLUMNS)
22
23
// EEPROM helpers
24
#define E_READ(X)        (EEPROM_DATA[X])
25
#define E_WRITE(X, Y)    (EEPROM_DATA[X] = (Y))
26
27
// Bit fiddling helpers
28
#define BYTES2INT(H, L)   ( ((H) << 8) + (L) )
29
#define UBYTES2INT(H, L) ( ((unsigned int)(H) << 8) + (unsigned int)(L) )
30
#define BYTE2INT(B)       ( ((int)(B) > 127) ? ((int)(B) - 256) : (int)(B) )
31
#define E_BYTES2INT(H, L) ( BYTES2INT(E_READ(H), E_READ(L)) )
32
#define E_UBytes2INT(H, L) ( UBYTES2INT(E_READ(H), E_READ(L)) )
33
#define E_BYTE2INT(X)     ( BYTE2INT(E_READ(X)) )
34
35
// I2C addresses
36
#define ADDR_EEPROM    0x50
37
#define ADDR_SENSOR    0x60
38
39
// I2C commands
40
#define CMD_SENSOR_READ    0x02
41
#define CMD_SENSOR_WRITE_CONF 0x03
42
#define CMD_SENSOR_WRITE_TRIM 0x04
43
44

```



```

// Addresses in the sensor RAM (see Table 9 in spec)
#define SENSOR_PTAT      0x90
#define SENSOR_CPIX      0x91
#define SENSOR_CONFIG    0x92

// Addresses in the EEPROM (see Tables 5 & 7 in spec)
#define EEPROM_A_I_00     0x00 // A_i(0,0) IR pixel individual offset coefficient (ends at 0x3F)
#define EEPROM_B_I_00     0x40 // B_i(0,0) IR pixel individual offset coefficient (ends at 0x7F)
#define EEPROM_DELTA_ALPHA_00 0x80 // Delta-alpha(0,0) IR pixel individual offset coefficient (ends at 0xBF)
#define EEPROM_A_CP       0xD4 // Compensation pixel individual offset coefficients
#define EEPROM_B_CP       0xD5 // Individual Ta dependence (slope) of the compensation pixel offset
#define EEPROM_ALPHA_CP_L 0xD6 // Sensitivity coefficient of the compensation pixel (low)
#define EEPROM_ALPHA_CP_H 0xD7 // Sensitivity coefficient of the compensation pixel (high)
#define EEPROM_TGC        0xD8 // Thermal gradient coefficient
#define EEPROM_B_I_SCALE  0xD9 // Scaling coefficient for slope of IR pixels offset
#define EEPROM_V_TH_L     0xDA // V_TH0 of absolute temperature sensor (low)
#define EEPROM_V_TH_H     0xDB // V_TH0 of absolute temperature sensor (high)
#define EEPROM_K_T1_L     0xDC // K_T1 of absolute temperature sensor (low)
#define EEPROM_K_T1_H     0xDD // K_T1 of absolute temperature sensor (high)
#define EEPROM_K_T2_L     0xDE // K_T2 of absolute temperature sensor (low)
#define EEPROM_K_T2_H     0xDF // K_T2 of absolute temperature sensor (high)
#define EEPROM_ALPHA_O_L  0xE0 // Common sensitivity coefficient of IR pixels (low)
#define EEPROM_ALPHA_O_H  0xE1 // Common sensitivity coefficient of IR pixels (high)
#define EEPROM_ALPHA_O_SCALE 0xE2 // Scaling coefficient for common sensitivity
#define EEPROM_DELTA_ALPHA_SCALE 0xE3 // Scaling coefficient for individual sensitivity
#define EEPROM_EPSILON_L  0xE4 // Emissivity (low)
#define EEPROM_EPSILON_H  0xE5 // Emissivity (high)
#define EEPROM_TRIMMING_VAL 0xF7 // Oscillator trimming value

// Config flag locations
#define CFG_TA      8
#define CFG_IR      9
#define CFG_POR     10

```

	<i>// Arduino EEPROM addresses</i>	79
	<i>#define AEEP_FREQ_ADDR 0x00</i>	80
		81
	<i>// Global variables</i>	82
	<i>unsigned int PTAT; // Proportional to absolute temperature value</i>	83
	<i>int CPIX; // Compensation pixel</i>	84
		85
	<i>int IRDATA[NUM_PIXELS]; // Infrared raw data</i>	86
	<i>byte EEPROM_DATA[EEPROM_SIZE]; // EEPROM dump</i>	87
		88
	<i>float ta; // Absolute chip temperature / ambient chip temperature (degrees celsius)</i>	89
	<i>float emissivity; // Emissivity compensation</i>	90
	<i>float k_t1; // K_T1 of absolute temperature sensor</i>	91
	<i>float k_t2; // K_T2 of absolute temperature sensor</i>	92
	<i>float da0_scale; // Scaling coefficient for individual sensitivity</i>	93
	<i>float alpha_const; // Common sensitivity coefficient of IR pixels and scaling coefficient for</i>	94
73	<i>↳ common sensitivity</i>	
		95
	<i>int v_th; // V_TH0 of absolute temperature sensor</i>	96
	<i>int a_cp; // Compensation pixel individual offset coefficients</i>	97
	<i>int b_cp; // Individual Ta dependence (slope) of the compensation pixel offset</i>	98
	<i>int tgc; // Thermal gradient coefficient</i>	99
	<i>int b_i_scale; // Scaling coefficient for slope of IR pixels offset</i>	100
		101
	<i>float alpha_ij[NUM_PIXELS]; // Individual pixel sensitivity coefficient</i>	102
	<i>int a_ij[NUM_PIXELS]; // Individual pixel offset</i>	103
	<i>int b_ij[NUM_PIXELS]; // Individual pixel offset slope coefficient</i>	104
		105
	<i>char hdbuf[2]; // Hex printing buffer</i>	106
	<i>int res; // Error code storage</i>	107
		108
	<i>float temp[NUM_PIXELS]; // Final calculated temperature values in degrees celsius</i>	109
		110
	<i>SimpleTimer timer; // Allows timed callbacks for temp functions</i>	111

```

void(* reset_arduino_now) (void) = 0;    // Creates function to reset Arduino
// Stores references to the 3 timers used in the program
int ir_timer;
int ta_timer;
int por_timer;

// Stores refresh frequency, read out of the EEPROM
short REFRESH_FREQ;

volatile bool pir_motion_detected = false;

/*
// Send assertion failures over serial
void __assert(const char *__func, const char *__file, int __lineno, const char *__sevp) {
    // transmit diagnostic informations through serial link.
    Serial.println(__func);
    Serial.println(__file);
    Serial.println(__lineno, DEC);
    Serial.println(__sevp);
    Serial.flush();
    // abort program execution.
    abort();
}*/

void reset_arduino() {
    Serial.flush();
    reset_arduino_now();
}

// Basic assertion failure function
void assert(boolean a) {
    if (!a) Serial.println("ASSFAIL");

```

```

}
// Takes byte value and will output 2 character hex representation on serial
void print_hex(byte b) {
    hdbuf[0] = (b >> 4) + 0x30;
    if (hdbuf[0] > 0x39) hdbuf[0] +=7;

    hdbuf[1] = (b & 0x0f) + 0x30;
    if (hdbuf[1] > 0x39) hdbuf[1] +=7;

    Serial.print(hdbuf);
}

// Will read memory from the given sensor address and convert it into an integer
int _sensor_read_int(byte read_addr) {
    Wire.beginTransaction(ADDR_SENSOR);
    Wire.write(CMD_SENSOR_READ);
    Wire.write(read_addr);
    Wire.write(0x00); // address step (0)
    Wire.write(0x01); // number of reads (1)
    res = Wire.endTransmission(false); // we must use the repeated start here
    if (res != 0) return -1;

    Wire.requestFrom(ADDR_SENSOR, 2); // technically the 1 read takes up 2 bytes

    int LSB, MSB;
    int i = 0;
    while( Wire.available() ) {
        i++;

        if (i > 2) {
            return -1; // Returned more bytes than it should have
        }
    }
}

```

```

    LSB = Wire.read();
    MSB = Wire.read();
}

return UBYTES2INT(MSB, LSB); // rearrange int to account for endian difference (TODO: check)

// Will read a configuration flag bit specified by flag_loc from the sensor config
bool _sensor_read_config_flag(int flag_loc) {
    int cur_cfg = _sensor_read_int(SENSOR_CONFIG);
    return (bool)(cur_cfg & ( 1 << flag_loc )) >> flag_loc;
}

// Reads Proportional To Absolute Temperature (PTAT) value
int sensor_read_ptat() {
    return _sensor_read_int(SENSOR_PTAT);
}

// Reads compensation pixel
int sensor_read_cpix() {
    return _sensor_read_int(SENSOR_CPIX);
}

// Reads POR flag
bool sensor_read_por() {
    return _sensor_read_config_flag(CFG_POR); // POR is 10th bit
}

// Read Ta measurement flag
bool sensor_read_ta_measure() {
    return _sensor_read_config_flag(CFG_TA);
}

// Read IR measurement flag

```

```

bool sensor_read_ir_measure() {
    return _sensor_read_config_flag(CFG_IR);
}

// Reads all raw IR data from sensor into IRDATA variable
boolean sensor_read_irdata() {
    int i = 0;

    // Due to wire library buffer limitations, we can only read up to 32 bytes at a time
    // Thus, the request has been split into multiple different requests to get the full 128 values
    // Each pixel value takes up two bytes (???) thus NUM_PIXELS * 2
    for (int line = 0; line < PIXEL_LINES; line++) {
        Wire.beginTransaction(ADDR_SENSOR);
        Wire.write(CMD_SENSOR_READ);
        Wire.write(line);
        Wire.write(0x04);
        Wire.write(0x10);
        res = Wire.endTransmission(false); // use repeated start to get answer

        if (res != 0) return false;

        Wire.requestFrom(ADDR_SENSOR, PIXEL_COLUMNS * BYTES_PER_PIXEL);

        byte PIX_LSB, PIX_MSB;

        for(int j = 0; j < PIXEL_COLUMNS; j++) {
            if (!Wire.available()) return false;

            // We read two bytes
            PIX_LSB = Wire.read();
            PIX_MSB = Wire.read();

            IRDATA[i] = BYTES2INT(PIX_MSB, PIX_LSB);
            i++;

```

```

    }
    }

    return true;
}

// Will send a command and the provided most significant and least significant bit
// with the appropriate check bit added
// Returns the Wire success/error code
boolean _sensor_write_check(byte cmd, byte check, byte lsb, byte msb) {
    Wire.beginTransaction(ADDR_SENSOR);
    Wire.write(cmd);           // Send the command
    Wire.write(lsb - check);   // Send the least significant byte check
    Wire.write(lsb);           // Send the least significant byte
    Wire.write(msb - check);   // Send the most significant byte check
    Wire.write(msb);           // Send the most significant byte
    return Wire.endTransmission() == 0;
}

// See datasheet: 9.4.2 Write configuration register command
// See datasheet: 8.2.2.1 Configuration register (0x92)
// Check byte is 0x55 in this instance
boolean sensor_write_conf() {
    byte cfg_MSB = B01110100;
    //          |||
    //          |||*--- Ta measurement running (read only)
    //          |||*---- IR measurement running (read only)
    //          |||*----- POR flag cleared
    //          |||*----- I2C FM+ mode enabled
    //          ||*----- Ta refresh rate (2 byte code, 2Hz hardcoded)
    //          |*----- ADC high reference
    //          *----- NA

    byte cfg_LSB = B00001110;

```

```

//          //
//          ///****-- 4 byte IR refresh rate (4 byte code, 1Hz default)
//          /**----- NA
//          /*----- Continuous measurement mode
//          *----- Normal operation mode

switch(REFRESH_FREQ) {
case 0: // 0.5Hz
    cfg_LSB = B00001111;
    break;
case 2:
    cfg_LSB = B00001101;
    break;
case 4:
    cfg_LSB = B00001100;
    break;
case 8:
    cfg_LSB = B00001011;
    break;
case 16:
    cfg_LSB = B00001010;
    break;
case 32:
    cfg_LSB = B00001001;
    break;
case 64:
    cfg_LSB = B00001000;
    break;
case 128:
    cfg_LSB = B00000111;
    break;
case 256:
    cfg_LSB = B00000110;
    break;

```





```

    }
    350

    if (i < EEPROM_SIZE) { // If we didn't get the whole EEPROM
    351
        return false;
    352
    }
    353
    354
    return true;
    355
}
    356
    357
    358
    // Writes various calculation values from EEPROM into global variables
    359
    void calculate_init() {
    360
        v_th = E_BYTES2INT(EEPROM_V_TH_H, EEPROM_V_TH_L);
    361
        k_t1 = E_BYTES2INT(EEPROM_K_T1_H, EEPROM_K_T1_L) / 1024.0;
    362
        k_t2 = E_BYTES2INT(EEPROM_K_T2_H, EEPROM_K_T2_L) / 1048576.0;
    363
    364
        a_cp = E_BYTE2INT(EEPROM_A_CP);
    365
        b_cp = E_BYTE2INT(EEPROM_B_CP);
    366
        tgc = E_BYTE2INT(EEPROM_TGC);
    367
    368
        b_i_scale = E_READ(EEPROM_B_I_SCALE);
    369
    370
        emissivity = E_UBYTES2INT(EEPROM_EPSILON_H, EEPROM_EPSILON_L) / 32768.0;
    371
    372
        da0_scale = pow(2, -E_READ(EEPROM_DELTA_ALPHA_SCALE));
    373
        alpha_const = (float)E_UBYTES2INT(EEPROM_ALPHA_0_H, EEPROM_ALPHA_0_L) * pow(2, -E_READ(EEPROM_ALPHA_0_SCALE));
    374
    375
        for (int i = 0; i < NUM_PIXELS; i++){
    376
            float alpha_var = (float)E_READ(EEPROM_DELTA_ALPHA_00 + i) * da0_scale;
    377
            alpha_ij[i] = (alpha_const + alpha_var);
    378
    379
            a_ij[i] = E_BYTE2INT(EEPROM_A_I_00 + i);
    380
            b_ij[i] = E_BYTE2INT(EEPROM_B_I_00 + i);
    381
        }
    382
    }
    383

```

```

// Calculates the absolute chip temperature from the proportional to absolute temperature (PTAT)
float calculate_ta() {
    float ptat = (float)sensor_read_ptat();
    assert(ptat != -1);
    return (-k_t1 +
        sqrt(
            square(k_t1) -
            ( 4 * k_t2 * (v_th-ptat) )
        )
    ) / (2*k_t2) + 25;
}

// Calculates the final temperature value for each pixel and stores it in temp array
void calculate_temp() {
    float v_cp_off_comp = (float) CPIX - (a_cp + (b_cp/pow(2, b_i_scale)) * (ta - 25));

    for (int i = 0; i < NUM_PIXELS; i++){
        float alpha_ij_v = alpha_ij[i];
        int a_ij_v = a_ij[i];
        int b_ij_v = b_ij[i];

        float v_ir_tgc_comp = IRDATA[i] - (a_ij_v + (float)(b_ij_v/pow(2, b_i_scale)) * (ta - 25)) -
        ↪ ((float)tgc/32)*v_cp_off_comp);
        float v_ir_comp = v_ir_tgc_comp / emissivity;
        temp[i] = sqrt(sqrt((v_ir_comp/alpha_ij_v) + pow((ta + 273.15),4))) - 273.15;
    }
}

// Prints all of EEPROM as hex
void print_eeprom() {
    Serial.print("EEPROM ");
    for(int i = 0; i < EEPROM_SIZE; i++) {

```

83

```
        print_hex(E_READ(i));
    }
    Serial.println();
}

// Prints a serial "packet" containing IR data
void print_packet(unsigned long cur_time) {
    Serial.print("START ");
    Serial.println(cur_time);

    Serial.print("MOVEMENT ");
    Serial.println(pir_motion_detected);

    for(int i = 0; i<NUM_PIXELS; i++) {
        Serial.print(temp[i]);

        if ((i+1) % PIXEL_COLUMNS == 0) {
            Serial.println();
        } else {
            Serial.print("\t");
        }
    }

    Serial.print("STOP ");
    Serial.println(millis());
    Serial.flush();
}

// Prints info about driver, build and configuration
void print_info() {
    Serial.println("INFO START");
    Serial.println("DRIVER MLX90620");

    Serial.print("BUILD ");
```

```

    Serial.print(__DATE__);
    Serial.print(" ");
    Serial.println(__TIME__);

    Serial.print("IRHZ ");
    Serial.println(REFRESH_FREQ);
    Serial.println("INFO STOP");
}

// Runs functions necessary to initialize the temperature sensor
void initialize() {
    assert(eeprom_read_all());
    assert(sensor_write_trim());
    assert(sensor_write_conf());

    calculate_init();

    ta_loop();
}

// Calculates absolute temperature
void ta_loop() {
    ta = calculate_ta();
}

// Checks if the sensor as been reset, and if so, re-runs the initialize functions
void por_loop() {
    if (!sensor_read_por()) { // there has been a reset
        initialize();
    }
}

// Runs functions necessary to compute and output the temperature data
void ir_loop() {

```

```

    unsigned long cur_time = millis();
    assert(sensor_read_irdata());

    CPIX = sensor_read_cpix();
    assert(CPIX != -1);

    calculate_temp();

    print_packet(cur_time);

    pir_motion_detected = false;
}

// Configures timers to poll IR and other data periodically
void activate_timers() {
    float hz = REFRESH_FREQ;

    if (REFRESH_FREQ == 0) {
        hz = 0.5;
    }

    // Calculate how many milliseconds each timer should run for
    // based upon the configured refresh rate of the IR data and
    // absolute temperature data
    long irlen = (1/hz) * 1000;
    long talen = (1/2.0) * 1000;

    if (talen < irlen) {
        talen = irlen;
    }

    ir_timer = timer.setInterval(irlen, ir_loop);
    ta_timer = timer.setInterval(talen, ta_loop);

```

	por_timer = timer.setInterval(POR_CHECK_FREQ, por_loop);	519
		520
	attachInterrupt(PIR_INTERRUPT_PIN, pir_motion, RISING);	521
	}	522
		523
	<i>// Disables timers to poll IR and other data periodically</i>	524
	void deactivate_timers() {	525
	timer.disable(ir_timer);	526
	timer.deleteTimer(ir_timer);	527
		528
	timer.disable(ta_timer);	529
	timer.deleteTimer(ta_timer);	530
		531
	timer.disable(por_timer);	532
	timer.deleteTimer(por_timer);	533
		534
86	detachInterrupt(PIR_INTERRUPT_PIN);	535
	}	536
		537
	void pir_motion() {	538
	pir_motion_detected = true;	539
	}	540
		541
	void read_freq() {	542
	byte rd = EEPROM.read(0);	543
		544
	if (rd > 9) {	545
	rd = 0;	546
	EEPROM.write(AEEP_FREQ_ADDR, 0);	547
	}	548
		549
	switch(rd) {	550
	case 1:	551
	REFRESH_FREQ = 1;	552

```

        break;
case 2:
    REFRESH_FREQ = 2;
    break;
case 3:
    REFRESH_FREQ = 4;
    break;
case 4:
    REFRESH_FREQ = 8;
    break;
case 5:
    REFRESH_FREQ = 16;
    break;
case 6:
    REFRESH_FREQ = 32;
    break;
case 7:
    REFRESH_FREQ = 64;
    break;
case 8:
    REFRESH_FREQ = 128;
    break;
case 9:
    REFRESH_FREQ = 256;
    break;
case 10:
    REFRESH_FREQ = 512;
    break;

default:
case 0:
    REFRESH_FREQ = 0;
    break;
}

```



∞

```
} 587

void write_freq(int freq) { 588
    byte wt; 589

    switch(freq) { 590
        case 1: 591
            wt = 1; 592
            break; 593
        case 2: 594
            wt = 2; 595
            break; 596
        case 4: 597
            wt = 3; 598
            break; 599
        case 8: 600
            wt = 4; 601
            break; 602
        case 16: 603
            wt = 5; 604
            break; 605
        case 32: 606
            wt = 6; 607
            break; 608
        case 64: 609
            wt = 7; 610
            break; 611
        case 128: 612
            wt = 8; 613
            break; 614
        case 256: 615
            wt = 9; 616
            break; 617
        case 512: // writing 512 to the config doesn't work for some reason 618
    } 619
} 620
```

	wt = 10;	621
	break;	622
		623
	default:	624
	case 0:	625
	wt = 0;	626
	break;	627
	}	628
		629
	EEPROM.write(AEEP_FREQ_ADDR, wt);	630
	}	631
		632
	<i>// Configure libraries and sensors at startup</i>	633
	void setup() {	634
	pinMode(2, INPUT);	635
		636
68	Wire.begin();	637
	Serial.begin(115200);	638
		639
	Serial.println();	640
	Serial.print("INIT ");	641
	Serial.println(millis());	642
		643
	read_freq();	644
	print_info();	645
	initialize();	646
		647
	Serial.print("ACTIVE ");	648
	Serial.println(millis());	649
	Serial.flush();	650
	}	651
		652
	char manualLoop = 0;	653
		654

```

// Triggered when serial data is sent to Arduino. Used to trigger basic actions. 655
void serialEvent() { 656
    while (Serial.available()) { 657
        char in = (char)Serial.read(); 658
        if (in == '\r' || in == '\n') continue; 659

        switch (in) { 660
            case 'R': 661
            case 'r': 662
                reset_arduino(); 663
                break; 664
            case 'I': 665
            case 'i': 666
                print_info(); 667
                break; 668
            case 'T': 669
            case 't': 670
                activate_timers(); 671
                break; 672
            case 'O': 673
            case 'o': 674
                deactivate_timers(); 675
                break; 676
            case 'P': 677
            case 'p': 678
                if (manualLoop == 16) { // Run ta_loop every 16 manual iterations 679
                    ta_loop(); 680
                    manualLoop = 0; 681
                } 682
        } 683
    } 684
} 685
686
687
688

```

```
        ir_loop();
        manualLoop++;
        break;

    case 'f':
    case 'F':
        write_freq(Serial.parseInt());
        reset_arduino();
        break;

    default:
        Serial.println("UNKNOWN COMMAND");
    }
}

void loop() {
    timer.run();
}
```

689  
690  
691  
692  
693  
694  
695  
696  
697  
698  
699  
700  
701  
702  
703  
704  
705  
706  
707  
708

## APPENDIX D

# Full Results

## D.1 Classifier Experiment Set 1

### D.1.1 Nominal Results

#### D.1.1.1 Multilayer Perceptron

=== Run information ===

Scheme:weka.classifiers.functions.MultilayerPerceptron -L 0.3 -M 0.2 -N 500 -V

↪ 0 -S 0 -E 20 -H a

Relation: persondata

Instances: 1018

Attributes: 4

npeople

numactive

numconnected

sizeconnected

Test mode:10-fold cross-validation

=== Classifier model (full training set) ===

Sigmoid Node 0

Inputs Weights

Threshold -17.82098538043138

Node 4 10.791969171144421

Node 5 11.691523214004624

Node 6 10.27822454007849

Sigmoid Node 1

Inputs Weights

Threshold -1.7152968701419837

Node 4 -7.571770467221156

Node 5 -5.127559825773417

Node 6 6.476543544185421

Sigmoid Node 2

Inputs Weights

```

Threshold      1.9339801770968827
Node 4      -2.6952562384782275
Node 5      2.620671306339044
Node 6      -8.20640522534469
Sigmoid Node 3
  Inputs      Weights
Threshold      -2.47686769207173
Node 4      3.378401295716778
Node 5      0.6306342479203954
Node 6      -3.925441217557144
Sigmoid Node 4
  Inputs      Weights
Threshold      3.5799482950612207
Attrib numactive      3.5468014230351153
Attrib numconnected    -1.9506325622725589
Attrib sizeconnected    15.731567321159028
Sigmoid Node 5
  Inputs      Weights
Threshold      -13.566502805330678
Attrib numactive      1.4688308541180812
Attrib numconnected    4.568878889123458
Attrib sizeconnected    -20.825158179068985
Sigmoid Node 6
  Inputs      Weights
Threshold      2.782123031368699
Attrib numactive      -17.96989902500443
Attrib numconnected    4.340499299171253
Attrib sizeconnected    15.599045813296243
Class 0
  Input
  Node 0
Class 1
  Input
  Node 1
Class 2
  Input
  Node 2
Class 3
  Input
  Node 3

```

Time taken to build model: 0.88 seconds

=== Stratified cross-validation ===  
 === Summary ===

Correctly Classified Instances	799	78.4872 %
Incorrectly Classified Instances	219	21.5128 %

Kappa statistic	0.6824
Mean absolute error	0.153
Root mean squared error	0.2936
Relative absolute error	44.3263 %
Root relative squared error	70.6965 %
Total Number of Instances	1018

=== Detailed Accuracy By Class ===

	TP Rate	FP Rate	Precision	Recall	F-Measure	ROC Area	Class
	0.908	0.133	0.822	0.908	0.862	0.926	0
	0.687	0.097	0.7	0.687	0.693	0.863	1
	0.801	0.074	0.812	0.801	0.806	0.903	2
	0.313	0.01	0.667	0.313	0.426	0.864	3
WAvg.	0.785	0.1	0.779	0.785	0.777	0.9	

=== Confusion Matrix ===

	a	b	c	d	<-- classified as
373	32	6	0	0	a = 0
63	173	16	0	0	b = 1
11	37	233	10	0	c = 2
7	5	32	20	0	d = 3

### D.1.1.2 IBk

=== Run information ===

```
Scheme:weka.classifiers.lazy.IBk -K 1 -W 0 -A
↳ "weka.core.neighboursearch.LinearNNSearch -A
↳ "\"weka.core.EuclideanDistance -R first-last\""
Relation:      persondata
Instances:     1018
Attributes:    4
               npeople
               numactive
               numconnected
               sizeconnected
Test mode:10-fold cross-validation
```

=== Classifier model (full training set) ===

IB1 instance-based classifier  
using 1 nearest neighbour(s) for classification

Time taken to build model: 0 seconds

=== Stratified cross-validation ===

=== Summary ===

Correctly Classified Instances	586	57.5639 %
Incorrectly Classified Instances	432	42.4361 %
Kappa statistic	0.4251	
Mean absolute error	0.2294	
Root mean squared error	0.4245	
Relative absolute error	66.4479 %	
Root relative squared error	102.2105 %	
Total Number of Instances	1018	

=== Detailed Accuracy By Class ===

	TP Rate	FP Rate	Precision	Recall	F-Measure	ROC Area	Class
	0.292	0.063	0.759	0.292	0.422	0.736	0
	0.782	0.307	0.456	0.782	0.576	0.849	1
	0.845	0.087	0.796	0.845	0.82	0.922	2
	0.359	0.101	0.193	0.359	0.251	0.748	3
WAvg.	0.576	0.132	0.659	0.576	0.563	0.818	

=== Confusion Matrix ===

```
  a   b   c   d  <-- classified as
120 196  16  79 |   a = 0
```



33	197	15	7		b = 1
4	31	246	10		c = 2
1	8	32	23		d = 3

### D.1.1.3 Naive Bayes

=== Run information ===

Scheme:weka.classifiers.bayes.NaiveBayes

Relation: persondata

Instances: 1018

Attributes: 4  
npeople  
numactive  
numconnected  
sizeconnected

Test mode:10-fold cross-validation

=== Classifier model (full training set) ===

Naive Bayes Classifier

Attribute	Class			
	0 (0.4)	1 (0.25)	2 (0.29)	3 (0.06)
=====				
numactive				
mean	1.9705	10.644	20.4324	31.7871
std. dev.	4.2009	7.0371	9.8619	10.01
weight sum	323	252	291	64
precision	1.0417	1.0417	1.0417	1.0417
numconnected				
mean	0.7864	1.5198	2.2165	2.375
std. dev.	1.005	1.0214	0.8522	0.7181
weight sum	323	252	291	64
precision	1	1	1	1
sizeconnected				
mean	3.481	10.2941	11.4944	19.6742
std. dev.	4.2277	4.7478	5.2921	7.8351
weight sum	151	223	282	64
precision	1.4848	1.4848	1.4848	1.4848

Time taken to build model: 0.01 seconds

=== Stratified cross-validation ===

=== Summary ===

Correctly Classified Instances	674	66.2083 %
Incorrectly Classified Instances	344	33.7917 %

Kappa statistic	0.4964
Mean absolute error	0.2087
Root mean squared error	0.3516
Relative absolute error	60.4564 %
Root relative squared error	84.6405 %
Total Number of Instances	1018

=== Detailed Accuracy By Class ===

	TP Rate	FP Rate	Precision	Recall	F-Measure	ROC Area	Class
	0.925	0.209	0.75	0.925	0.828	0.889	0
	0.357	0.127	0.481	0.357	0.41	0.746	1
	0.608	0.149	0.621	0.608	0.615	0.826	2
	0.422	0.013	0.692	0.422	0.524	0.914	3
WAvg.	0.662	0.159	0.643	0.662	0.644	0.837	

=== Confusion Matrix ===

	a	b	c	d	<-- classified as
380	16	15	0	0	a = 0
100	90	60	2	1	b = 1
27	77	177	10	2	c = 2
0	4	33	27	3	d = 3

#### D.1.1.4 SMO

=== Run information ===

```
Scheme:weka.classifiers.functions.SMO -C 1.0 -L 0.001 -P 1.0E-12 -N 0 -V -1 -W
↳ 1 -K "weka.classifiers.functions.supportVector.PolyKernel -C 250007 -E
↳ 1.0"
```

```
Relation:      persondata
Instances:     1018
Attributes:    4
               npeople
               numactive
               numconnected
               sizeconnected
Test mode:10-fold cross-validation
```

=== Classifier model (full training set) ===

SMO

Kernel used:

Linear Kernel:  $K(x,y) = \langle x,y \rangle$

Classifier for classes: 0, 1

BinarySMO

Machine linear: showing attribute weights, not support vectors.

```
      4.7748 * (normalized) numactive
+      0.1637 * (normalized) numconnected
+      1.3126 * (normalized) sizeconnected
-      1.245
```

Number of kernel evaluations: 16017 (72.105% cached)

Classifier for classes: 0,2

BinarySMO

Machine linear: showing attribute weights, not support vectors.

```
      5.3248 * (normalized) numactive
+      0.2183 * (normalized) numconnected
+     -0.9654 * (normalized) sizeconnected
-      1.2858
```

Number of kernel evaluations: 6722 (54.43% cached)

Classifier for classes: 0, 3

BinarySMO

Machine linear: showing attribute weights, not support vectors.

```
      4.1027 * (normalized) numactive
+      0.9892 * (normalized) numconnected
+      1.5031 * (normalized) sizeconnected
-      2.5291
```

Number of kernel evaluations: 1053 (69.645% cached)

Classifier for classes: 1, 2

BinarySMO

Machine linear: showing attribute weights, not support vectors.

```
      6.7667 * (normalized) numactive
+      1.8327 * (normalized) numconnected
+     -5.9496 * (normalized) sizeconnected
-      1.5238
```

Number of kernel evaluations: 6180 (65.167% cached)

Classifier for classes: 1, 3

BinarySMO

Machine linear: showing attribute weights, not support vectors.

```
      4.672  * (normalized) numactive
+     -0.1629 * (normalized) numconnected
+      0.3922 * (normalized) sizeconnected
-      2.6961
```

Number of kernel evaluations: 1687 (59.747% cached)

Classifier for classes: 2, 3

BinarySMO

Machine linear: showing attribute weights, not support vectors.

```
      0.5273 * (normalized) numactive
+     -0.4524 * (normalized) numconnected
+      2.7006 * (normalized) sizeconnected
-      1.8285
```

Number of kernel evaluations: 3332 (53.353% cached)

Time taken to build model: 0.07 seconds

=== Stratified cross-validation ===

=== Summary ===

Correctly Classified Instances	585	57.4656 %
Incorrectly Classified Instances	433	42.5344 %
Kappa statistic	0.3603	
Mean absolute error	0.297	
Root mean squared error	0.3795	
Relative absolute error	86.0431 %	
Root relative squared error	91.3677 %	
Total Number of Instances	1018	

=== Detailed Accuracy By Class ===

	TP Rate	FP Rate	Precision	Recall	F-Measure	ROC Area	Class
	0.74	0.338	0.597	0.74	0.661	0.777	0
	0.353	0.167	0.41	0.353	0.38	0.625	1
	0.649	0.132	0.663	0.649	0.656	0.774	2
	0.047	0.004	0.429	0.047	0.085	0.855	3
WAvg.	0.575	0.216	0.559	0.575	0.554	0.743	

=== Confusion Matrix ===

a	b	c	d	<-- classified as
304	101	6	0	a = 0
128	89	35	0	b = 1
76	22	189	4	c = 2
1	5	55	3	d = 3

### D.1.1.5 J48

=== Run information ===

Scheme:weka.classifiers.trees.J48 -C 0.25 -M 2

Relation: persondata

Instances: 1018

Attributes: 4

npeople

numactive

numconnected

sizeconnected

Test mode:10-fold cross-validation

=== Classifier model (full training set) ===

J48 pruned tree

-----

```
numactive <= 4
|  numactive <= 2: 0 (351.37/45.0)
|  numactive > 2
|  |  numconnected <= 1: 1 (3.28/0.28)
|  |  numconnected > 1
|  |  |  numactive <= 3: 1 (16.42/6.42)
|  |  |  numactive > 3: 0 (15.32/3.0)
numactive > 4
|  numactive <= 20
|  |  sizeconnected <= 7
|  |  |  numactive <= 7
|  |  |  |  sizeconnected <= 5: 2 (18.61/5.61)
|  |  |  |  sizeconnected > 5: 1 (54.73/8.73)
|  |  |  numactive > 7: 2 (88.66/17.66)
|  |  sizeconnected > 7
|  |  |  numconnected <= 1: 1 (95.23/21.23)
|  |  |  numconnected > 1
|  |  |  |  sizeconnected <= 13
|  |  |  |  |  numconnected <= 2
|  |  |  |  |  |  sizeconnected <= 12: 2 (20.8/4.8)
|  |  |  |  |  |  sizeconnected > 12: 1 (13.14/4.14)
|  |  |  |  |  numconnected > 2
|  |  |  |  |  |  numactive <= 16: 0 (22.99/10.0)
|  |  |  |  |  |  numactive > 16
|  |  |  |  |  |  |  numactive <= 17: 0 (2.19/1.0)
|  |  |  |  |  |  |  numactive > 17: 1 (6.57/1.57)
|  |  |  |  sizeconnected > 13: 1 (49.26/14.26)
|  numactive > 20
|  |  numactive <= 36
|  |  |  sizeconnected <= 15: 2 (157.63/30.63)
```

```

| | | sizeconnected > 15
| | | | numactive <= 29
| | | | | sizeconnected <= 23
| | | | | | numactive <= 22
| | | | | | | sizeconnected <= 17: 0 (2.19/1.0)
| | | | | | | sizeconnected > 17: 1 (6.57/2.57)
| | | | | | | numactive > 22
| | | | | | | numactive <= 26: 2 (3.28/1.28)
| | | | | | | numactive > 26: 0 (2.19/1.0)
| | | | | | sizeconnected > 23: 3 (8.76/1.76)
| | | | | numactive > 29: 2 (44.88/15.88)
| | | numactive > 36: 3 (33.93/9.93)

```

Number of Leaves : 22

Size of the tree : 43

Time taken to build model: 0.06 seconds

=== Stratified cross-validation ===

=== Summary ===

Correctly Classified Instances	844	82.9077 %
Incorrectly Classified Instances	174	17.0923 %
Kappa statistic	0.7487	
Mean absolute error	0.1731	
Root mean squared error	0.2878	
Relative absolute error	50.1407 %	
Root relative squared error	69.3014 %	
Total Number of Instances	1018	

=== Detailed Accuracy By Class ===

	TP Rate	FP Rate	Precision	Recall	F-Measure	ROC Area	Class
	0.929	0.102	0.86	0.929	0.894	0.925	0
	0.71	0.063	0.789	0.71	0.747	0.855	1
	0.873	0.073	0.827	0.873	0.849	0.91	2
	0.453	0.012	0.725	0.453	0.558	0.87	3
WAvg.	0.829	0.078	0.825	0.829	0.824	0.9	

=== Confusion Matrix ===

```

a  b  c  d  <-- classified as
382 23  5  1 | a = 0
 52 179 19  2 | b = 1
 10  19 254  8 | c = 2
  0  6  29 29 | d = 3

```



## D.1.2 Numeric Results

### D.1.2.1 Multilayer Perceptron

=== Run information ===

Scheme:weka.classifiers.functions.MultilayerPerceptron -L 0.3 -M 0.2 -N 500 -V

↪ 0 -S 0 -E 20 -H a

Relation: persondata

Instances: 1018

Attributes: 4

npeople

numactive

numconnected

sizeconnected

Test mode:10-fold cross-validation

=== Classifier model (full training set) ===

Linear Node 0

Inputs Weights

Threshold -0.948400203247411

Node 1 -0.5404909952916884

Node 2 1.216178867266227

Sigmoid Node 1

Inputs Weights

Threshold -0.43529405839714014

Attrib numactive -5.375212304536006

Attrib numconnected 8.485535675559154

Attrib sizeconnected 10.222854781726667

Sigmoid Node 2

Inputs Weights

Threshold -1.6694708298582563

Attrib numactive 20.69453148975731

Attrib numconnected -4.263624121611814

Attrib sizeconnected -17.140018798993825

Class

Input

Node 0

Time taken to build model: 0.27 seconds

=== Cross-validation ===

=== Summary ===

Correlation coefficient 0.6865

Mean absolute error 0.5969

Root mean squared error 0.7768

Relative absolute error	72.7731 %
Root relative squared error	79.9255 %
Total Number of Instances	1018

### D.1.2.2 IBk

=== Run information ===

```
Scheme:weka.classifiers.lazy.IBk -K 1 -W 0 -A
↳ "weka.core.neighboursearch.LinearNNSearch -A
↳ "\"weka.core.EuclideanDistance -R first-last\""
Relation:      persondata
Instances:     1018
Attributes:    4
               npeople
               numactive
               numconnected
               sizeconnected
Test mode:10-fold cross-validation
```

=== Classifier model (full training set) ===

IB1 instance-based classifier  
using 1 nearest neighbour(s) for classification

Time taken to build model: 0 seconds

=== Cross-validation ===

=== Summary ===

Correlation coefficient	0.3194
Mean absolute error	0.7674
Root mean squared error	1.1947
Relative absolute error	93.5545 %
Root relative squared error	122.9183 %
Total Number of Instances	1018

### D.1.2.3 Linear Regression

=== Run information ===

Scheme:weka.classifiers.functions.LinearRegression -S 0 -R 1.0E-8

Relation: persondata

Instances: 1018

Attributes: 4

npeople

numactive

numconnected

sizeconnected

Test mode:10-fold cross-validation

=== Classifier model (full training set) ===

Linear Regression Model

npeople =

0.0783 \* numactive +  
-0.0616 \* numconnected +  
-0.0331 \* sizeconnected +  
0.4923

Time taken to build model: 0.01 seconds

=== Cross-validation ===

=== Summary ===

Correlation coefficient	0.7339
Mean absolute error	0.5085
Root mean squared error	0.6589
Relative absolute error	61.9941 %
Root relative squared error	67.7949 %
Total Number of Instances	1018

#### D.1.2.4 Decision Stump

=== Run information ===

Scheme:weka.classifiers.trees.DecisionStump

Relation: persondata

Instances: 1018

Attributes: 4  
npeople  
numactive  
numconnected  
sizeconnected

Test mode:10-fold cross-validation

=== Classifier model (full training set) ===

Decision Stump

Classifications

sizeconnected <= 3.5 : 0.14788732394366197

sizeconnected > 3.5 : 1.657439446366782

sizeconnected is missing : 0.15771812080536912

Time taken to build model: 0.01 seconds

=== Cross-validation ===

=== Summary ===

Correlation coefficient	0.7649
Mean absolute error	0.4756
Root mean squared error	0.6249
Relative absolute error	57.9858 %
Root relative squared error	64.291 %
Total Number of Instances	1018

## APPENDIX E

# Physical Form

To enable the prototype to be easily mounted on the ceiling, the prototype was placed on a flat board with feet that would enable it to be screwed into a pole, and the pole extended to jam the sensor against the ceiling and the floor using the pole (Figure E.2 on the next page, Figure E.1). Due to a wireless module and battery pack being added to the Raspberry Pi, it was feasible for the sensor to operate entirely wirelessly for several hours. However, in most cases it was more convenient to operate using wired power and Ethernet.

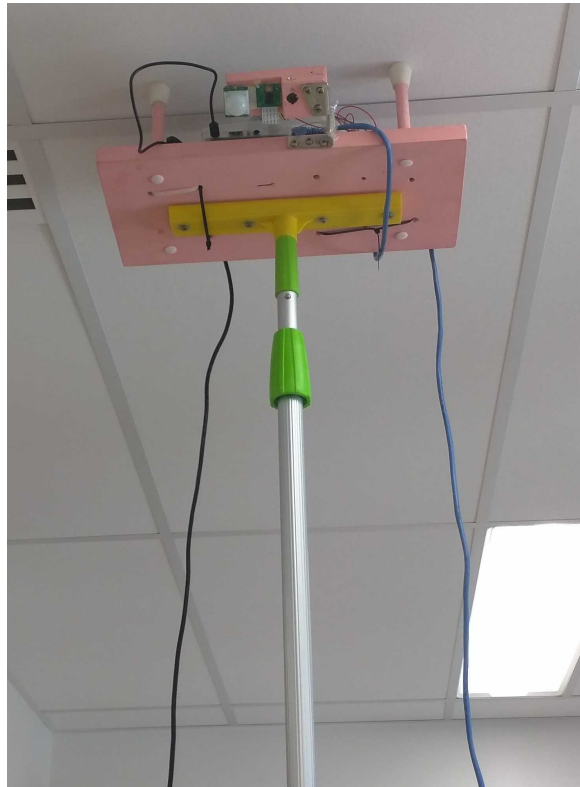
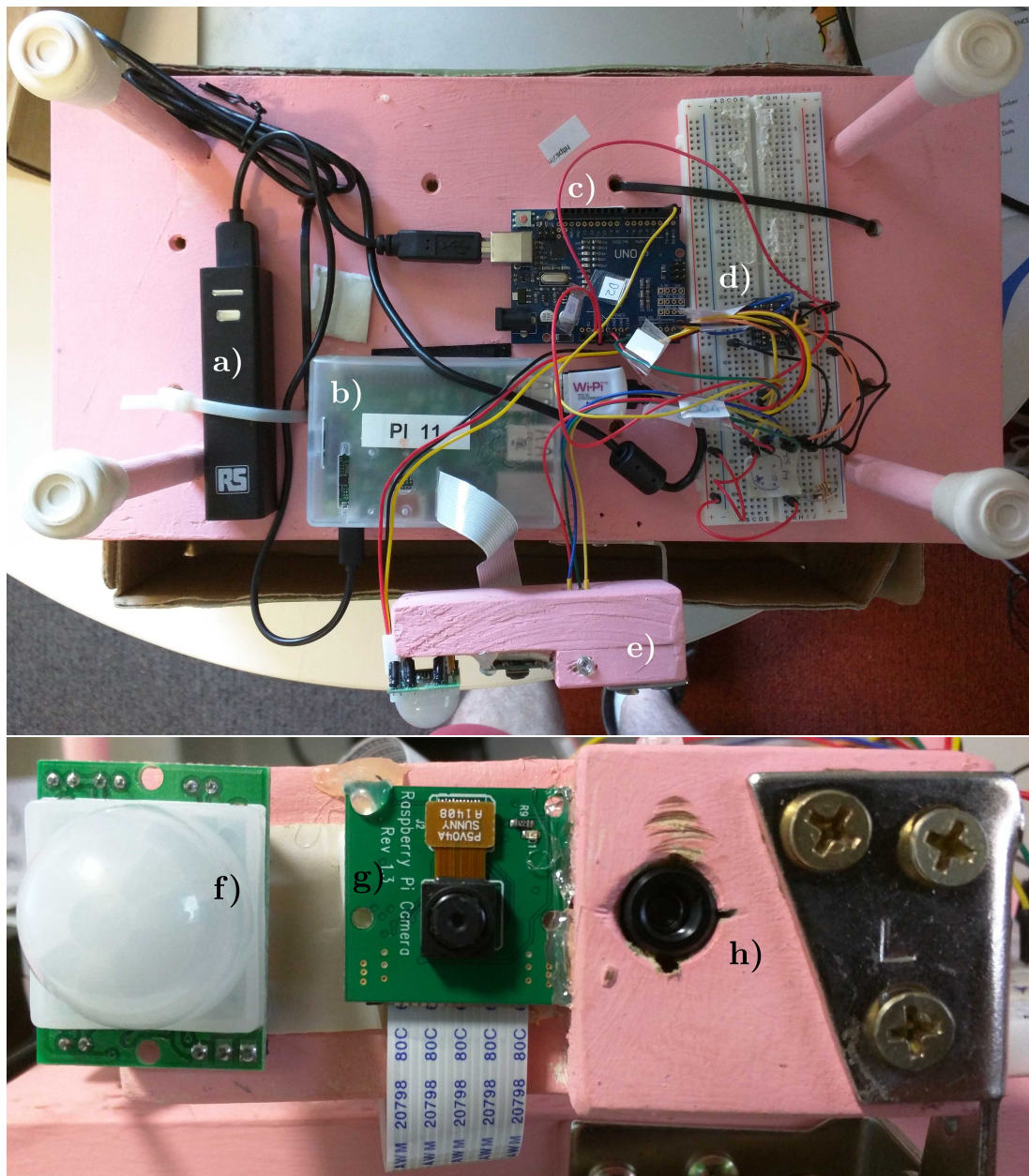


Figure E.1: Prototype in action



- |                             |                                        |
|-----------------------------|----------------------------------------|
| a) Battery pack             | e) Movable sensor mount                |
| b) Raspberry Pi             | f) PIR                                 |
| c) Arduino                  | g) Camera                              |
| d) Level-shifting circuitry | h) Melexis MLX90620 ( <i>Melexis</i> ) |

Figure E.2: Prototype Physical Form

# Bibliography

- [1] ADAFRUIT. 4-channel I2C-safe bi-directional logic level converter - BSS138 (product ID 757). <http://www.adafruit.com/product/757>. Accessed: 2015-01-07.
- [2] ADAFRUIT. PIR (motion) sensor (product ID 189). <http://www.adafruit.com/product/189>. Accessed: 2015-02-08.
- [3] ARDUINO FORUMS. Arduino and MLX90620 16X4 pixel IR thermal array. <http://forum.arduino.cc/index.php/topic,126244.0.html>, 2012. Accessed: 2015-01-07.
- [4] ATZORI, L., IERA, A., AND MORABITO, G. The internet of things: A survey. *Computer networks* 54, 15 (2010), 2787–2805.
- [5] AUSTRALIAN BUREAU OF STATISTICS. Household water and energy use, Victoria: Heating and cooling. Tech. Rep. 4602.2, October 2011. Retrieved October 6, 2014 from <http://www.abs.gov.au/ausstats/abs@.nsf/0/85424ADCCF6E5AE9CA257A670013AF89>.
- [6] BALAJI, B., XU, J., NWOKAFOR, A., GUPTA, R., AND AGARWAL, Y. Sentinel: occupancy based HVAC actuation using existing WiFi infrastructure within commercial buildings. In *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems* (2013), ACM, p. 17.
- [7] BELTRAN, A., ERICKSON, V. L., AND CERPA, A. E. ThermoSense: Occupancy thermal based sensing for HVAC control. In *Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings* (2013), ACM, pp. 1–8.
- [8] CHAN, M., CAMPO, E., ESTÈVE, D., AND FOURNIOLS, J.-Y. Smart homes - current features and future perspectives. *Maturitas* 64, 2 (2009), 90–97.
- [9] ERICKSON, V. L., ACHLEITNER, S., AND CERPA, A. E. POEM: Power-efficient occupancy-based energy management system. In *Proceedings of the 12th international conference on Information processing in sensor networks* (2013), ACM, pp. 203–216.



- [10] FISK, W. J., FAULKNER, D., AND SULLIVAN, D. P. Accuracy of CO2 sensors in commercial buildings: a pilot study. Tech. Rep. LBNL-61862, Lawrence Berkeley National Laboratory, 2006. Retrieved October 6, 2014 from [http://eaei.lbl.gov/sites/all/files/LBNL-61862\\_0.pdf](http://eaei.lbl.gov/sites/all/files/LBNL-61862_0.pdf).
- [11] GUINARD, D., ION, I., AND MAYER, S. In search of an internet of things service architecture: REST or WS-\*? a developers perspective. In *Mobile and Ubiquitous Systems: Computing, Networking, and Services*. Springer, 2012, pp. 326–337.
- [12] GUINARD, D., TRIFA, V., MATTERN, F., AND WILDE, E. From the internet of things to the web of things: Resource-oriented architecture and best practices. In *Architecting the Internet of Things*. Springer, 2011, pp. 97–129.
- [13] GUPTA, M., INTILLE, S. S., AND LARSON, K. Adding gps-control to traditional thermostats: An exploration of potential energy savings and design challenges. In *Pervasive Computing*. Springer, 2009, pp. 95–114.
- [14] HAILEMARIAM, E., GOLDSTEIN, R., ATTAR, R., AND KHAN, A. Real-time occupancy detection using decision trees with multiple sensor types. In *Proceedings of the 2011 Symposium on Simulation for Architecture and Urban Design* (2011), Society for Computer Simulation International, pp. 141–148.
- [15] HNAT, T. W., GRIFFITHS, E., DAWSON, R., AND WHITEHOUSE, K. Doorjamb: unobtrusive room-level tracking of people in homes using doorway sensors. In *Proceedings of the 10th ACM Conference on Embedded Network Sensor Systems* (2012), ACM, pp. 309–322.
- [16] KLEIMINGER, W., BECKEL, C., DEY, A., AND SANTINI, S. Inferring household occupancy patterns from unlabelled sensor data. Tech. Rep. 795, ETH Zurich, 2013. Retrieved October 6, 2014 from [http://eaei.lbl.gov/sites/all/files/LBNL-61862\\_0.pdf](http://eaei.lbl.gov/sites/all/files/LBNL-61862_0.pdf).
- [17] KLEIMINGER, W., BECKEL, C., STAAKE, T., AND SANTINI, S. Occupancy detection from electricity consumption data. In *Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings* (2013), ACM, pp. 1–8.
- [18] KOVATSCH, M. CoAP for the web of things: from tiny resource-constrained devices to the web browser. In *Proceedings of the 2013 ACM conference on Pervasive and ubiquitous computing adjunct publication* (2013), ACM, pp. 1495–1504.

- [19] LI, N., CALIS, G., AND BECERIK-GERBER, B. Measuring and monitoring occupancy with an RFID based system for demand-driven HVAC operations. *Automation in construction* 24 (2012), 89–99.
- [20] MELEXIS. Datasheet IR thermometer 16X4 sensor array MLX90620. <http://www.melexis.com/Asset/Datasheet-IR-thermometer-16X4-sensor-array-MLX90620-DownloadLink-6099.aspx>, 2012. Accessed: 2015-01-07.
- [21] PALATTELLA, M. R., ACCETTURA, N., VILAJOSANA, X., WATTEYNE, T., GRIECO, L. A., BOGGIA, G., AND DOHLER, M. Standardized protocol stack for the internet of (important) things. *Communications Surveys & Tutorials, IEEE* 15, 3 (2013), 1389–1406.
- [22] SERRANO-CUERDA, J., CASTILLO, J. C., SOKOLOVA, M. V., AND FERNÁNDEZ-CABALLERO, A. Efficient people counting from indoor overhead video camera. In *Trends in Practical Applications of Agents and Multiagent Systems*. Springer, 2013, pp. 129–137.
- [23] SHELBY, Z., AND BORMANN, C. *6LoWPAN: The wireless embedded Internet*, vol. 43. John Wiley & Sons, 2011.
- [24] TEIXEIRA, T., DUBLON, G., AND SAVVIDES, A. A survey of human-sensing: Methods for detecting presence, count, location, track, and identity. Tech. rep., Embedded Networks and Applications Lab (ENALAB), Yale University, 2010. Retrieved October 6, 2014 from [http://www.eng.yale.edu/enalab/publications/human\\_sensing\\_enalabWIP.pdf](http://www.eng.yale.edu/enalab/publications/human_sensing_enalabWIP.pdf).
- [25] WINTER, T., THUBERT, P., CISCO SYSTEMS, BRANDT, A., ET AL. RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks. RFC 6550, Internet Engineering Task Force, March 2012. Retrieved October 6, 2014 from <http://tools.ietf.org/html/rfc6550>.