Low Cost Thermal Imaging System for Monitoring Building Insulation

ABSTRACT

Thermal Imaging helps detect air leakages, uneven heating or cooling pockets, and damped walls in building environments. For detection of such unseen insulation problems, we present a Thermal Imagery system that captures heat signatures of wall surfaces and provides an integrated thermal image of an entire room. In this paper, we build an alternative compared to the expensive commercially available circuit module consisting of an IR camera connected to a micro-controller with I^2C communication protocol, by a Raspberry-Pi module, to reduce the cost of existing thermal imaging system by an order of magnitude. The unit is capable of rotating automatically in pre-calibrated angle and capturing surface thermal images of 16×4 resolution which are then run by an Image Stitching technique to produce an integrated thermal image of the wall surfaces. Finally, another camera unit is placed in-situ to capture the digital images of the wall surface to combine with the reconstructed thermal images to get an overall high-resolution thermal layout of the wall surfaces. The proposed system, based on our preliminary studies, is proven to be a cost effective and user friendly system to detect building leakages, damps and irregular heating/ cooling losses.

1. INTRODUCTION

Building structures, openings and leakages have direct effect on the heating and cooling of homes. Often it has been found that the utility bill is exorbitantly high. Maryland has one of the highest bills in USA [2], where the average monthly utility bill is about $140. Typically utility costs go up in winter and mostly during bouts of bitter cold when more people are likely to stay indoors HVAC usage spikes up. Times like the winter storm which disrupts may result in families to stay indoors for more number of days hence increasing utility consumption. As such proper heating in the house is a requisite and minimizing the heat loss is necessary to reduce utility bills and also for comfort. Structural openings and leakages can result in uneven thermal pockets in a room or house. Slight openings in doors and windows can be major reasons for heat leakages which can be detected using thermal imagery. Apart from that infrared building diagnosis provides detection of - water leaks and their origin - walls, flooring, roof; plumbing issues like blockages; electrical "hot spots" which can cause potential fire hazards; Pest & rodent nests; Moisture that cannot be physically reached with moisture meters; HVAC problem areas - loose, ill-fitting or disconnected fittings. However diagnosis providers or self-diagnosis using IR cameras needs manual searching of leakages and uses expensive thermal imaging devices.

Our system description is somewhat similar to SPOT+ [3, 4] although our intention and the hardware is completely different. The SPOT system consist of a Kinect sensor, a Infrared Sensor and servo motor, along with environment sensors as the main objective of the system is occupancy based comfort management. The system is described as - " *When a worker enters the work space, the Kinect tracks the worker and sends a skeleton stream to the PC. The PC finds the location of the worker's body center and calculates the rotation angle of the servos. It then communicates with the micro-controller to adjust the angle of the two servos so that the infrared sensor is facing the body center. When the tracked worker is moving, the infrared sensor may not be actually facing towards the worker. Therefore, we introduce a 0.5 second measurement delay into the system. That is, the infrared sensor starts collecting data only when the worker has been standing still for at least 0.5s. The system then estimates the clothing insulation by the clothing surface temperature ..*".

Technical Questions: Our investigations in this paper address the following technical questions:

- The commercially available imaging systems are expensive and range from $250 upwards upto almost $40000. Although such an expensive system is not necessary even the ones on low range are expensive. The IR research module also has an expensive board which cost $170.
- We use an IR camera having a coarse resolution of 16×4 pixels. Calibration with the digital camera is a challenge and ground truth evaluation is difficult. From such a coarse resolution thermal image it is difficult to interpret what camera actually captures.
- The system in SPOT+ has a Kinect and IR sensor together. As such the system is quite cumbersome and not suitable for portable deployment. Also the cost goes high up with the Kinect attached.

Key Contributions: We believe that our innovations and results provide strong preliminary evidence that such a hybrid model, where low resolution thermal imagery is used to detect the several thermal sources, can prove to be an attractive and practically viable alternative for building leakage and occupancy detection. The key contributions of our work are as follows.

- We develop an integrated thermal imaging system which is capable of capturing snippets of thermal images of wall surfaces. The system can rotate automatically in a pre-calibrated angle to capture continuous IR snapshots in small offsets. The system also has a digital camera which captures images of wall surface.
- The second part of the system is the Image Reconstruction Unit. The IR images and the digital image is transferred to the external Image processing unit where the thermal images are stitched to get a panoramic image and then we detect - human body, cold surface and hot surface.

Rest of the paper is organized as follows. In Section 2 we present the overall architecture of the system. In Section 3 the different components of the imaging system and their detailed description.

2. 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.

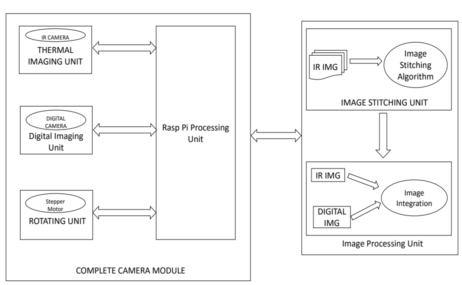

Figure 1: Thermal Imaging System Block Diagram

3. THERMAL IMAGING SYSTEM

In this section we describe the different components of our prototype, *Thermal Imaging System* as shown in Fig. **??**. 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 Complete 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 etc.) and appliances (refrigerator door is kept open, washer is unnecessarily getting heated etc.). While commercially available systems are available to scan through but

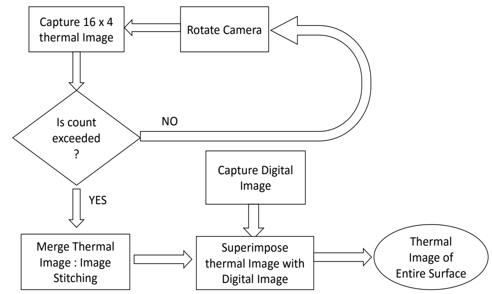

Figure 2: Thermal Imaging System Flow Diagram

they are expensive and warrant professionals to operate. Motivated by this, we integrate a low-cost, near zero-power IR camera (MLX90621) [] with 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. Figure **??** depicts the circuit for the two camera modules.

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 x° every XXX seconds 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 develop a basic image stitching algorithm to solve this problem. We address the image displacement problems from two differing image sources and stitch the heatmaps and digital images collectively to create a complete panorama such that it can provide meaningful feedback to the tenants for their corrective actions. First we stitch together the overlapping digital images and create a single panoramic image. Subsequently, we use the thermal images from the IR camera and stitched them together. We use the Hugin tool [?] for this thermal image stitching purpose. Figure 3 represents the individual digital image-stream as baseline. The stitched image and thermal mask are also shown in Figure 4.

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 as shown in Figure 4 (b). 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 5.

4. ANALYTICS

In this section we discuss the analytic done using the panoramic thermal images. We perform initial set of experiments which includes discerning among cold surfaces, hot surfaces and human bodies. We also articulate the challenges involved which frame our future goals for upgrading the system. We noted down the temperatures of the different surfaces which are stated in Table 4.

Object	Temperature (F)
Background/Wall	73
Human Body 1	83
Human Body 2	81
Fridge	50
Heater	100

Table 1: Temperature of different Surfaces

4.1 Experiment 1: Discerning Human body and Open Fridge

In this experiment we aim to find a human body and an open refrigerator, where the inputs are Figure 7. There are three thermal regions in the image - background, open fridge and the person. 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. This is possible because of the careful settings of the color palette for the thermal images. 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 6.

4.2 Experiment 2: Discerning Two Human bodies and an Open Fridge

4.3 Experiment 3: Discerning Two Human bodies and a Running Portable Heater

4.4 Insights

5. CONCLUSION

6. REFERENCES

[1] Matthew Brown and David G. Lowe. 2007. Automatic Panoramic Image Stitching using Invariant Features. Int. J. Comput. Vision 74, 1 (August 2007), 59-73.

[2] EIA 2014 http://www.eia.gov/electricity/sales_revenue_price/pdf/table5_a.pdf, 2014.

[3] P. X. Gao and S. Keshav. SPOT: A Smart Personalized Office Thermal Control System. In Proc. ACM e-Energy 2013, 2013.

[4] P. X. Gao and S. Keshav. Optimal Personal Comfort Management Using SPOT+. In Proceedings of the Fifth ACM Workshop on Embedded Systems For Energy-Efficient Buildings, pages 1-8. ACM, 2013.

[5] M. Sezgin and B. Sankur. Survey over image thresholding techniques and quantitative performance evaluation. Journal of Electronic Imaging 13, 2004.

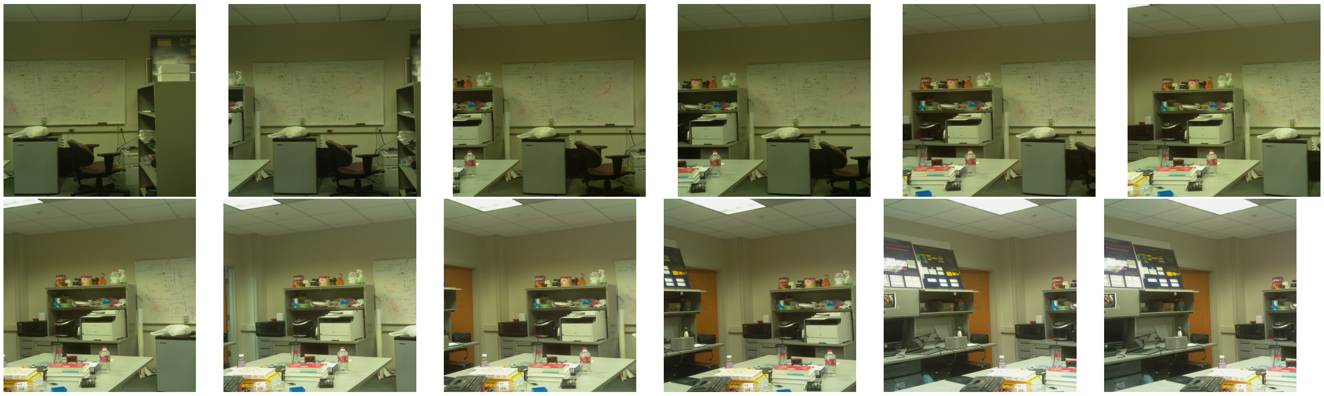

Figure 3: Baseline Stream of Images

Figure 4: Stitched Result for Baseline Stream of Images

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 5: IPU procedure

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 6: Thermal region identification: Two object case Hot and Cold

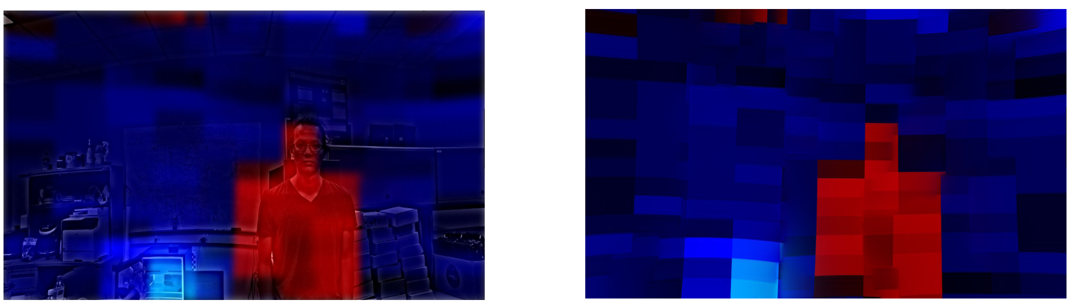

Figure 7: Stitched Image: Fridge and Human body