The Future Role of Thermography in Human-Building Interaction

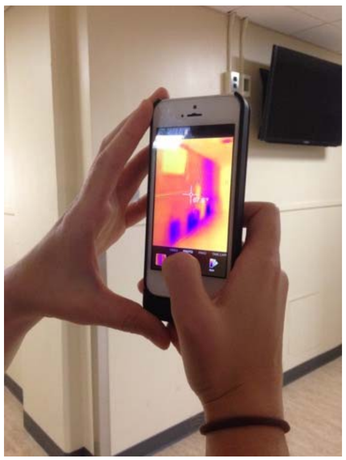

Figure 1: Thermal cameras have recently been introduced into the smartphone ecosystem and provide an opportunity for users to detect, identify, and assess thermal defects in buildings. Here, a FLIR One [21] (connected to an iPhone 5s) is used by one of our pilot study participants to assess a hallway in a building on the University of Maryland's campus.

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Abstract

With recent sensor improvements and falling costs, energy auditors are increasingly using thermography—infrared (IR) cameras—to detect thermal defects and analyze building efficiency. In this workshop paper, we view thermographic energy auditing as a Human-Building Interaction (HBI). We provide an overview of emerging thermal data collection techniques in research and industry. We also reflect on our own work in this area and present our vision of citizen-science/DIY thermography (Figure 1), which has the potential to engage the public in new HBIs by expanding their ability to: perform energy audits, survey public infrastructure, and contribute to urban energy analysis.

Author Keywords

Thermography; Human-Building Interaction

ACM Classification Keywords

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

Introduction

Buildings account for 41% of primary energy consumption in the US—more than any other sector—and contribute an increasing portion of carbon dioxide emissions (33% in 1980 *vs.* 40% in 2009) [18]. One reason for these high emissions is building age.

Figure 2: Smartphone-based thermal cameras (top to bottom): FLIR One (version 1), FLIR One (version 2), Seek Thermal. The fourth item is a FLIR Lepton Camera and connective housing that can be used for electronics projects (and hackathons).

Residential buildings, for example, constitute 95% of all buildings in the US and are on average over 50 years old [20]. Aging buildings often suffer from inefficient doors and windows, poor air seals, and degraded insulation. To help identify and address these issues, the US Department of Energy (DOE) recommends professional energy audits, which typically lead to 5-30% reductions in monthly utility bills and increases in structural safety [19].

With recent improvements in sensor technology and falling costs, auditors are increasingly using thermography—infrared (IR) scanning with thermal cameras—to detect otherwise invisible problems (*e.g.,* air leakage, poor insulation). While typically a standalone device, new relatively inexpensive thermal camera attachments have emerged for smartphone platforms (Figure 1) [21,22]. Interestingly, these attachments are not just marketed to professional auditors but the general consumer as well (for DIY energy audits, art projects, and outdoor recreation [23])[1]. While still early, this trend foreshadows a potential future where thermal cameras are *pervasive*—perhaps fully integrated into all cameras—enabling new types of human-building interaction. Imagine, for example, the following scenario:

Ralph, a homeowner, is determining the best places to insulate and repair his home. Directed by a mobile application on his smartphone, he scans his living room rapidly with the integrated thermal camera. After requesting supplemental data (e.g., wall thickness), the application suggests adding insulation to the exterior walls and around a picture window to increase energy efficiency and comfort in the room. With Ralph's permission, the application uploads data to a cloud service that provides pictures and reports from similar projects to help Ralph verify the recommendation.

[1] Indeed, you can purchase the FLIR One iPhone attachments at your local Apple Store.

With this scenario in mind, our group is exploring research questions related to *pervasive thermography*, for example: How may emerging thermographic tools enable new forms of HBI (*e.g.,* understanding hidden structures, diagnosing problems)? How can thermographic applications be designed to allow minimally trained users (*e.g.,* homeowners) to perform effective thermal scans/analyses themselves? What role do machine learning and computer vision have in assisting in the capture/analysis of thermal imagery? Can we engage citizen scientists to perform energy audits of public infrastructure (*e.g.,* government buildings)? If so, how should we support this practice?

In this workshop paper, we discuss thermal energy auditing as a form of HBI [2]. We provide an overview of emerging thermographic techniques in the research literature and industry. We also reflect on our own work in this area and present our recent vision of citizen-science/DIY thermography which has the potential to engage people in new HBIs by expanding the public's ability to: perform energy audits, survey public infrastructure, and contribute to urban energy analysis.

Thermography Overview

In this overview, we provide background on energy auditing and thermography's role therein. We also discuss current trends in industry and research aimed at scaling thermal data collection, which we believe supports the possibility of pervasive thermography.

Figure 3: A participant in our pilot study noticed a small drip in the ceiling of her apartment and used her thermal camera to survey the extent of the moisture damage. To the unassisted eye (top), the leak appeared to impact only a small section of the ceiling where there was a visible crack; however, the thermal photograph (bottom) shows that the damage extended throughout the hallway. This photo (and others) was used to report the issue to maintenance personnel.

Role of Thermography in Building Energy Auditing

Energy audits are aimed at identifying building energy inefficiencies through walkthrough inspections, computer simulations, and analyses of energy flows [17]. Walkthrough inspections are used to collect information on equipment efficiency, construction materials, and safety and comfort issues via direct examination and conversation with building occupants. This data is often complemented by more quantitative metrics (*e.g.,* historical electricity records) [3].

The use of thermography is common in energy audits of residential and commercial buildings. Thermal cameras can readily show insulation issues, air leakage, and water damage (Figure 3), which helps an auditor diagnose comfort issues and suggest retrofits. Additionally, thermal imagery can be useful to document problems, communicate these problems to clients, and motivate improvements (*e.g.,* Goodhew *et al.* [8] found that thermal imagery from audits increased a homeowners likelihood to install a retrofit by nearly five times). And, while modern thermal cameras are not difficult to use, knowing when to use them and how to interpret the imagery takes training and experience (which we discuss in detail in [14]).

Once an energy auditor has surveyed a building, an energy model is created that balances the energy use from utility bills with building end-uses (*e.g.,* heating). This energy balance is necessary to estimate the energy savings from retrofit measures. While it is possible to approximate this energy balance from utility and weather data alone [7], the energy audit and thermographic data gives a better estimation of heat transfer through the building enclosure. When making improvements, this analysis translates to greater certainty of expected costs, savings, and scope of work.

Towards Pervasive Thermography: Supporting Trends

Below, we enumerate three key trends that further suggest a pervasive thermographic future.

Increasingly pervasive thermal cameras. In the last three years, there have been numerous commercial innovations in thermal camera technology. New cameras have been introduced for: Unmanned Aerial Vehicles (UAVs)[2], smartphones [21,22] (Figure 2), and even hobbyist electronics projects[3]. These innovations are creating new marketplaces and broadening adoption of thermal cameras.

Scaling data collection. Thermography is labor intensive, time consuming, and expensive. Thus, researchers and start-ups are investigating ways to scale-up data collection (Figure 4). For example, a startup company out of MIT, Essess Inc. [12], uses a Google Street View-like approach to data collection: cars carrying sensor arrays (*e.g.,* thermal cameras, LiDAR) capture thermographic images of building facades. This imagery is combined with utility and demographic data (via energy providers) to produce energy scores and suggest improvements to building owners. This highly scalable approach allowed Essess Inc. to collect thermographic data about the majority of the City of Cambridge, Massachusetts. However, while scalable, there are concerns about the value of external building thermography and only imaging facades could miss thermal signatures not visible from the street.

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[2] FLIR Vue: http://www.flir.com/flirvue/.
[3] FLIR Dev Kit: https://www.sparkfun.com/products/13233

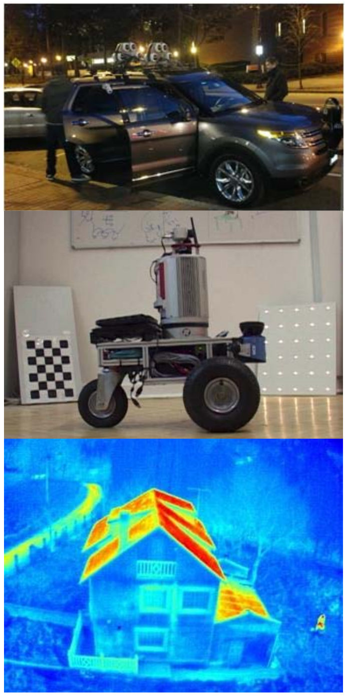

Figure 4: Examples of thermal data collection techniques from research literature and in industry: (a) Essess Inc.'s Google Street View like cars with mounted thermal cameras [12]; (b) Irma3D indoor thermal mapper robot [15]; (c) residential data from a UAV with a mounted thermal camera [11].

Another active area of research explores using autonomous or semi-autonomous robotic platforms (*i.e.,* ground based and aerial) to improve scalability. Ground robotics are frequently employed for data collection tasks because of their carrying capacity and reliability [4,5]. For example, Nüchter *et al.* [15] demonstrated how ground robotics could be successfully employed to collect thermal data in large urban centers. Alternatively, UAVs are viewed as an attractive option because they can reach inaccessible regions of buildings (*e.g.,* roofs) [6,13]. Additionally, Lagüela *et al.* [11] demonstrates that geographic sensing and 3D modeling techniques can be adapted to take advantage of UAVs as data collection platforms. However, urban scenarios pose navigation challenges for robotics and UAVs are limited by payload weight.

Crowdsourcing. Finally, although less common, crowdsourcing is a promising, complementary approach to scaling data collection. The HEAT project, for example, combines professional (aerial) thermographic data collection with crowdsourced information from city residents [1,10]. An energy score is produced for each city building based on assumed features (*e.g.,* roof material). Citizens update the score by providing more information online. However, this project did have difficulties motivating sustained participation [1].

Citizen-Science / DIY Thermography

Most of the thermal data collection techniques covered in our overview are techno-centric. More human-oriented approaches (*i.e.,* utilizing volunteers from the DIY and citizen science communities) have largely been overlooked. One long-term vision of our work is to assess the feasibility of buildings interactive tools to support motivated citizen science/DIY volunteers to perform thermographic scans of their cities to identify problems with aging infrastructure, locate issues with leaks, and to generally help audit the built environment. For example, using smartphone-based thermography, we imagine these volunteers walking down a city street, entering a public building, or passing point of interest and being asked (via smartphone) to take thermal/optical photos and answer location specific questions that assist on-going analysis.

One potential advantage to working with citizen science/DIY volunteers (vs professional auditors) is that, while they may lack specificity, they can provide a larger volume of images that are taken over different times—which may enable new sorts of thermographic analyses (*e.g.,* tracking temporal thermal flows in buildings). Compared to more techno-centric techniques, we believe advantages include: the person's ability to access and navigate urban environments compared to robotic platforms, their potential sensitivity to social issues (*e.g.,* personal privacy), and their ability to adapt to changes in the task. Additionally, working with volunteers could (as discussed previously) complement other methods.

Volunteers could be recruited from homeowner and eco-concerned populations, but encouraging them to collect thermal imagery is unexplored. Additionally, motivating sustained contributions [16] and achieving high data quality standards [9] are challenges for volunteer systems. However, while smartphone-based thermal cameras are fairly new to consumers there are examples of citizen thermography on social media[4].

[4] Fracking: https://www.youtube.com/watch?v=UwAvP-vrHsw

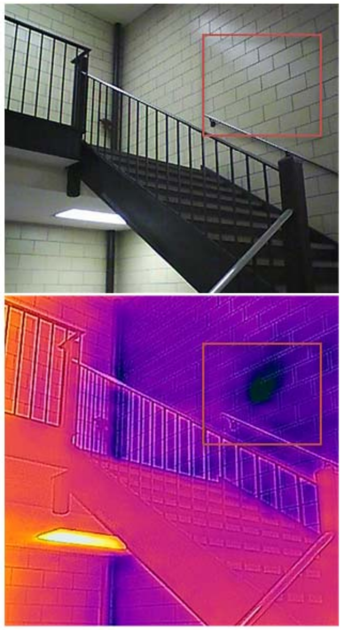

Figure 5: A participant in our pilot study surveyed a campus building and noticed an anomalous signature (center of red boxes) in an exterior wall that they could not explain. It was suggested, by other occupants of the building, that this was the site of a previous repair and that perhaps the wall was not restored to its previous condition.

Preliminary Work

To explore the role of citizen science/DIY volunteers in urban energy analysis and potential motivating factors, we designed a field study to examine their (i) use of smartphone-based thermal cameras, (ii) interests and experiences, and (iii) ability to capture appropriate energy analysis data. We piloted our procedure with three graduate students who had little/no experience using thermal cameras, described below.

Method. The pilot study lasted four weeks. Pilot participants were provided limited training (*e.g.,* how to connect the camera to their phones) and encouraged to freely explore their environment. Participants were also asked to complete a weekly task which gave specific locations to sample from (*e.g.,* "collect images of your home"). At the end of each week pilot participants completed an online survey about the collected images. After completing all weeks, pilot participants were debriefed about their experience.

Results. While pilot participants reacted positively to all tasks, they showed the most enthusiasm for the week where they explored their home. One pilot participant commented that while it was interesting to explore different environments, their home was most important to them because it is where they spent the most time. Pilot participants tended to focus on windows and doors of buildings, as well as appliances and areas of missing insulation. Participants often felt uncomfortable taking thermal photos in public; however, this feeling seemed to diminish over time. Pilot participants were excited to investigate possible areas where air was escaping from buildings. Overall, pilot participants were curious and provided encouraging anecdotes about the types of things we might expect from volunteers (presented via Figures 3, 5, & 6). As a result, we are currently running a larger, formal study with external participants.

Discussion and Future Work

We believe that extensive thermographic data about the built environment will become available in the future, that it will likely play a role in large-scale urban energy analysis, and that it will enable new HBIs (*e.g.,* to empower homeowners to better understand their homes, to assist energy analysts verify the accuracy of their energy models, to help urban planners make energy efficiency decisions).

We are interested in knowing: What can we learn from large-scale thermal data? Since a building's radiative heat loss is visible to anyone with a thermal camera, who owns that data and what ethical considerations are involved in its collection? How can volunteers support, and benefit from, current urban energy analysis initiatives? Finally, how might thermal imagery be integrated into future building sensor networks and what opportunities, interactions, and applications will this integration enable?

We believe smartphone-based thermal cameras could make thermographic data more accessible and present an opportunity to investigate how thermal data collection by citizen science/DIY volunteers could assist current energy analysis initiatives while addressing challenges with other techniques; however, it is unclear what role these volunteers might play. Next steps include analyzing data from our formal study, exploring smartphone-based energy analysis, and investigating computational techniques to support these interactions.

Figure 6: A participant in our pilot study described using a thermal camera to measure temperature exchange in her apartment resulting from the floor-to-ceiling windows (behind the curtains). The pilot participant took photographs over several hours and deduced that the rate of thermal exchange increased as a function of the difference between the internal and external temperatures; this experiment was designed to confirm a previous comfort concern.

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