IRLeak: Continuous Low cost Virtual Audits Using Thermal Imaging

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ABSTRACT

Energy wasted in residential and commercial buildings from leaky windows and doors, open refrigerator doors, and unnecessarily switched-on small to medium load everyday appliances account for a large fraction of the energy budget of a country. Energy audit systems provide a remedy to this problem where certain types of energy wastage due to leakages and poor insulation can be analyzed and addressed. However, there is a critical need for low cost systems that can *continuously* monitor such wastage and provide recommendations to users on how to mitigate such wastage. To this end, in this paper we present a low cost thermal imaging system, **IRLeak** that can detect open and drafty windows, open refrigerator and microwave doors, and computers left accidentally on, as well as humans in the room. The system comprises a low resolution, 16×4 IR camera and a low cost digital camera mounted on the steerable platform. It automatically scans a room and takes low resolution IR and RGB images at a low frequency. It then uses image stitching and a segmentation algorithm to determine temperature hotspots in a panoramic image. Finally, it uses pre-captured data on the surface temperature of different appliances, walls, and windows to determine anomalous energy consumption. The system obviates the need to equip every appliance with an energy meter to detect energy wastage and costs less than $30. The preliminary evaluation in a lab setting shows that **IRLeak** can reliably detect these events leading to significant energy savings.

1. INTRODUCTION

It is estimated that energy wasted in 75,000 US homes in one year is equivalent to the energy loss due to the British Petroleum oil spill calamity [2]. A portion of this energy wastage can be attributed to callous use of appliances—open refrigerator doors, open microwave doors, televisions and computers switched on when there is no one in the room, and open doors and windows. The other portion can be attributed to poor wall insulation as well as drafty doors and windows. While poor insulation can be detected using energy audits, it is more challenging to determine wastage due to careless usage of appliances and opening or closing of windows/door. To determine such invisible wastages, continuous monitoring using a low-cost non-intrusive sensing system is ideal.

A plausible solution to the problem is energy metering. Every appliance can be instrumented with an energy meter and analytics on the energy consumption data can determine appliance (mis-)use. Unfortunately, however, blanketing a home with such energy meters can be prohibitively expensive and cumbersome. Energy disaggregation on data from a single point measurement system is another solution whose accuracy is limited if the number of appliances are large and the sampling rate is low [**?**]. To address this problem, in this paper, we present the design and preliminary evaluation of a low-cost thermal imaging system that uses a single low resolution IR and RGB camera to determine energy consumption hotspots in a room.

Our system, **IRLeak** comprises two cameras (IR and RGB) mounted on a steerable base. The system scans a room at a very low frequency. It then uses a combination of image stitching and image segmentation to determine clusters of temperature hotspots in the room. The system can overlay panoramic views of the thermal images with the digital images to provide a visualization of the hotspots. It then uses pre-collected temperature profiles of different surfaces (appliances, doors, windows, and walls) to determine which appliance is being used anomalously. The system can also determine the occupancy of the room. **IRLeak** costs only $30, and a single camera suffices for a room. Through a preliminary evaluation using an experimental setup in the lab, we show that **IRLeak** can accurately find open windows and doors, open refrigerator door, open microwave door, and switched on computers and televisions.

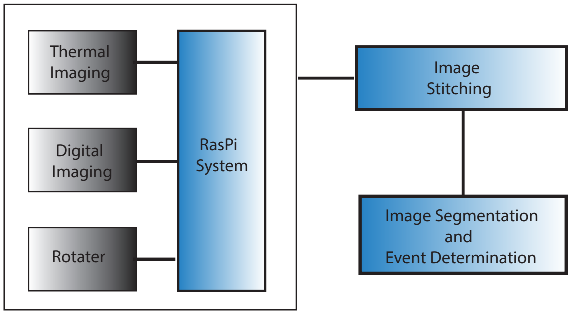

Figure 1: Thermal Imaging System Block Diagram

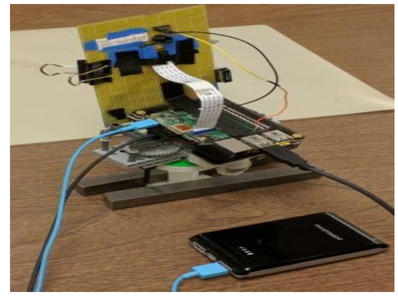

Figure 2: IRLeak System

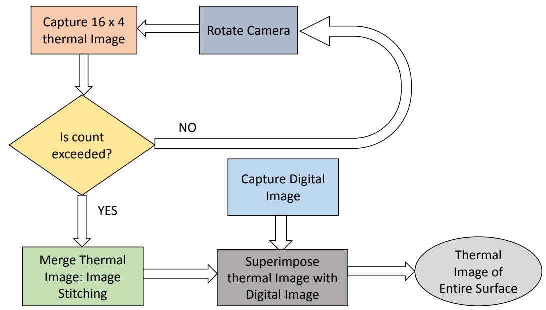

Figure 3: Thermal Imaging System Flow Diagram

Research Contributions

The design, implementation, and evaluation of **IRLeak** presents the following research contributions.

- **A low-cost virtual audit system**. **IRLeak** is a low-cost thermal imaging system that can determine anomalous use of appliances and energy wasted due to open windows and doors. It obviates the need to instrument appliances with individual energy meters. We develop a simple image segmentation and processing algorithm that can reliably detect temperature hotspots in the room. This provides the ability to collect longitudinal data on energy wastage of homes.

- **Functional prototype and Evaluation**. We have developed a fully functional prototype of **IRLeak** and present preliminary evaluation on the accuracy of detecting anomalous appliance use, human occupancy, and open windows. We show, using a laboratory setup, that **IRLeak** is highly accurate inspite of its simplicity.

2. SYSTEM OVERVIEW

The overview of the system has been described in 1. The system has two major components - Complete Camera Module and the Image Processing Unit. The Complete Camera Module (CCM) consists of the IR camera, Digital camera and the Motor modules. All three modules are controlled by a Raspberry Pi. The motor rotates by a pre-calibrated angle and both the digital and infrared images are taken simultaneously and sent over to a PC where the Image Processing Unit (IPU) is present. The first task of IPU is pre-processing images and generate the heat maps for the thermal data. In the training phase the digital images are stitched together and the same stitching mechanism is applied for the IR images in testing phase. Processed images give the thermal layout of a wall surface which can be used for analytics.

3. THERMAL IMAGING SYSTEM

In this section we describe the different components of our prototype, *Thermal Imaging System*. The two subsystems are the *Complete Camera Module* and the *Image Processing Unit*. We describe the configurations and the operating principles of each of the components below.

3.1 Camera Module

One of our goals in this work is to develop a low-cost IR camera based system for a one-time longitudinal heatmap scanning of an entire room which helps to find the potential air leakages, insulation problems or unattended and anomalous usage of any objects (doors and windows are open for a subtle amount of time or air leakages are quite persistent) and appliances (refrigerator door is kept open, washer is unnecessarily getting heated). While commercially available systems are available to perform the scanning but they are expensive and warrant professionals to operate. Motivated by this, we integrate a low-cost, near zero-power IR camera (MLX90621) [6] with a Raspberry Pi to build a simple prototype which can be deployed at ease by the home owners, residential and commercial occupants at their own comfort.

The IR camera helps detect the background radiant temperature between -40°C to +85°C with a resolution of 0.02°C and -50°C to -300°C for the object temperature and generates the corresponding heatmaps. We also integrate a digital camera with the circuit board to collect the pictures of the scanned area for mapping the control points of the objects of interest with the heatmaps. We employ a simple image stitching algorithm to map the boundaries and contours of the objects with the heatmaps and validate them with the ground truths as obtained from the digital images.

To achieve a 360° scanning views at a specific angle, we integrate a stepper motor unit with our proposed camera module. The entire camera module is mounted on a case which is rotated by the stepper motor. The stepper motor is calibrated to move at 5° with a low frequency to capture the thermal images. A digital camera is synchronised with the IR camera in-situ to take the images of the surrounding wall surfaces and the objects/appliances as the IR camera scan through. The data from both the IR and digital cameras is stored locally and transferred to the server periodically.

3.2 Image Processing Unit

We propose to use the IR camera in tandem with a digital camera to detect and appropriately map the heatmap's points of interest in contrast to the presence of buildings air leakages, heat dissipation associated with different objects and appliances while achieving high precision and detection accuracy. While the specific color codes of heatmaps help detect the moderate, extreme or regular hot and cold surfaces, augmenting this with digital images helps detect any unusual usage behaviors, and operating conditions of everyday appliances in smart home environment. For example, if a room has multiple windows and doors with air leakages or multiple similar small to medium load appliances, solely the heatmaps may not provide the home owners the adequate information as needed to detect any abnormal energy usage. While the IR camera albeit helps detect the region of interest but fails to provide the detailed identifications of the similar type of objects and appliances.

We employ the digital stitching procedure to create the thermal panorama. We first stitch the digital images and maintain the respective control points for the stitching procedure which we reemploy to process the stitched thermal image generation. Next we augment the digital image in the background of the stitched thermal image based on the respective control points.We use a hybrid image construction methodology where the mask image or the thermal image is passed through a low pass filter and the digital image is passed through a high frequency filter to construct the digital image augmented heatmaps. A complete procedure of the this image processing step have been described in Algorithm 4. We then apply a image segmentation algorithm described in Algorithm 3 to determine the different heatzone clusters in the stitched image. The temperature of each cluster is them compared with entries in a lookup table to determine the state of a specific appliance. For instance, we pre-measure the surface temperature of the refrigerator with the door open at 40°F and store it in the lookup table. If the measured temperature of the cluster is closest to 40° F then the system determines that the refrigerator door is open.

```
Procedure IPU(Input:  Individual set of baseline digital
  images(D) and corresponding thermal images (I))
Output:  Thermal Panoramic Image
1.  Create panoramic image for the
 baseline digital images using Hugin tool
2.  Replace the digital images with the thermal images
  and load the saved project again to construct the
 panoramic thermal image
3.  Employ High pass filter on the digital image
4.  Employ Low pass filter on the IR image
5.  Combine the two to get masked thermal image
```

Figure 4: IPU procedure

4. EVALUATION

In this section we discuss the analytics using the panoramic thermal images. We perform initial set of experiments which includes discerning among cold surfaces, hot surfaces and human bodies. The purpose is to identify - *Appliance States/Energy Wasting Appliances* and also *Occupancy Detection*. In Table 4 the list of objects, their temperature for appliances and objects which has effect of energy consumption. We collected data from two locations - LAB 1 and LAB 2. LAB 1 is much colder inside and have an average temperature of 71-73°F and the LAB 2 is an older building with poor ventilation and have windows which can be opened. The average temperature there is 78-81°F. The appliances present in the different labs are listed in Table 4. For ground truth validation we used a commercial Infrared thermometer and took multiple readings to get the range of temperature values.

Object	Temperature Appliance OFF(F)	Temperature Appliance ON(F)	Setting Location
Wall	-	73	LAB1
Wall	-	77-81	LAB2
Fridge	73	50	LAB1
Fridge	75	50-55	LAB2
Freezer	75	50-55	LAB2
Heater	74	120	LAB1
Heater	74	100-140	LAB2
Coffee-Maker	72-77	90-180	LAB2
Microwave	77-78	77-78	LAB2
Window	76-77	75	LAB2

Table 1: Temperature of different Surfaces

There are three possible types of thermal regions in an image - background, cold region and hot region. The image that needs to be segmented is the stitched IR image and the objective is to create a thermal mask which separates the hot and cold regions from the background. Since the thermal image is being used for segmentation, the results are subjected to the choice of color palette and range selection. We ensure that the background has darker tones than the hot or cold surfaces which helps achieve the desired segmentation after image binarization using Otsu's method [5]. We apply a 7×7 neighborhood 2-D median filter to eliminate small blobs and get the few major thermal zones. Next step is to find the contour and their location of the blobs and then for each blob the average temperature is computed and the lookup table 4 is used to identify the object closest to that temperature. A pseudocode for the entire procedure has been given in 5.

```
Procedure Hot and Cold Zone Segmentation(Input:
Constructed panoramic thermal image (I)
Output:  Matched Thermal Regions
1.  Apply Otsu's thresholding
2.  Find the contours of the hot and cold regions
3.  Match the internal temperatures with the
LIST OF SURFACE TEMPERATURES
```

Figure 5: Thermal region identification: Two object case Hot and Cold

4.1 Appliance State Detection/Energy Wasting Object Detection:

In this section we discuss the experiments performed using the mentioned methods for Appliance State Detect or Energy Wasting Object Detection. By an appliance state we mean an appliance turning 'ON' and those who generate heat when turned ON. For example Coffee-Maker and Heater both generate heat when turned ON. In Fig 4.1, it is shown that the Heater and Coffee-Maker and be distinctly distinguished as two hot sources when they are kept at a distance of about 2 feet apart. However the temperature value for both the appliances can vary in a range and distinguishing them using the particular lookup becomes difficult.

Discerning two definite thermal regions become difficult when they are in close proximity. For example in case of the Fridge-Freezer Fig 4.1, the location is determined as cold zone as a whole and not separately as Fridge and Freezer. The open window in Lab 2 can't be detected as the difference between inside and outside temperature was less. In Lab 1, we took data for two humans and an open fridge and a heater turned 'ON' and all the objects could be detected Fig 4.1.

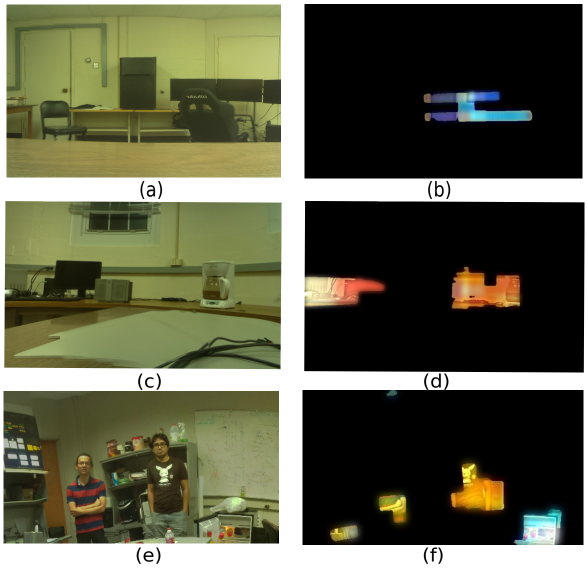

Figure 6: Appliance and Object Detection Results

Event	Detected	Est. Temp.	Actual Temp	Location
Heater ON	Yes	108	120	LAB1
Fridge Open	Yes	98	100	LAB1
Man 1 Standing	Yes	99	81	LAB1
Man 2 Standing	Yes	103	83	LAB1
Heater ON	Yes	110	120	LAB2
Coffee ON	Yes	98	100	LAB2
Fridge Open	Yes	98	100	LAB2
Fridge & Freezer Open	No	98	100	LAB2
Man Hoodie	No	80	78	LAB2
Man No-Hoodie	No	80	78	LAB2
Window Open	No	78	75	LAB2

Table 2: Results Table

4.2 Occupancy Detection

In this section we discuss the experiments performed for occupancy detection. Body heat can be detected through thermal imaging. In case of the Fig 7 it can be seen that two distinct human beings can be detected. However, for this technique to work the body temperature has to be significantly more than the background temperature. We don't consider a case where the room is much hotter than body temperature as that is an improbable scenario. The temperature measured by the IR is the radiation from the human body. However this is subjected to variation - for example we considered two cases where a human is wearing a hoodie and not wearing one in Fig 7. It was found that the one wearing hoodie has lower temperature than the one not wearing hoodie. This creates a problem when the room temperature becomes same as that of the human body and detection of bodies is difficult. We found that its easier to identify a person in LAB 1 which has colder temperature than the one at LAB 2, as LAB2 had poor air-conditioning and hence hot.

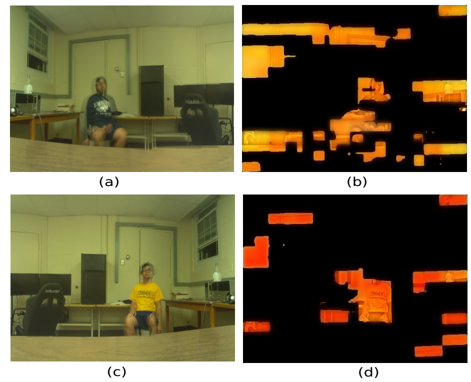

Figure 7: Occupancy Detection Results

5. CONCLUSION AND FUTURE WORK

We design a low-cost thermal imaging system prototype, **IRLeak** which is capable of scanning an entire room for identifying a multitude of building structural leakage problems, and mechanical or human initiated everyday appliances abnormal energy usage context. Our prototype is simple, user friendly and an effective solution for commercial and residential home owners to deploy and measure the invisible energy leakages with a one-time scanning. The **IRLeak** system holds promise to advocate a virtual energy auditing system without instrumenting each and every appliance with an energy meter. We plan to investigate sophisticated image processing methodologies to improve the IR and RGB image stitching procedure and augment this temperature profiling data from different appliances and objects to improve the performance of existing energy disaggregation algorithms.

6. REFERENCES

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