A Temporal Thermography System for Supporting Longitudinal Building Energy Audits

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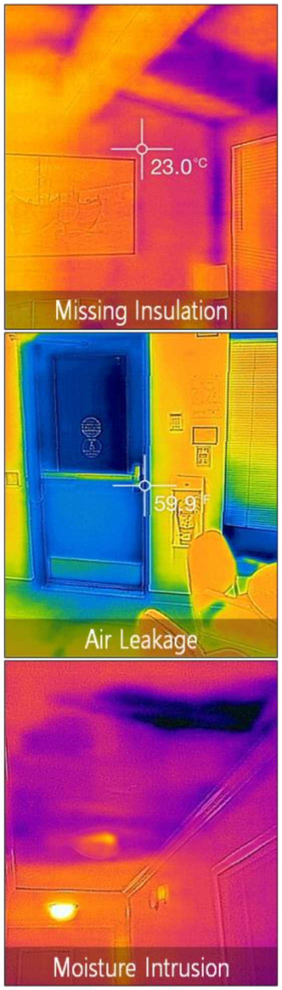

Figure 1: Common energy efficiency issues visible to a thermal camera.

Abstract

With advances in thermal sensor technology and falling costs, energy auditors are increasingly using thermography to detect thermal defects and analyze building energy efficiency. However, collecting thermal imagery is laborious and results can be misleading or ineffective if environmental conditions for conducting a proper scan are not met. In this abstract, we present a novel sensor kit for collecting and analyzing *temporal* thermography data, which reduces manual labor and enables new types of thermographic analyses. To gather initial user reactions and better understand the potential of this temporal data, we conducted a usability pilot study and a small field study deployment. We describe initial results, drawbacks, and enumerate directions forward for this emerging area.

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Introduction

The building sector consumes 41% of energy produced in the US and makes up an increasing portion of CO2 emissions [9]. There have been three main approaches to addressing the impact of buildings on the environment in the ubicomp community: (i) behavior change research (see survey [4]), (ii) building sensors that monitor energy related characteristics (*e.g.,* [5]), and (iii) interactive visual analysis tools (*e.g.,* [1]). Here, we

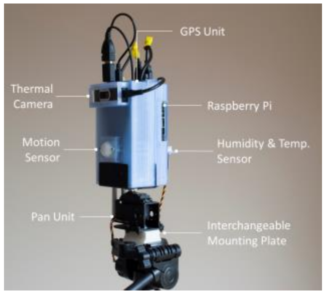


Figure 2: Prototype temporal thermography sensor kit used in the studies.

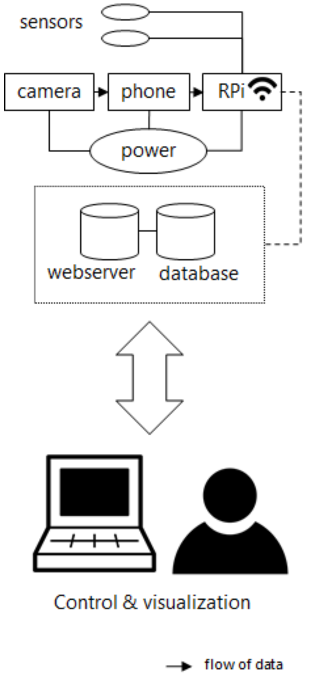


Figure 3: The sensor kit provides a webserver allowing users to set schedules and view results, which are fed into the visualization tool. ***Icons: https://thenounproject.com/***

focus on a combination of (ii) and (iii) by exploring new methods and tools to support the growing community of professional and novice energy auditors who inspect buildings to estimate their energy efficiency and generate improvement recommendations [6–8].

Energy auditors investigate buildings using a variety of techniques including *thermography* where an infrared thermal camera is used to scan for anomalous heat signatures, which may indicate insulation problems, air leakage locations, or other issues with a building's envelope (Figure 1). Thermal imagery is also an effective visual communication aid used to describe problems to building owners [6]. However, collecting thermal imagery can be laborious and, if environmental conditions are incorrect, misleading or ineffective [6]. Compounding this problem, energy auditors must also adjust measurement parameters (*e.g.,* emissivity) that impact measurement accuracy [3]. Enabling auditors to analyze a sequence of images of the same location over time (*i.e.,* temporal thermograms) is one method which may mitigate these issues and provide new insights [3]. However, widely available tools (*e.g.,* consumer thermal cameras) do not support this use case well.

In this paper, we introduce a temporal thermography system that consists of: (i) a novel sensor kit mounted on a servo motor to periodically collect panoramic thermograms paired with humidity, temperature, and motion sensor data and (ii) a corresponding interactive visual analytics tool for viewing and analyzing this temporal data. Through a pilot usability study and a small field deployment, we begin examining the utility of temporal thermograms and reactions to our tools. This work is a first step toward exploring: *What value and insights, if any, does temporal thermography provide energy auditor? And, how might temporal thermography be incorporated into building energy audits?* Our work contributes to the growing area of using sensor kits, and similar Internet of Things (IoT) devices, for building analytics and energy assessments.

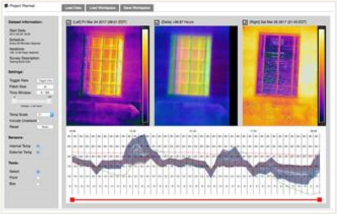
System Design

Our sensor kit consists of a custom 3D-printed enclosure that contains a FLIR One™ thermal camera, humidity, temperature, and motion sensors, and a Raspberry Pi for data processing (Figures 2, 3). The sensor kit rests on a pan unit atop an interchangeable mounting plate. The system can be deployed in a location to collect data over days or weeks based on a user-specified schedule. Users specify a data collection schedule and access the results via a web application hosted on the Raspberry Pi.

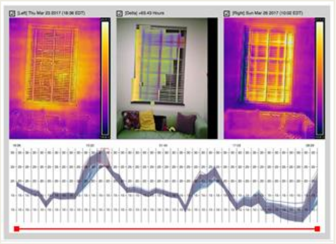
The multi-modal sensor data is viewable in a web application developed in JavaScript and Python (Figure 4). D3.js was used to develop two modes of interactive visualizations: A *Single-Image Mode* and a *Temporal Mode*. In both modes, users can make *point* and *box* selections to extract and display temperature data about the region of interest along with descriptive statistics (*e.g.,* maximum, minimum, mean).

Single-Image Mode. This mode was developed to provide auditors with a view of the data similar to FLIR Tools™, a commercially available application for viewing an analyzing thermal images (*e.g.,* using *point* and *box* selections). A single image from the dataset is displayed with a slider that allows the user to move through time.

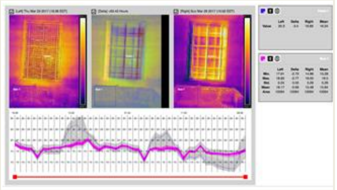
Temporal Mode. To more deeply explore comparing images over time, we created a "temporal mode" based on [2]. This mode is centered on a Parallel Coordinate



(a) In this view, we show the overview of the "window dataset" with the settings and tools pane on the left and file menu on the top.



(b) By dragging the cursor along one the axes of PCP timeline, the user can filter by temperature and view corresponding spatial regions in the center image.



(c) Selection tools allow the user to select regions of interest and help identify trends in the data. Descriptive statistics are calculated about selections and displayed in the pane on the right.

Figure 4: The visualization tool used by participants during the usability pilot and deployment studies.

Plot (PCP) of the temperature changes between the images, which visualizes temperature trends at each pixel location over time. Additionally, the sensor kit's measured internal and outdoor temperatures at the deployment location can be overlaid on the graph. Above the PCP are two user-selected images from the dataset, taken at separate times, controlled the bottom slider.

Usability Study

Participants were recruited for a usability pilot study via emails sent to a student listserv and enrolled on a first-come, first-served basis. Four University of Maryland graduate students participated in the study; three of whom had prior experience using thermal cameras for building energy auditing applications but no formal training. Sessions lasted approximately 40 minutes. Participants were asked to analyze two datasets previously collected with the sensor kit using both the commercially available FLIR Tools software and the two modes of our visualization tool. The first dataset was used to train participants. The second dataset was from a test deployment—where the sensor kit faced an exterior window of a second story building—and comprised the usability study. As participants used the tools to analyze the datasets they were asked to "think aloud." Participants were then asked to describe their experience, what they learned, and how they might use the system in the future during a brief semi-structured interview. Session notes were thematically analyzed.

Usability Study Results. All four participants stated that the visualization tool was easy-to-learn and allowed them to more easily notice temporal changes in thermal data compared to the widely available tool. All participants recognized the transient conditions caused by solar loading and reflections from surrounding buildings. Participants suggested that this type of information and visualization could be included in home automation systems. One participant said, *"I'd like to connect this with my smart thermostat to compare the data and see what impacts different settings have"* (P3). Two participants discussed continually collecting this data for personal use and, when prompted, were not concerned about potential privacy implications.

We also noted usability issues. The most pressing, as one participant said, was that *"using the tool is easy if I know what I want to look at,"* (P2) but that it could otherwise be unclear what to focus on. All participants pointed out that comparing images was difficult because the color scales were relative to the observed temperatures; they suggested normalizing the images and scales to help synchronize the displayed data.

Field Deployment Study

Next, we deployed our sensor kit to assist with an energy audit of a university building. The audit was being conducted by a Mechanical Engineering MS student on behalf of the Office of Facilities Management; he had some thermography experience, but no professional training. The sensor kit was deployed in a room that staff had reported to be thermally unstable (Figure 5). The goals were to: (i) investigate whether recent changes to the room's HVAC settings were properly regulating the conditions since the room housed archival materials and (ii) check for any adverse effects caused by solar loading or structural degradation. The sensor kit was scheduled to collect data in 30-minute intervals over three-day spans on two separate occasions, first during winter weather (*i.e.,* cold, snow) and again during spring weather conditions (*i.e.,* warm, sunny, clear). The participant reviewed the data using our analysis tool.

Figure 5: (top to bottom) Our sensor kit was placed in the center of the film archive, analysis was performed on large sections of walls and windows by the auditor, and the visualization tool provided views of the data.

Deployment Study Results. The participant found no evidence of structural issues during the observation periods; all sensor data indicated stable environmental conditions that seemed to be invariant of external weather conditions. The PCP suggested there was some evidence of solar loading, but this was likely not significant. The participant commented, "*The data supports the conclusions I made based on my models and makes me more confident in the recommendations that I'll make going forward*" (P5). Additionally, the participant was positive about the potential uses of the sensor kit itself, indicating that our system could be used to aid facilities management in other deployments.

Conclusion

Through our usability pilot study, we found that the temporal data may make identifying certain transient environmental conditions easier, which would be useful for auditors of varying skill. However, inexperienced users will likely require more support before they can meaningfully interact with the system and extract insights. Moreover, through our case study deployment we explored augmenting traditional energy audits (*e.g.,* those that rely on walkthrough inspections and building modeling) with temporal thermography data. Future work will focus on: (i) integrating additional sensors (*e.g.,* air quality) useful for auditing applications, (ii) implementing advanced signal processing and anomaly detection algorithms, (iii) exploring a wider range of visualizations that can be applied to temporal thermography and other collected data sources, (iv) assessing what insights, if any, professional and novice energy auditors derive from temporal thermographic data collection and analysis, and (v) investigating best practices for augmenting building energy audits, building automation systems, and smart homes.

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