Scalable Methods and Tools to Support Thermographic Data Collection and Analysis for Energy Audits

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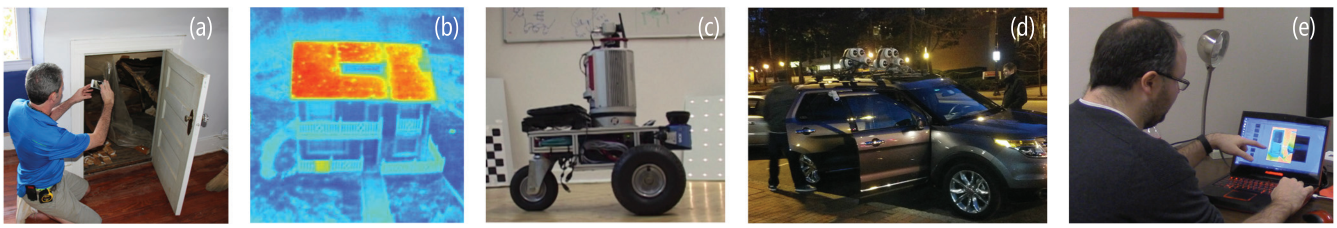

Figure 1: (a) Professional energy auditor inspects an attic storage space [15], (b) UAV collected thermographic data [11], (c) Ground-based robot for indoor and outdoor thermographic data collection [4], (d) Thermographic data collection using cars [12], (e) Novice auditor retrospectively analyzes thermal imagery [16].

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ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous

INTRODUCTION

Buildings consume 41% of energy produced in the US and contribute an increasing portion of total carbon dioxide emissions—40% in 2009 compared to 33% in 1980 [9]. One factor contributing to these issues is building age. Residential buildings, for example, constitute 95% of all buildings in the US and are on average over 50 years old [23]; most of these buildings were constructed using energy inefficient designs and their materials have degraded over time. Moreover, the US Department of Energy has set a goal of reducing housing energy use by up to 70% [18]. To meet this goal, renovations and retrofits of existing building stock has become a pressing need. One effective practice for motivating these improvements is energy auditing, which has seen a resurgence of interest in recent years [20].

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Energy auditing helps identify building inefficiencies through walk-through inspections, on-site measurements, and computer simulations [21]. With improvements to handheld infrared sensors and their falling costs, energy auditors are increasingly using thermography during audits [10]. Thermography is a data collection and visual analytics technique that uses thermal cameras to help detect, diagnose, and document problems that are visible to a thermal camera as anomalous patterns of surface temperatures [15]. While the DOE recommends thermographic-based energy audits, criticisms include that it remains a qualitative method subject to the expertise of the auditor and lacks specialized software support tools, algorithms, and audit guidelines [22]. Moreover, thermographic-based energy audits are laborious. Research in this area has largely focused on how to scale thermographic assessments through technical approaches to automating data collection (*e.g.,* using robotics [2–4], Figure 1b-d) as a means of reducing costs and scaling thermographic assessments. However, there has been a surprising lack of attention given to developing methods and tools that support human-oriented thermographic data collection and analysis activities (Figure 1a, e).

In my dissertation, I plan to examine currently unexplored dimensions of scaling thermographic assessment: dimensions of *who* and *time.* To do this, I plan to develop novel tools and methods that can (i) increase the number of people who are able to perform thermographic assessments and (ii) explore what benefits, if any, temporal analysis might offer energy auditing. More specifically, I will demonstrate that *by integrating image processing, machine learning, and information visualization techniques we can develop mixed-initiative support tools for both in-situ and temporal thermographic data collection and analysis that* *will allow end-users of varying skill to gain insights that lead to improvements in building energy efficiency.* While the space of thermography research is an active one, my work uniquely focuses on providing support for human-oriented data collection and analysis activities while attempting to answer multiple research questions including: *How might off-the-shelf machine learning and image processing techniques aid interpreting thermal imagery? How might temporal thermography be incorporated into energy auditing activities? And, how might mixed-initiative support tools contribute to improved recommendations?* Moreover, my work is distinct within thermography research as my evaluations involve the end-users of this technology. Finally, some of the expected contributions of my work include: an improved understanding of current thermographic energy auditing practices, novel methods and tools to support end-users, and a typology of the insights gained from temporal thermography data.

RELATED WORK

Here, I provide background on building thermography as well as brief discussions on scaling thermographic data collection and thermographic support tools.

Building Thermography

As noted in the introduction, thermographic-based energy audits are becoming more common due to the increased availability of thermal cameras and their decreased cost. Thermal cameras work by detecting the electromagnetic radiation emitted by all objects above absolute zero [5]. The thermal data is automatically combined with images from a conventional camera to produce a contextualized thermal image or *thermogram*. Energy auditors use thermal cameras to measure surface temperatures in walls, roofs, ceilings, and other parts of a building's envelope while looking for inconsistent patterns, discontinuities, and other anomalous heat signatures that may indicate the presence of an efficiency issue [10]. However, before surveying a building thermographers must assess environmental conditions such as weather, wind, HVAC operations, and direction/intensity of the sun—all of which can prevent proper scans (*e.g.,* the ISO standard requires a minimum temperature differential of 10° C between the interior and exterior to properly detect thermal irregularities [8]).

Scaling Thermograpic Data Collection

While prior work has demonstrated the value of thermographic-based energy audits (*e.g.,* [20]), collecting and analyzing thermal imagery is laborious and time consuming. As a result, much of the recent work in thermography research has focused on scaling-up data collection using automatic [2, 15] and semi-automatic [3, 4] robotics systems. These systems promise to make thermographic assessments of urban environments easy, provide data about inaccessible areas (*e.g.,* rooftops), and make frequent, temporal scanning possible. However, limitations to these solutions include: (i) an inability to configure the environment for an accurate inspection, (ii) a focus on capturing exterior views of building facades, and (iii) a tendency to exacerbate the laboriousness of analyzing collected imagery to create end-user reports [15]. Furthermore, there has been little research into the new analysis possibilities enabled by frequent, temporal scanning. My work not only contributes to the area of automated thermographic data collection using sensor kits, but also explores temporal analyses which may be enabled by such systems.

Thermographic Support Tools

Developing support tools for human auditors is a growing area of thermographic research. Several systems explore augmenting human-oriented data collection and analysis activities with wearables [19], augmented reality devices [3], and new analysis software [6]. My interests are in taking advantage of the ubiquitous nature of smartphones, which are particularly attractive tools for energy auditing as they are equipped (or can be equipped) with sensors including thermal cameras, provide light weight computing capabilities, and generate easily shareable data. While there are several commercial applications for thermal imaging (*e.g.,* FLIR ONE™), they are limited in how they assist end-users of varying skill and in the types of analyses that they support. My research innovates in both areas.

METHODOLOGICAL APPROACH

My thesis is comprised of three threads of research: (i) formative inquiries aimed at better understanding professional and novice thermographic energy auditing practices, (ii) the development of analysis methods that can be used in mixed-initiative building thermography tools, and (iii) explorations into temporal thermograpic data collection and analysis. In the first thread, which is completed, I focused on conducting semi-structured interviews, observations, and exploratory field studies. For threads two and three, I am currently developing methods and tools for in-situ and temporal data collection and analysis. I will evaluate these tools through lab-based usability studies and small deployments. Following these studies, I plan to refine the tools I have designed and perform final evaluations. For the in-situ tools, I will evaluate them by conducting a controlled, between-subjects field study. For the temporal tools, I will perform multiple case study deployments. Below, I summarize my completed and proposed work corresponding to these three threads.

COMPELTED WORK

Studies of energy auditing focus largely on potential environmental benefits [1] and on the building owner's perspectives of energy audits [7]. However, studies of professional energy auditors themselves are rare and studies of novice thermographers are virtually nonexistent despite the increasing accessibility of consumer-oriented thermographic tools. To understand the potential benefits and challenges associated with the use of thermography during energy audits, acquire feedback on current approaches to scaling thermography with automation, and gain insights into the design of future technologies, I completed three studies with thermographers. The first two studies, published at CHI 2015 [15], were focused on the current role of thermography in professional energy auditing; they involved semi-structured interviews with 10 professional thermographers recruited from across the United States and an observational case study of a residential audit. The third study, published at CHI 2017 [16], was an exploratory field study focused on understanding novice approaches to building thermography; it involved weekly tasks, corresponding surveys, and a debrief interviews.

Contributions

Unlike other work in this area, my published work in this completed research thread offers a qualitative perspective on energy auditing with a specific emphasis on thermography. Additionally, it presents the perspectives of both professional and novice thermographers. The research has contributed: (i) improvements to our understanding of current, human-oriented thermographic energy auditing practices and techniques; (ii) a synthesis of feedback on proposed automated thermographic systems, and (iii) design recommendations for future thermographic tools.

PROPOSED WORK

The remainder of my dissertation work, and what I am interested in discussing during the Doctoral Colloquium, focuses on investigating: (i) in-situ methods and tools to support energy audits and (ii) methods and tools to support temporal thermographic data collection and analysis. Here, I discuss my progress, evaluation plans, and expected contributions for both research threads.

Methods and Tools for In-Situ Thermography

This thread of my research explores ways that machine learning and image processing can support thermographic data collection and analysis. My formative research suggested that there are several areas of human-oriented data collection and analysis that could benefit from these approaches including: (i) automatic anomaly detection; (ii) thermographic image correction (*e.g.,* automatically calculating the emissivity of observed materials); (iii) encodings of environmental data; and (iv) in-situ onboarding for thermographic tasks. I will first collect and analyze thermal imagery using conventional tools followed by exploring the use of off-the-shelf image processing and machine learning techniques to classify regions-of-interest. Next, I will develop a mixed-initiative classification workflow using my corpus of thermographic images, which I believe will be helpful to users of varying skill. When this workflow detects an anomaly, it will calculate metrics about the detections including both thermal and material properties to help determine whether the detection is worth further investigation. Using these methods, I will develop a prototype smartphone-based tool to be evaluated through a between-subjects field study. My work in this thread will evaluate how mixed-initiative tools might complement human auditors and what impact, if any, such tools have on renovation and retrofit decisions.

Progress. Using the thermal imagery collected by my research team and participants in the formative studies I have begun developing a classification workflow for automatically detecting regions-of-interest based on common objects within thermographic inspection tasks (*e.g.,* air leakage around a window or door). My current pipeline uses a Haar Cascades with Local Binary Patterns as previous work suggested the utility of this training approach and the relative ease of implementation using OpenCV. This implementation has allowed me to prototype a basic process for uploading an image, running the classifier, and generating descriptive statistics about the thermal data contained within the regions-of-interest. I am currently exploring the use of convolutional neural networks (specifically Caffe and Caffe2, which offer pre-trained models) for recognizing not only objects but also material properties that could offer in-situ support during thermographic assessment activities. Next steps include building a mixed-initiative smartphone application that can interface with this workflow, provide user input and metadata, and display the processed image results to end-users (Figure 2a).

Evaluation. After further development, I will recruit 20 novice participants to participate in a 3-week field study of smartphone-based thermographic energy auditing tools similar to [20]. Participants will complete a short eligibility questionnaire and then I will randomly divide the recruited population into control and intervention groups, balancing demographic factors (*e.g.,* age, gender). Participants in this between-subjects study will be provided with a FLIR ONE™ thermal camera attachment for their personal

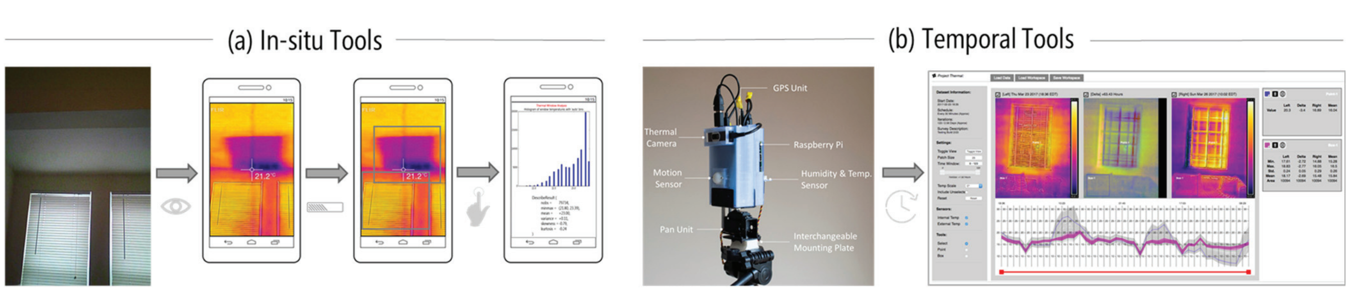

Figure 2: (a) User investigates an area of their home and takes a picture, which is automatically analyzed; results are shown by tapping on the detected problems. (b) A temporal thermographic sensor kit collects data over several days and displays the data through an interactive information visualization web application.

smartphones and asked to use either the FLIR ONE application or my intervention application. They will complete weekly auditing tasks, weekly surveys about these activities, and participate in a debrief semi-structured interview session. A brief follow-up survey will be administered one month later to explore any long-term influences from participation in the study; this survey will not only ask if they tried to address specific issues they noticed during the study, but also whether their perspectives on energy use or the built environment may have changed. I will follow the same analysis protocol used in my previous study for all similar data; however, with the addition of an intervention technology, I will specifically look for differences between the two groups. For the new instruments (*i.e.,* follow-up survey), I will analyze open-ended questions using thematic analysis and a set of qualitative codes in addition to basic counts and descriptive statistics of the closed-end questions.

Contributions. The expected contributions from this thread of research include: (i) a novel in-situ tool and methods for collecting and analyzing thermographic imagery; (ii) a dataset of labeled thermal imagery for use in future thermography research; (iii) a practical evaluation of off-the-shelf image processing and machine learning algorithms that support thermographic analysis; and (iv) recommendations for future thermographic systems.

Methods and Tools for Temporal Thermography

Recent research has suggested that temporal visualizations can provide energy auditors with insights about energy efficiency issues [17]. However, studies in this area largely focus on proof-of-concept visualizations within the space of historical building preservation [2]. These studies generally do not involve end-users as participants, but rather focus on the insights gained by the researchers themselves. Thus, it is currently unclear if there is actual value for energy auditors to collect and analyze temporal data within the context of energy auditing. In this thread of research, I will: (i) design and build an easy-to-deploy, low cost temporal thermographic sensor kit and (ii) develop a novel, interactive information visualization system. I will focus on using these tools in deployments with energy auditors to explore the potential benefits of temporal thermographic data collection and analysis within the space of energy auditing.

Progress. I have constructed a sensor kit for collecting temporal thermographic and environmental data; I have also prototyped a web application for visualizing this data that centers on a Parallel Coordinate Plot (Figure 2b). Using these tools, I have conducted a usability pilot study and a case study deployment in support of an energy audit being conducted on a university building [13]. Based on these studies, I learned that participants: preferred being able to rapidly access temporal images by loading them into a timeline view (versus manually accessing images in a folder view), could quickly identify transient conditions (*e.g.,* effects of solar loading), and consistently desired normalizing the color scales applied to thermal images across the temporal dataset they were analyzing. Next steps include improving the ease in which the sensor kit can be deployed and incorporating participant feedback into the visualization tool before conducting further evaluations.

Evaluation. After further iteration, I will recruit 8 participants and provide them with the sensor kit, which they will use to assess energy efficiency issues in locations of their choosing. While I will not instruct them specifically on how to use the sensor kit, I will recommend that they set up the sensor kit to record data over the course of a few days or a week. After performing data collection, participants will participate in a semi-guided analysis session to review their data using an updated version of the visualization tool and a "*think aloud*" protocol. During these sessions, I will track metrics such as time-to-first-insight, the perceived value of their insights, likes and dislikes with respect to system features, the types of insights that they are able to gain, and any impediments to their success. After exploring the data, participants will complete a short debrief activity.

Contributions. The expected contributions from this thread of research include: (i) novel tools and methods for exploring temporal thermography data; (ii) a typology of insights gained from temporal thermographic analysis; and (iii) recommendations for future thermographic systems.

RESEARCH STATE & EXPECTED BENEFITS

I am a sixth year Ph.D. candidate at the University of Maryland. I expect thoughtful feedback on my research methodology, tools, and evaluations. I plan to finish my proposed work and defend my dissertation in 2018.

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