

Thermporal: An Easy-to-Deploy Temporal Thermographic Sensor System to Support Residential Energy Audits

CHI 2019 | May 9th
Session on Sustainable HCI

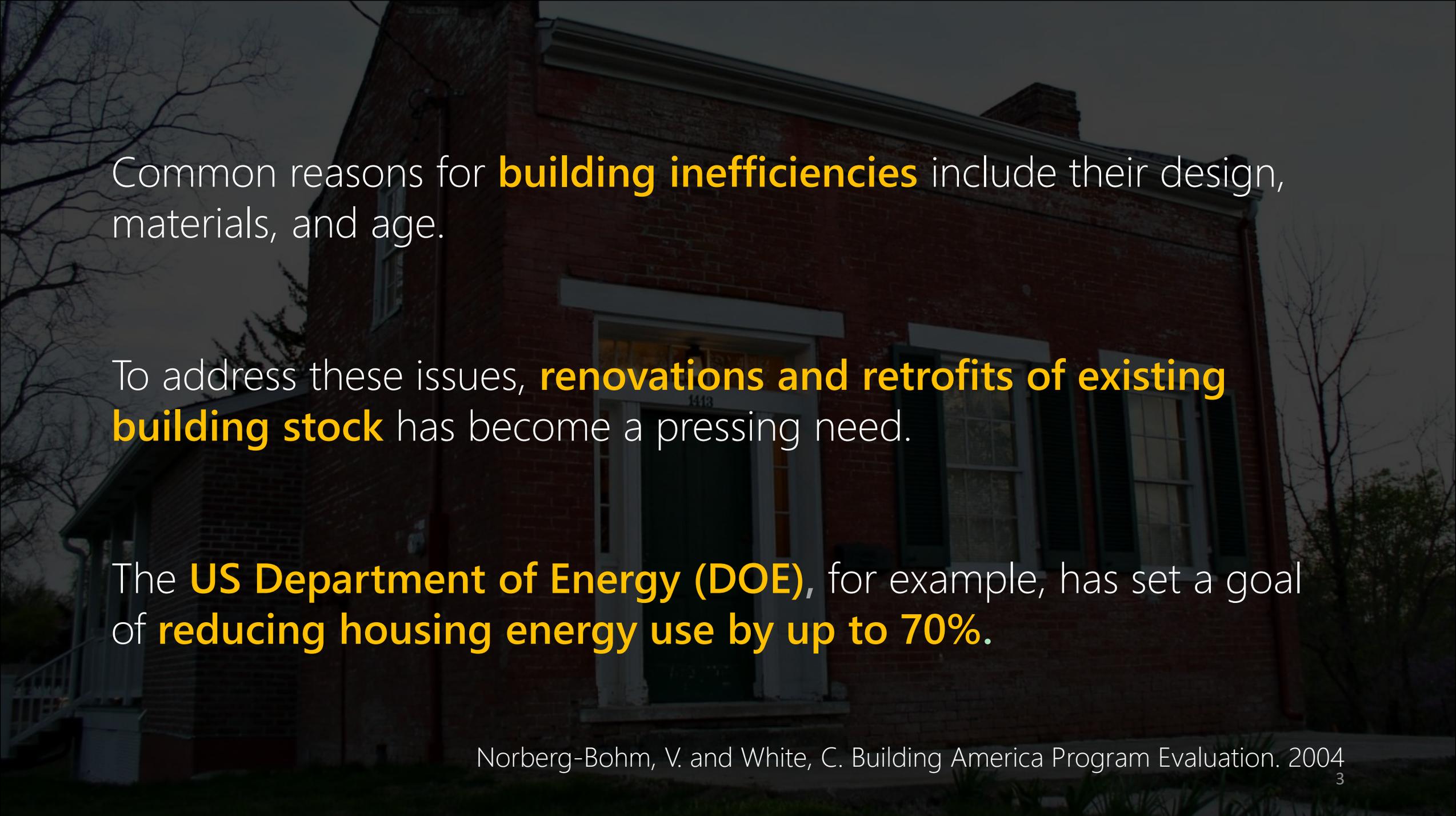
Matthew Louis Mauriello
@mattm401

Brenna McNally
Jon E. Froehlich





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Common reasons for **building inefficiencies** include their design, materials, and age.

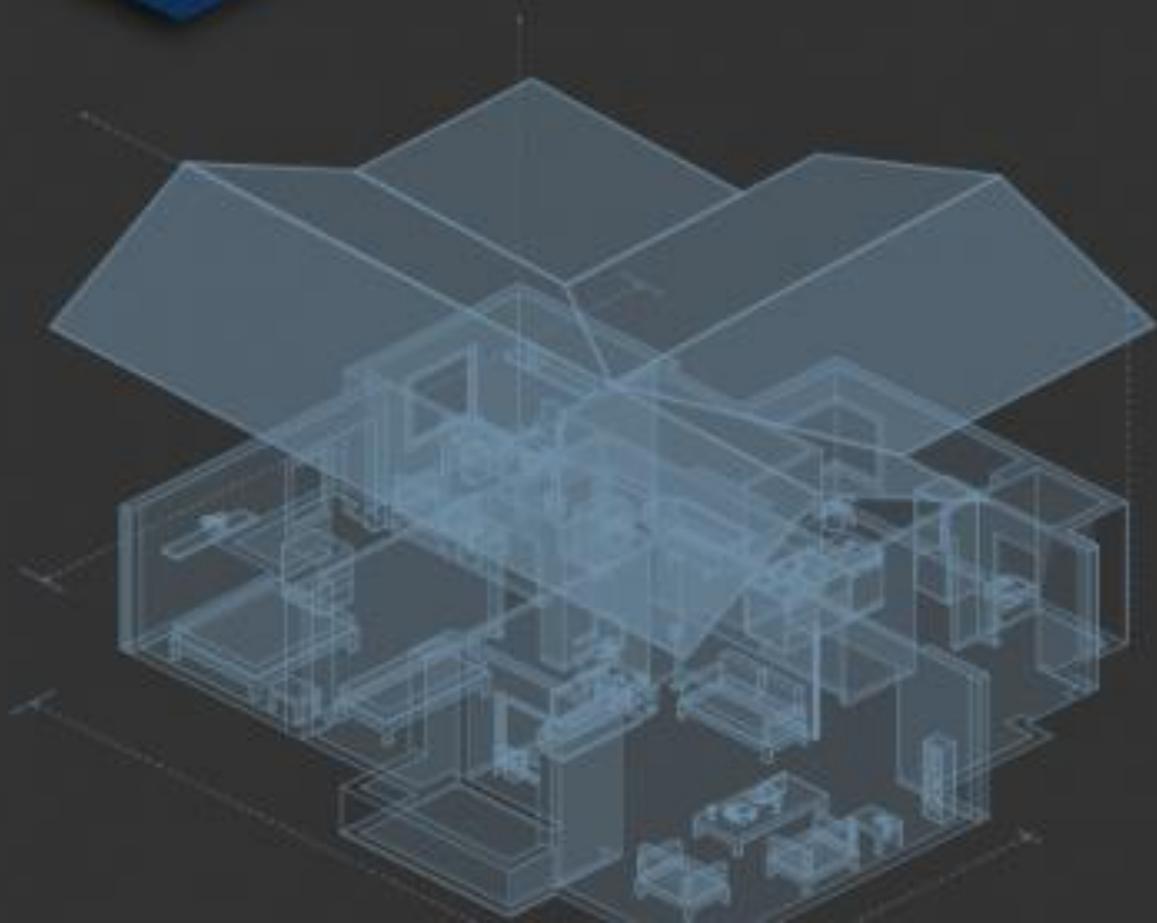
To address these issues, **renovations and retrofits of existing building stock** has become a pressing need.

The **US Department of Energy (DOE)**, for example, has set a goal of **reducing housing energy use by up to 70%**.



Energy Saver 101: Home Energy Audits

Take the first step to improving your home's energy efficiency: get a home energy audit.



What is a home energy audit?

A home energy audit helps you pinpoint where your house is losing energy and **what you can do to save money**. A home energy auditor will also assess health and safety issues that might exist in your home.

The audit involves two parts: the **home assessment** and **analysis** using computer software.

Home > Thermographic Inspections

Thermographic Inspections

June 25, 2012 - 3:27pm

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WHAT DOES THIS MEAN FOR ME?

Energy auditors may use thermography -- or infrared scanning -- to detect thermal defects and [air leakage](#) in building envelopes.

RELATED ARTICLES



[Professional Home Energy Audits](#)

Energy Audits

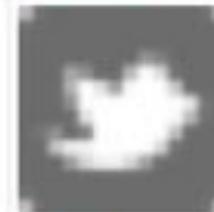


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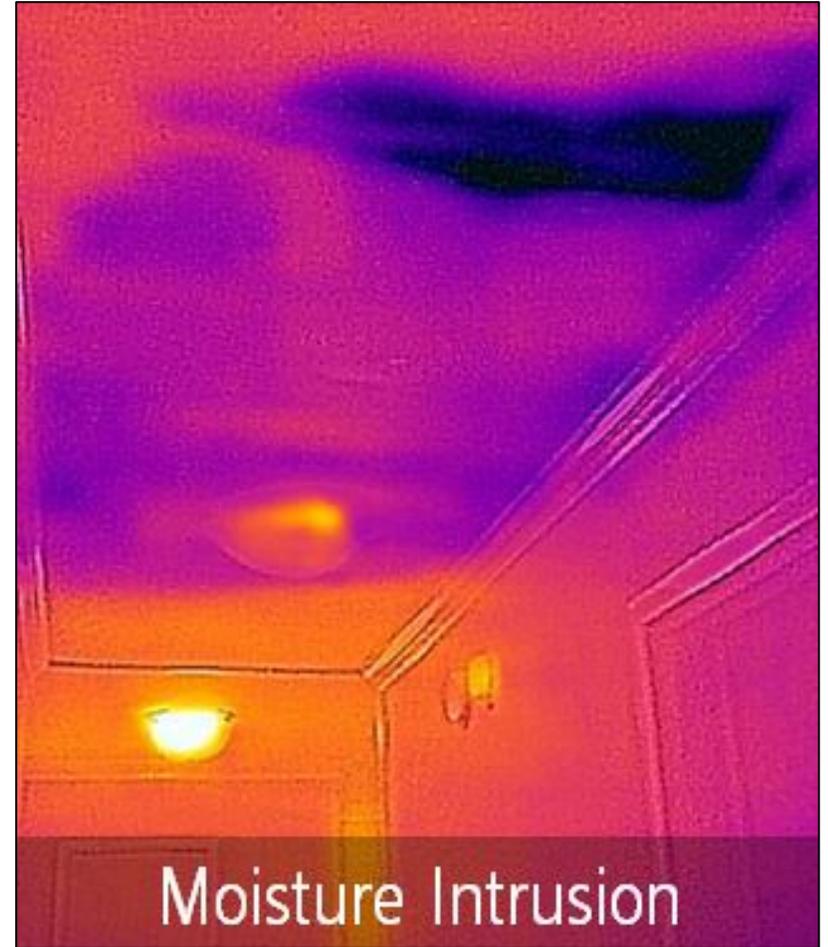
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Thermal Cameras



- Thermal cameras (or infrared cameras) detect electromagnetic radiation with lower frequencies than visible light (*i.e.*, infrared frequencies).
- All objects above absolute zero emit infrared radiation, so thermal cameras can 'see' in the dark without external illumination.
- The amount of radiation emitted by an object increases with temperature, so thermal cameras can also measure heat.

Common Thermographic Issues





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Find problems around the home fast, like where you're losing heat, how your insulation's holding up,

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EXPAND YOUR WORLD

Detecting tiny variations in heat means that you can see in total darkness, create new kinds of art,

Energy audits and thermographic surveying are time and labor intensive



Understanding the Role of Thermography in Energy Auditing: Current Practices and the Potential for Automated Solutions

Matthew Louis Mauriello¹, Leyla Norooz², Jon E. Froehlich¹
 Makeability Lab | Human-Computer Interaction Lab (HCIL)
 Department of Computer Science¹, College of Information Studies²
 University of Maryland, College Park
 {mattm401, leylan, jonf}@umd.edu

ABSTRACT

The building sector accounts for 41% of primary energy consumption in the US, contributing an increasing portion of the country's carbon dioxide emissions. With recent sensor improvements and falling costs, auditors are increasingly using thermography—infrared (IR) cameras—to detect thermal defects and analyze building efficiency. Research in *automated* thermography has grown commensurately, aimed at reducing manual labor and improving thermal models. Though promising, we could find no prior work exploring the professional auditor's perspectives of thermography or reactions to emerging automation. To address this gap, we present results from two studies: a semi-structured interview with 10 professional energy auditors, which includes design probes of five automated thermography scenarios, and an observational case study of a residential audit. We report on common perspectives, concerns, and benefits related to thermography and summarize reactions to our automated scenarios. Our findings have implications for thermography tool designers as well as researchers working on automated solutions in robotics, computer science, and engineering.

Author Keywords

Energy audits; thermography; robotics; formative inquiry; design probes; Sustainable HCI; human-robotic interaction

ACM Classification Keywords

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

INTRODUCTION

The building sector accounts for 41% of primary energy consumption in the US, far more than any other sector, and contributes an increasing portion of total carbon dioxide emissions—40% in 2009 compared to 33% in 1980 [46]. One reason for these high emissions is building age. Residential buildings, for example, constitute 95% of all buildings in the US and are on average over 50 years old [51]. Most were constructed using energy inefficient

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Exploring Novice Approaches to Smartphone-based Thermographic Energy Auditing: A Field Study

Matthew Louis Mauriello¹, Manaswi Saha¹, Erica Brown², Jon E. Froehlich¹
 Makeability Lab | Human-Computer Interaction Lab
 Department of Computer Science¹, Department of Bioengineering²
 University of Maryland, College Park
 {mattm401, manaswi, ebrown17, jonf}@umd.edu

ABSTRACT

The recent integration of thermal cameras with commodity smartphones presents an opportunity to engage the public in evaluating energy-efficiency issues in the built environment. However, it is unclear how novice users without professional experience or training approach thermographic energy auditing activities. In this paper, we recruited 10 participants for a four-week field study of end-user behavior exploring novice approaches to semi-structured thermographic energy auditing tasks. We analyze thermographic imagery captured by participants as well as weekly surveys and post-study debrief interviews. Our findings suggest that while novice users perceived thermal cameras as useful in identifying energy-efficiency issues in buildings, they struggled with interpretation and confidence. We characterize how novices perform thermographic-based energy auditing, synthesize key challenges, and discuss implications for design.

Author Keywords

Thermography; Mobile Devices; Formative Inquiry; Field Study; Sustainable HCI; Energy Efficiency

ACM Classification Keywords

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

INTRODUCTION

Improving energy efficiency in the built environment is an important global concern [54]. In the United States, for example, buildings account for 41% of primary energy consumption—more than any other sector—and contribute an increasing portion of carbon dioxide emissions (33% in 1980 vs. 40% in 2009) [38]. To reduce consumption and emission levels, the U.S. Department of Energy (DOE) recommends conducting energy audits to help identify sources of inefficiencies and make recommendations for renovations and retrofits. Home energy audits typically identify improvements that lead to 5-30% reductions in utility use [64]. Energy audit requirements are increasingly becoming part of city legislation [4] and building

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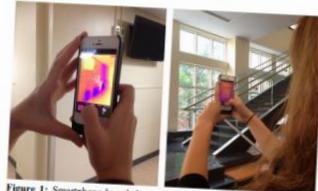


Figure 1: Smartphone-based thermal cameras present an opportunity to engage novice users in thermographic energy auditing activities, which could increase engagement in efficiency initiatives.

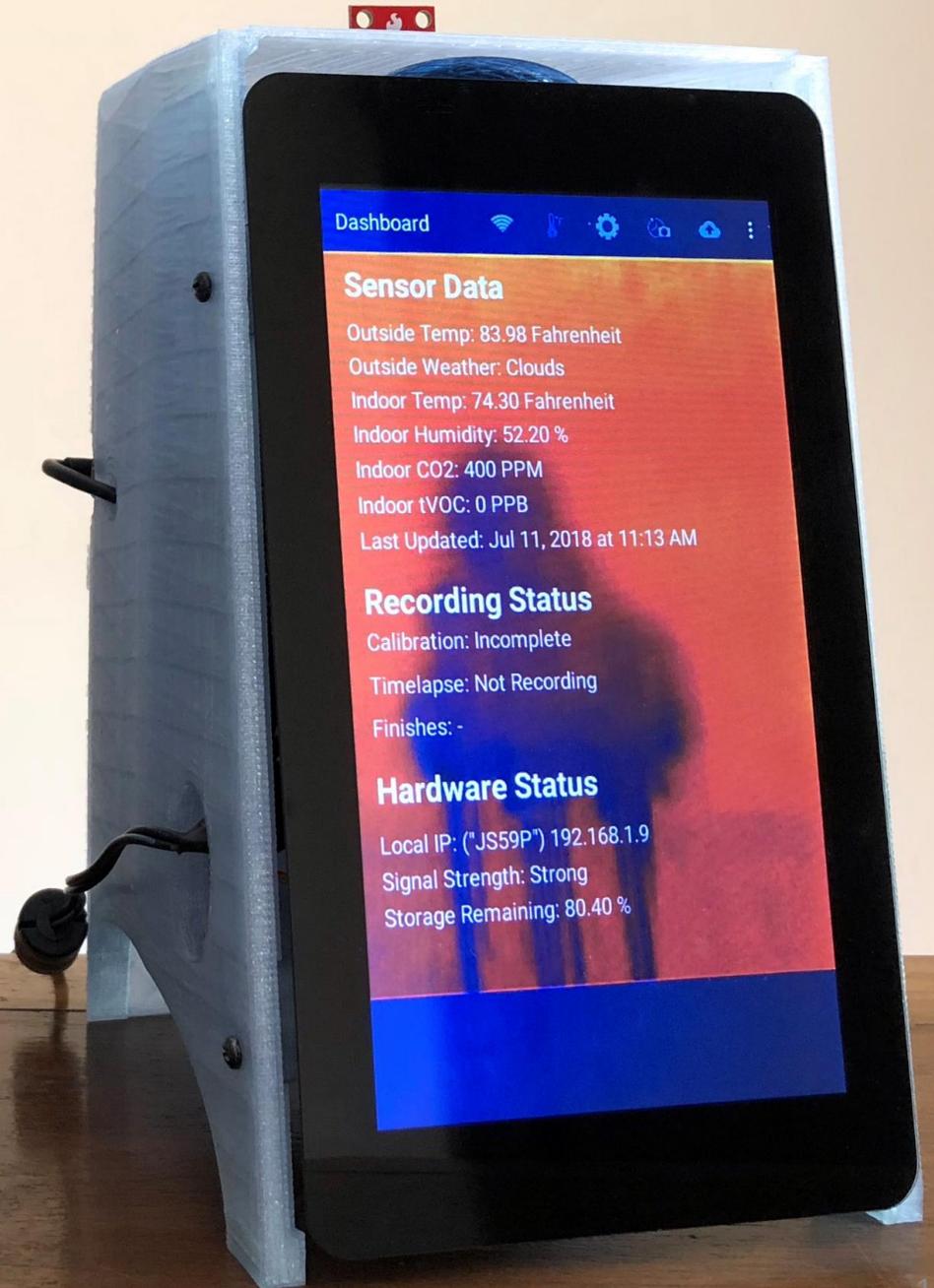
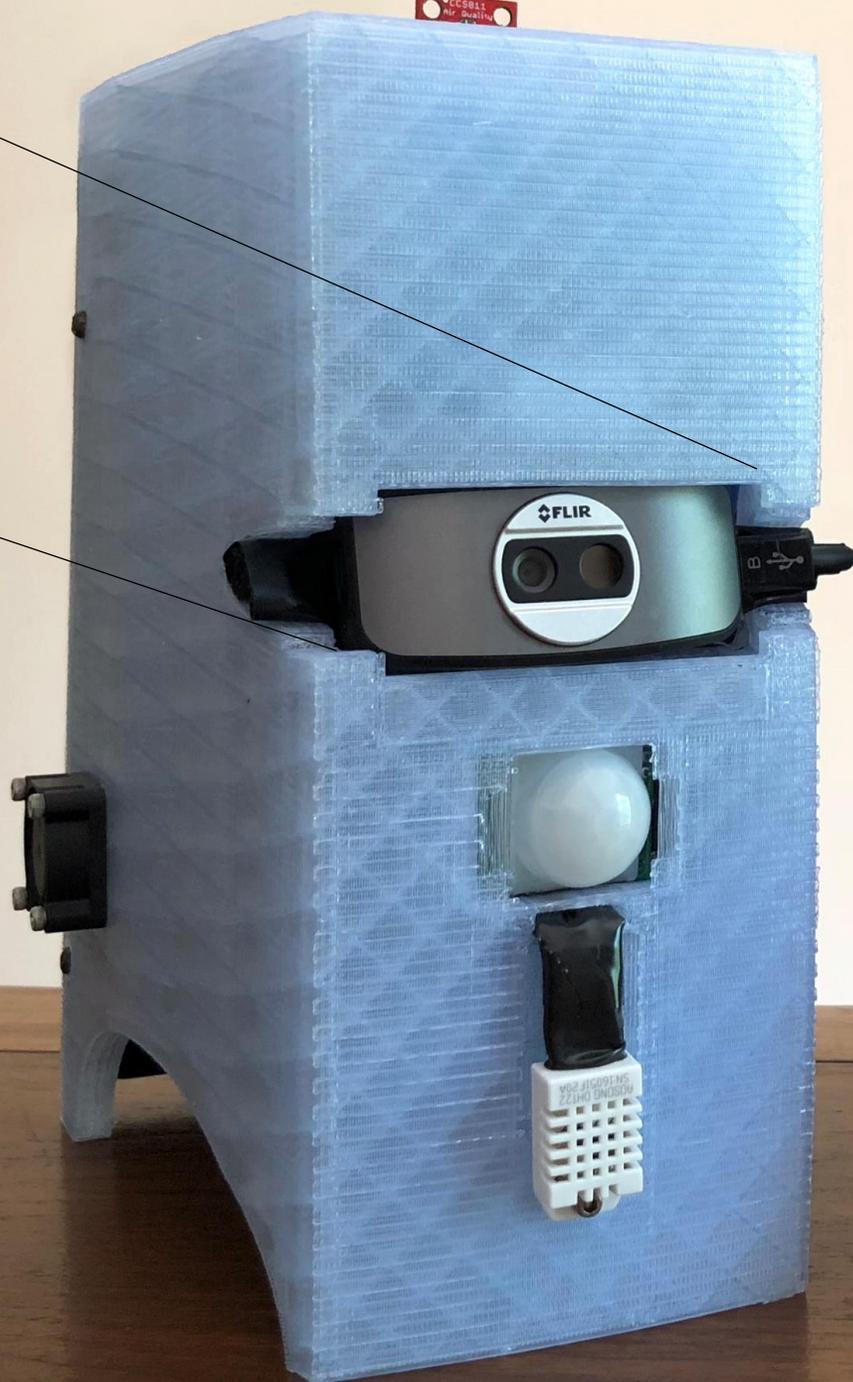
certification programs [37,62]. In response, interest in professional energy auditing has increased [35,52].

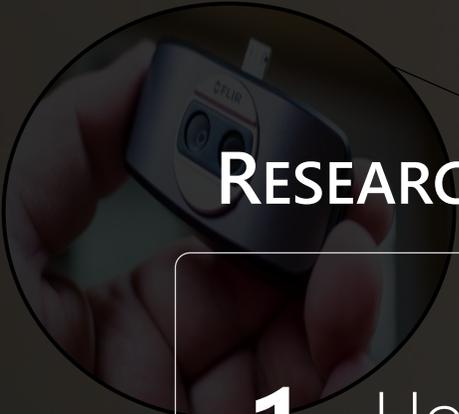
Professional energy auditors assess buildings using an array of diagnostic tests. With improvements in handheld infrared sensors and falling costs, auditors have been increasingly using *thermography* during energy audits [5,9,21,42]. Thermographic-based energy auditing is a data collection and a visual analytics technique that uses thermal cameras to help detect, diagnose, and document energy issues such as building defects and air leakage that produce thermal signatures (e.g., areas of missing insulation) [47,51]. Prior work has shown that including thermal imagery, or *thermograms*, in end-user reports positively influences (homeowner) retrofit decisions and conservation behaviors [29,51]. However, despite technological advances, thermographic-based energy audits remain a laborious activity requiring training and expertise [47].

Recently, thermal camera attachments have emerged for smartphones, which have begun to broaden the adoption of this technology (Figure 1) [70,71]. Marketing materials suggest diverse use, including for DIY energy audits, art and electronics projects, and outdoor recreation (e.g., see [72]). The release of smartphone-based thermal camera attachments—and even fully integrated smartphone thermal cameras [74]—has prompted the development of an increasing number of mobile apps that use and support thermography [22]. While still early, these trends foreshadow a future in which thermal cameras are ubiquitous—integrated into commodity electronics and part of a range of services and applications.

Recent Work at CHI

- Energy auditors who use building thermography techniques experience varying degrees of certainty when interpreting thermograms.
- Energy auditors generally have limited time to conduct scans, collect data, and review their results.





RESEARCH QUESTIONS

- 1 How does using our temporal thermography system influence homeowner's behaviors or perspectives?
- 2 What do professional auditors think of temporal thermography systems and how do their views differ from homeowners?

Dashboard

Sensor Data

Outside Temp: 83.98 Fahrenheit
Outside Weather: Clouds
Indoor Temp: 74.29 Fahrenheit
Indoor Humidity: 42%
Indoor CO2: 400 PPM
Indoor TVOC: 0 PPB
Last Updated: Jul 11, 2018 at 11:13 AM

Recording Status

Calibration: Incomplete
Timelapse: Not Recording

Finishes: -

Hardware Status

Signal Strength: Strong
Storage Remaining: 80.40 %

TALK OVERVIEW



Introduction

Background

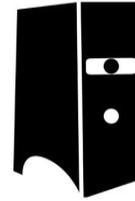
System Overview

Field Deployment

Expert Review

Conclusion

TALK OVERVIEW



Introduction

Background

System Overview

Field Deployment

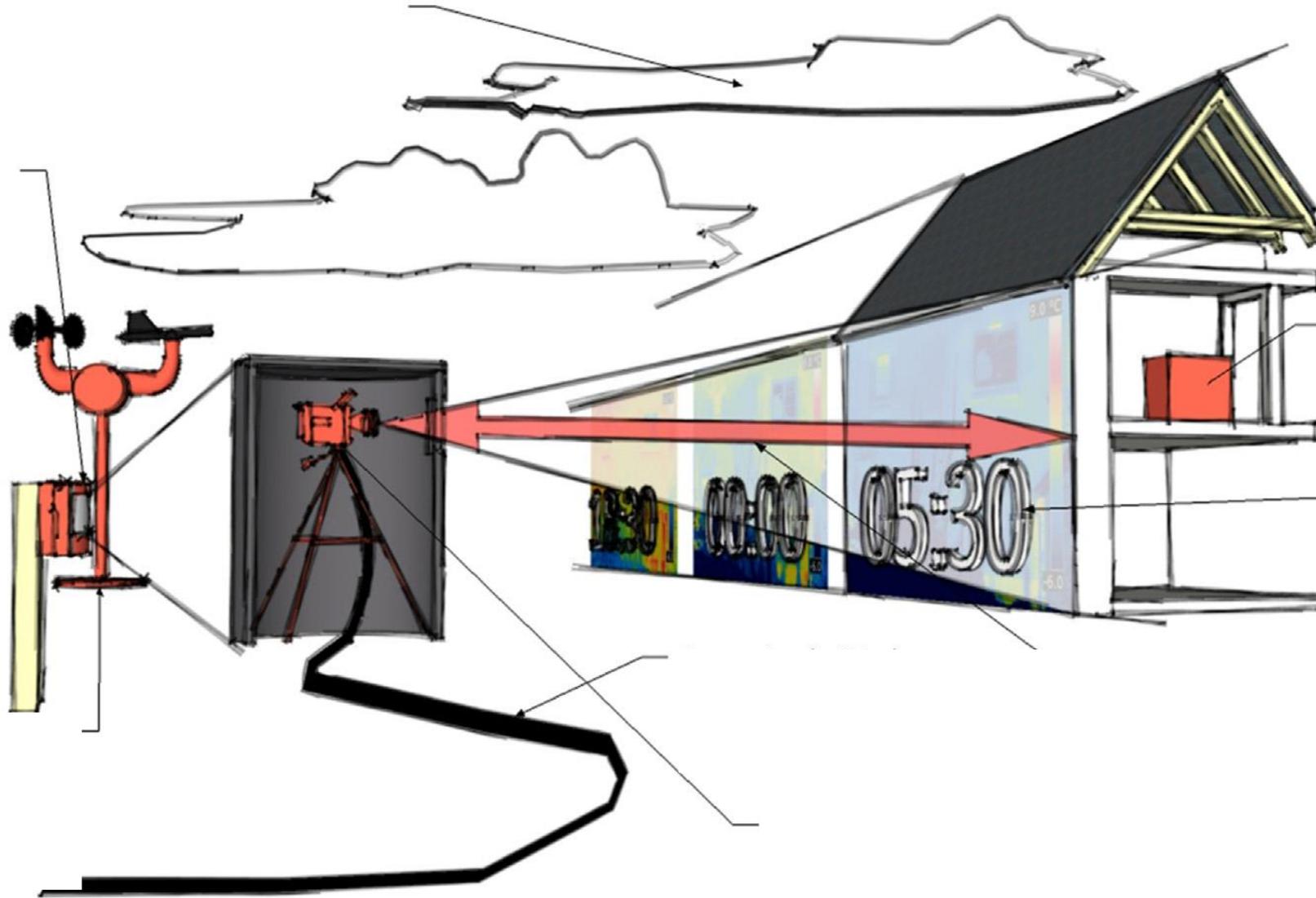
Expert Review

Conclusion



RELATED WORK: TEMPORAL DATA COLLECTION

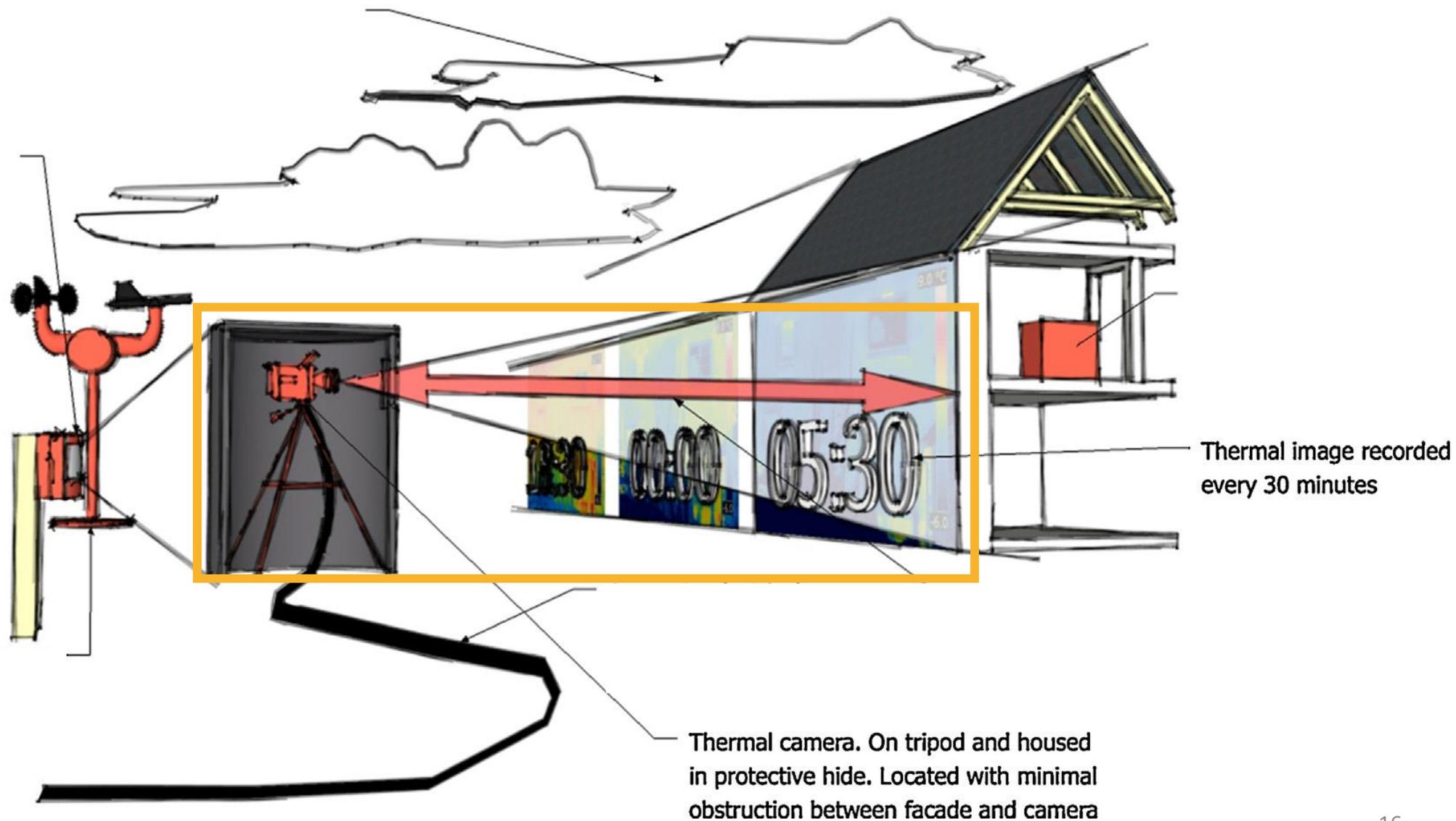
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RELATED WORK: TEMPORAL DATA COLLECTION

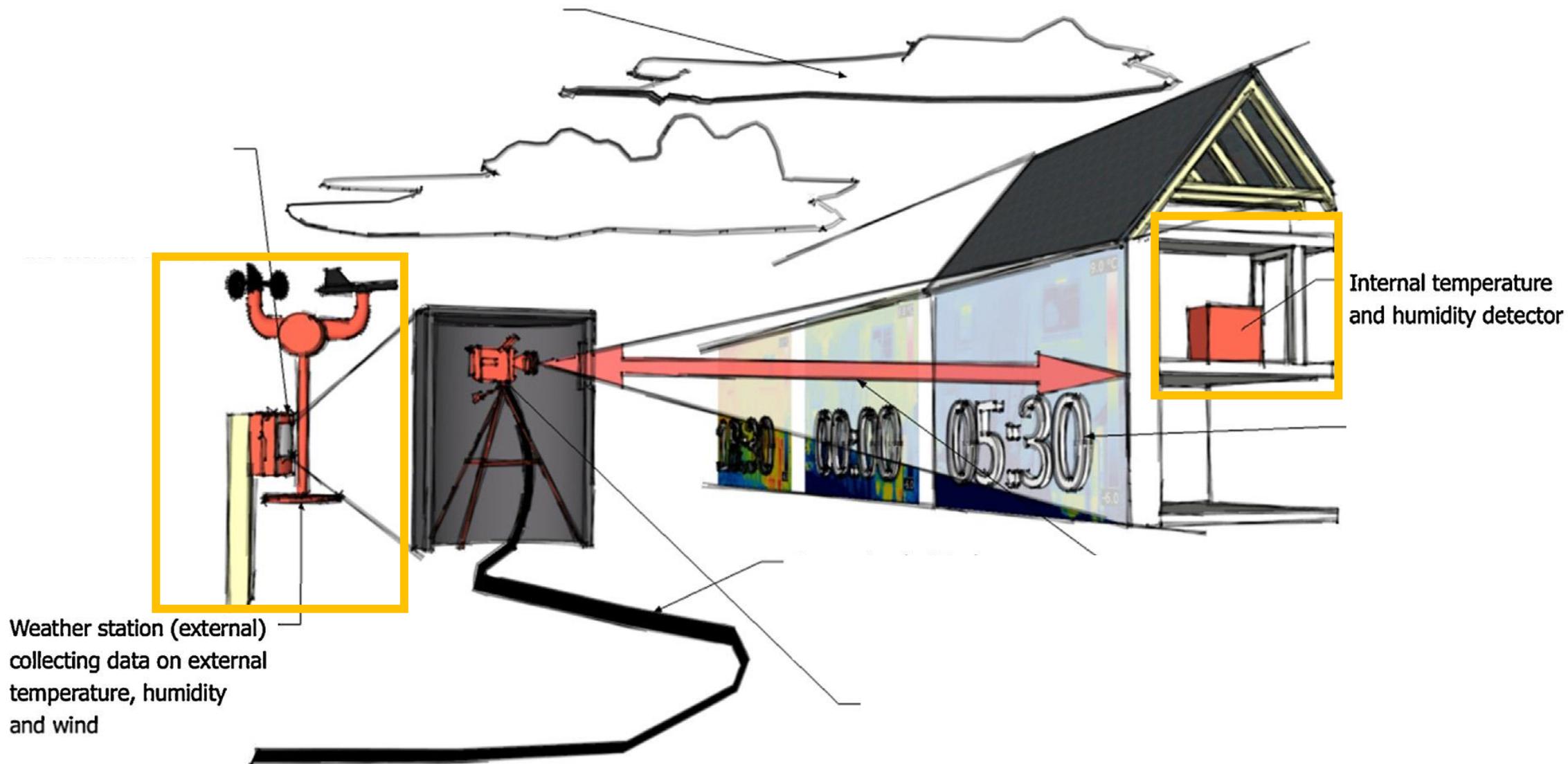
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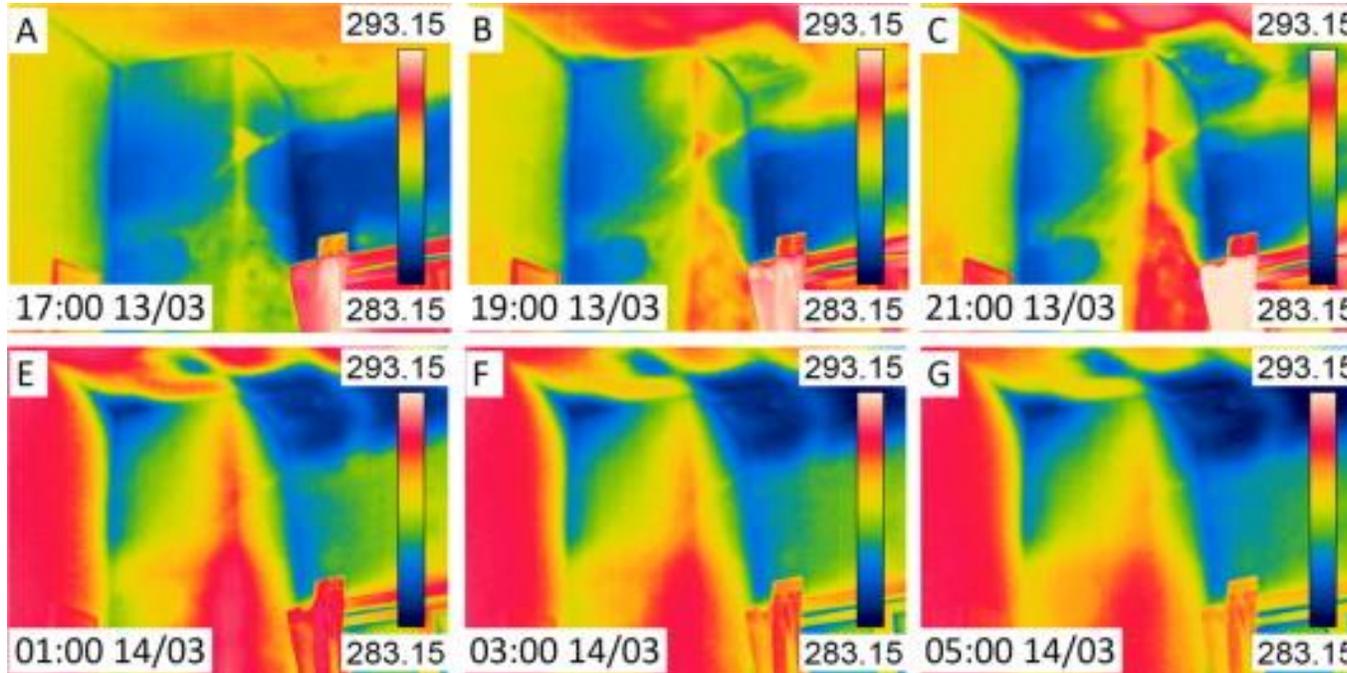
RELATED WORK: TEMPORAL DATA COLLECTION

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RELATED WORK: TEMPORAL VISUALIZATIONS



Energy and Buildings 92 (2015) 95–106

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journal homepage: www.elsevier.com/locate/enbuild

Time-lapse thermography for building defect detection

Matthew Fox^{a,*}, David Coley^b, Steve Goodhew^b, Pieter De Wilde^a

^a School of Architecture, Design and Environment, Plymouth University, Roland Levinsky Building, Drake Circus, Plymouth, Devon PL4 8AA, United Kingdom
^b Department of Architecture and Civil Engineering, University of Bath, Claverton Down, Bath BA2 7AY, United Kingdom

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ABSTRACT

Building thermography traditionally captures the thermal condition of building fabric at one single point in time, rather than changes in state over a sustained period. Buildings, materials and the environment are, however, rarely in a thermal equilibrium, which therefore risks the misinterpretation of building defects by employing this standard methodology. This paper tests the premise that time-lapse thermography can better capture building defects and dynamic thermal behaviour. Results investigating the temporal resolution required for time-lapse thermography over two case study houses found that under typical conditions small temperature differences (approximately 0.2 K) between thermal areas could be expected for 30-min image intervals. Results also demonstrate that thermal patterns vary significantly from day-to-day, with a 2.0 K surface temperature difference experienced from one day to the next. Temporal resolutions needed adjusting for different types of construction. Time-lapse experiments raised practical limitations for the methodology that included problems with the distance to target and foreground obstructions. At the same time, these experiments show that time-lapse thermography could greatly improve our understanding of building transient behaviour and possible building defects. Time-lapse thermography also enables enhanced differentiation between environmental conditions (such as clear sky reflections), actual behaviour and construction defects, thereby mitigating the risk of misinterpretation.

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1. Introduction

According to the United Nations Environment Programme, buildings account for over 40% of the world's energy use [1]. Within the European context, building energy use is rising, with EU dwellings responsible for approximately 70% of all energy use in buildings [2]. Of the 22.4 million dwellings in England, almost 90% were built prior to 1991 [3], a pattern which mirrors the housing trend throughout Europe [2]. Since new build construction in England for 2013 only totalled 109,370 units [4], the aim of the UK government to meet carbon reduction targets of 80% on 1990 levels by 2050 [5] appears unachievable unless widespread action is taken to thermally improve existing dwellings. In addition, increased energy costs are leading to increased levels of fuel poverty [6]. The risk of fuel poverty is typically larger amongst occupants of rural buildings [7] due to a lower uptake of gas central heating

and less energy efficient construction. It is therefore important to improve existing dwellings that are energy inefficient thermally and to minimise the energy demand required for heating buildings.

The ability to identify thermally inefficient areas successfully, such as specific thermal defects, is fundamental to the subsequent success of thermally improving existing buildings [8]. Thermography is an analysis technique which is increasingly being used by construction professionals as a non-destructive tool suited for this task [9]. Thermography, also named thermal imaging, uses a special type of camera to detect infrared radiation, which is emitted from surfaces [10] such as the building fabric. Since the infrared radiation relates to temperature, this in turn depends on heat transfer through the building envelope. Providing there is sufficient temperature difference across a construction, thermography can be used as a tool to identify quickly potential building defects, such as moisture ingress, without the need to undertake costly and damaging physical exploratory investigations. However, image interpretation is a key limitation since thermographers need to be particularly mindful of the external conditions and parameters which can inhibit defect detection, such as emissivity, distance, level, span, [11].

At present, building thermographers tend to capture a series of thermal images during a visit to a building but do not undertake

* Corresponding author at: Room 301, Roland Levinsky Building, Drake Circus, Plymouth, Devon PL4 8AA, United Kingdom. Tel.: +44 7957471225.
 E-mail addresses: m.fox@plymouth.ac.uk (M. Fox), d.a.coley@bath.ac.uk (D. Coley), s.goodhew@plymouth.ac.uk (S. Goodhew), pieter.dewilde@plymouth.ac.uk (P. De Wilde).
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Fox et al., Energy and Buildings '14

Danese et al., Archaeometry '08

HISTORIC
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PHIC DATA*

ARTIN CHARLTON*

Interpretation of
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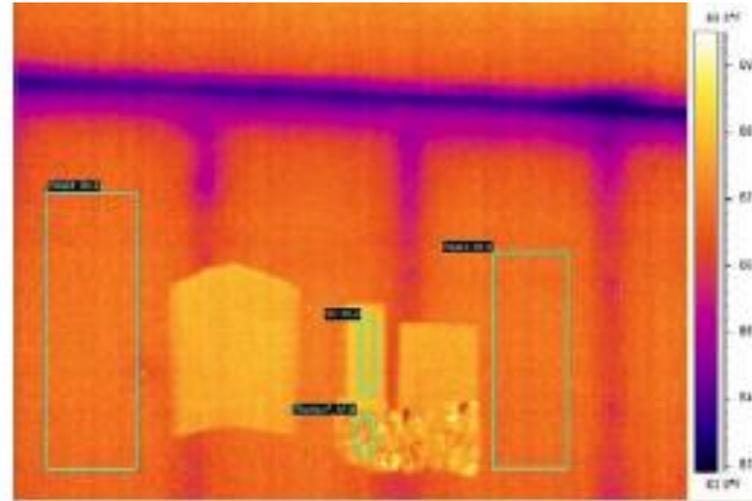
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RELATED WORK: QUANTITATIVE THERMOGRAPHY



$$R - Value = \frac{\Delta T_{io}}{4\epsilon\sigma T_m^3 \Delta T_r + h_c \Delta T_a}$$

INFRAMATION

Finding R-Values of Stud Frame Constructed Houses with IR Thermography

*Robert Madding
Infrared Training Center, FLIR Systems, Inc.*

ABSTRACT
One can calculate the R-Value for an exterior wall segment by estimating the heat flow between the interior of a room and the interior wall surface. In steady state heat transfer conditions, all the heat that flows to the wall flows through the wall. Quantifying the heat flow through the "air film" near the surface of the wall is a straightforward radiation and convection calculation. One needs to know the indoor, outdoor, wall surface and reflected temperatures and the wall emissivity. One does not need to know the wall construction. The challenge is, especially for well insulated walls, that the difference in temperature between the room and wall surface can be small, sometimes only a degree or two, sometimes even less. Calculations based on small delta-T's can result in large errors. For this work the necessary temperatures were measured with FLIR Systems, Inc. model P640 and P65HS IR cameras and a Davis Vantage Pro 2 weather station every 15 minutes for a 24 hour period for a real world experiment. These measurements were done on different wall segments and different dates. Controlled tests were performed using a P65HS and Extech data logger on a box we call our "inside-out house" comprised of differently insulated stud frame constructed bays with wood studs and standard construction, albeit the height was limited to about four feet. The author developed Excel spreadsheet software to download the series of images and automatically calculate R-Values. For steady state conditions and proper measurement, the R-Value should remain constant. Measurement uncertainties were using the Standard Deviation to Average Value ratio for various measurement techniques and weather conditions for both the real-world home and our inside-out house. The best consistency was 2% to 5% for a controlled environment with a real world variation of 7% to 12%. The author performed an uncertainty analysis to evaluate the sensitivity of R-Value calculation to the variables involved. The paper discusses measurement techniques and procedures, weather conditions and interior conditions that will minimize the error of estimating R-values using IR thermography.

INTRODUCTION
According to U.S. Government statistics we spend \$160 billion per year on home energy costs, 21% of national energy costs. Of this, we spend \$72 billion, almost half on heating and cooling our homes. And with reasonable, economic energy conservation efforts we can save 10% that's 7.2 billion annually on our home heating and cooling energy costs.

Anyone faced with over \$4.50 per gallon heating fuel costs is feeling the pain of increased energy costs. Switching fuels is one alternative, but all energy costs are rising and we cannot control them. What we do have a measure of control over is our energy consumption, especially for home heating and cooling. We can upgrade to Energy Star rated heating and cooling systems. We can reduce our temperature difference, the driving force for heat flow, by reducing the indoor temperature in the heating season and increasing it in the cooling season. We can reduce air infiltration/exfiltration by proper caulking and weather stripping. We can reduce the effective size of our living spaces by zoned temperature control. We can improve our home envelope insulation by adding good, properly installed insulation, replacing old, ineffective or missing insulation. But wait, where is the insulation bad or missing? Am I to poke holes throughout my home in the dry wall just to find out? No. IR thermography under the right conditions can readily spot bad or missing insulation. We do need a good temperature difference between the inside and outside of a home to do this, but with modern IR cameras the job is straightforward. How much of a temperature difference we need is discussed in a later section. It depends a lot on the quality of the IR camera being used.

Insulation retrofits cost money and one could reasonably ask what the cost benefit ratio is for doing this. To this end the author has developed an algorithm that estimates the R-Value of a wall section, then estimates savings in energy cost by improving the insulation level to a higher value. The user has control over the input variables, including R-values, energy costs, efficiencies, affected area and degree days. Uncertainties exist at every turn, so the estimates aren't going to be to the nearest dollar, but should give a reasonable guideline.

InfraMation 2008 Proceedings ITC 126 A 2008-05-14

Madding, 2008



RELATED WORK: QUANTITATIVE TEMPORAL THERMOGRAPHY

Applied Energy 88 (2011) 4058–4065

Contents lists available at ScienceDirect

Applied Energy

Journal homepage: www.elsevier.com/locate/apenergy

Application of infrared thermography for the determination of the overall heat transfer coefficient (*U*-Value) in building envelopes

Paris A. Fokaides^a, Soteris A. Kalogirou^{b,*}

^aUniversity of Cyprus, Department of Civil and Environmental Engineering, Cyprus
^bCyprus University of Technology, Department of Mechanical Engineering and Materials Science and Engineering, Cyprus

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 Sensitivity analysis
 Thermal emissivity
 Reflected temperature

ABSTRACT

Infrared (IR) thermography constitutes a reliable measurement method for the determination of spatially resolved surface temperature distributions. IR thermography may be used for several research problems, applications, and measurement environments with a variety of physical arrangements, to the extent that the results of the determination of the overall heat transfer coefficient (*U*-Value) with the use of IR thermography for building envelopes are presented. The obtained *U*-Values are validated by means of measurements performed with the use of a thermochromogram for two seasons (summer and winter), as well as with the overall results provided by the reference EN standard. Issues related to the applicability of the method due to the non-steady heat transfer phenomena observed at building shells are also discussed. A more precise validation of the proposed technique was also performed with the use of heat flux meters. The percentage absolute deviation between the obtained and the measured *U*-Values for IR thermography is found to be in an acceptable level, in the range of 10–20%. Finally, a sensitivity analysis is conducted in order to define the most important parameters which may have a significant influence on the measurement accuracy.

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1. Introduction

The use of infrared (IR) thermography has increased dramatically throughout the world over the past few years. This technique is employed for the measurement of surface characteristics for a variety of research investigations involving all possible heat transfer phenomena. The method is especially important and useful because it gives spatially resolved surface temperature distributions non-invasively, even when large gradients of surface temperature are present [1]. IR thermography can be used in building envelopes to detect heat losses, missing or damaged thermal insulation in walls and roofs, thermal bridges, air leakages and sources of moisture. IR thermography can also be employed in building diagnostics for the determination of the thermo-physical properties of building envelopes. Currently, this application is becoming more important, as the knowledge of the *U*-Value is a precondition for the classification of the energy performance of existing buildings [2]. This information may not be in some cases accessible or available, especially in the case of old buildings or in member states of the European Union where the regulatory

authorities did not keep detailed building records at the time of construction. Therefore, the question to answer is how reliable is the implementation of IR thermography for the determination of the *U*-Value of building shells.

The discussion on the applicability of the IR thermography for building diagnosis has been held since this technique was widely commercialized at the early 90s. One of the most important questions to answer is whether this technique may provide reliable quantitative measurements, or if the extent of this application is limited to qualitative results. Another issue which is also under discussion, especially in the case of building thermography is the non-steady character of the heat transfer in building envelopes and the interpretation of an instantaneous thermogram under non-steady conditions.

The main areas for using IR thermography in building diagnostics are presented in detail by Bakara and Agrigoro [3]. In particular, representative examples of building envelopes, mechanical and electrical systems inspection in audited office buildings are presented to demonstrate common problems and data interpretation. In this study, it is suggested that building IR thermography on external building elements should be performed either at night or during a cloudy day. This was found to be important in order to avoid the problem of temperature increase which occurs as a result of the incident solar radiation, and the impact from the absorbed solar energy, which presents a time lag of a few hours. Additionally in this work it is pointed out that measurements

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Fokaides & Kalogirou, 2011

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Article

Infrared Screening of Residential Buildings for Energy Audit Purposes: Results of a Field Test

Giuliano Dall’O^a, Luca Sarto and Angela Panza

Architecture, Building Environment and Construction Engineering (A.B.C.) Department, Polytechnic of Milan, Via E. Bonardi 9, 10133 Milano, Italy; E-Mails: luca.sarto@polimi.it (L.S.), angela.panza@polimi.it (A.P.)

* Author to whom correspondence should be addressed. E-Mail: giuliod@polimi.it; Tel.: +39-02-2399-4649; Fax: +39-02-2399-9491.

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ABSTRACT

Infrared (IR) thermography constitutes a reliable measurement method for the determination of spatially resolved surface temperature distributions. IR thermography may be used for several research problems, applications, and measurement environments with a variety of physical arrangements, to the extent that the results of the determination of the overall heat transfer coefficient (*U*-Value) with the use of IR thermography for building envelopes are presented. The obtained *U*-Values are validated by means of measurements performed with the use of a thermochromogram for two seasons (summer and winter), as well as with the overall results provided by the reference EN standard. Issues related to the applicability of the method due to the non-steady heat transfer phenomena observed at building shells are also discussed. A more precise validation of the proposed technique was also performed with the use of heat flux meters. The percentage absolute deviation between the obtained and the measured *U*-Values for IR thermography is found to be in an acceptable level, in the range of 10–20%. Finally, a sensitivity analysis is conducted in order to define the most important parameters which may have a significant influence on the measurement accuracy.

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1. Introduction

The use of infrared (IR) thermography has increased dramatically throughout the world over the past few years. This technique is employed for the measurement of surface characteristics for a variety of research investigations involving all possible heat transfer phenomena. The method is especially important and useful because it gives spatially resolved surface temperature distributions non-invasively, even when large gradients of surface temperature are present [1]. IR thermography can be used in building envelopes to detect heat losses, missing or damaged thermal insulation in walls and roofs, thermal bridges, air leakages and sources of moisture. IR thermography can also be employed in building diagnostics for the determination of the thermo-physical properties of building envelopes. Currently, this application is becoming more important, as the knowledge of the *U*-Value is a precondition for the classification of the energy performance of existing buildings [2]. This information may not be in some cases accessible or available, especially in the case of old buildings or in member states of the European Union where the regulatory

authorities did not keep detailed building records at the time of construction. Therefore, the question to answer is how reliable is the implementation of IR thermography for the determination of the *U*-Value of building shells.

The discussion on the applicability of the IR thermography for building diagnosis has been held since this technique was widely commercialized at the early 90s. One of the most important questions to answer is whether this technique may provide reliable quantitative measurements, or if the extent of this application is limited to qualitative results. Another issue which is also under discussion, especially in the case of building thermography is the non-steady character of the heat transfer in building envelopes and the interpretation of an instantaneous thermogram under non-steady conditions.

The main areas for using IR thermography in building diagnostics are presented in detail by Bakara and Agrigoro [3]. In particular, representative examples of building envelopes, mechanical and electrical systems inspection in audited office buildings are presented to demonstrate common problems and data interpretation. In this study, it is suggested that building IR thermography on external building elements should be performed either at night or during a cloudy day. This was found to be important in order to avoid the problem of temperature increase which occurs as a result of the incident solar radiation, and the impact from the absorbed solar energy, which presents a time lag of a few hours. Additionally in this work it is pointed out that measurements

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Dall’O et al., 2013

Applied Energy 141 (2015) 218–228

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Applied Energy

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A comprehensive experimental approach for the validation of quantitative infrared thermography in the evaluation of building thermal transmittance

Rossano Albatici^{a,*}, Arnaldo M. Tonelli^b, Michela Chiogna^c

^aUniversity of Trento, Department of Civil, Environmental and Mechanical Engineering, Via Mesiano 77, 38023 Trento, Italy
^bUniversità del Piemonte Orientale, Via Montebello 1, 13100 Biella, Italy
^cUniversità del Piemonte Orientale, Via Montebello 1, 13100 Biella, Italy

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 Thermal transmittance
 On-site measurement
 Energy performance

ABSTRACT

Quantitative thermography is a newly adopted method to measure energy performance of existing buildings. In particular, the thermal transmittance (*U*-value) of opaque elements. Some researchers have been conducting in this field, each presenting a different procedure verified by the application on single case studies. Anyway, a comprehensive approach, based on a systematic analysis of walls with different typologies and exposure, but same boundary conditions, is still missing. This study proposes a systematic approach to the problem, based on a three years research activity carried out on an experiment of building where timber (light) and brick (heavy) structures were tested simultaneously with Infrared Thermography Technique (ITT) also equipped with heat flux meter (HFMM) sensors and a steady metro station. Standard deviation of *U*-values measured with ITT is given as well as absolute deviation against values calculated following international standards and measured with HFMM method. Parameters having high significance for the achievement of good results compared to the expected *U*-values are analyzed through a sensitivity analysis. Influence of weather conditions during the survey are also considered and a repeatable procedure is finally set up. The findings presented in this study show that the method gives good results for heavy construction, while further studies are still needed for light and super insulated walls.

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1. Introduction

This paper deals with a research project that follows the procedure for the on-site determination of thermal transmittance (*U*-value) of opaque building elements based on Infrared Thermography Technique (ITT) previously proposed by the authors [1] in order to deeply understand limits and strength of the method and to determine its accuracy for different walls typologies; the procedure has been validated on an experimental purpose-built construction. The importance of a proper evaluation of the building envelope real energy performance as well as the state of the art of the use of quantitative thermography has been already presented and discussed [1]. Anyway, from 2010 there have been important innovations and breakthroughs in the research area.

Considering international energy regulations, two European Directives came recently into force, the 2010/18/EU [2] so called NZEB (nearly zero energy buildings) and the 2012/27/EU [3]. They have forced public administrations, designers, private companies

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 doi:10.1016/j.apenergy.2014.12.035

Albatici et al., 2015

Energy and Buildings 122 (2016) 211–221

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Energy and Buildings

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U-value assessment by infrared thermography: A comparison of different calculation methods in a Guarded Hot Box

Iole Nardi^a, Domenica Poletti, Dario Ambrosini, Tullio de Rubelis, Stefano Sfarra

^aUniversità del Piemonte Orientale, Dipartimento di Ingegneria Industriale e Informatica (DIII), Università di Aquila, P.zza dei Vestiboli 1, 67100 L'Aquila, Italy

ARTICLE INFO

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Keywords:
 Infrared thermography
 Thermal transmittance
 Heat flux meter
 Guarded hot box
 Experimental measurements

ABSTRACT

The thermal transmittance (*U*-value) of the vertical opaque building envelope plays a key role for the evaluation of the thermal performance of a structure. In order to speed up the assessment procedure and to investigate wider portions of building directly in situ, new methods based on the use of quantitative infrared thermography have been proposed during the last years. Although the studies agree about the influence of the operative conditions, a detailed report, based on measurements effected on a large wall in a controlled environment and in different boundary conditions, is still missing in literature. The aim of this work is to assess the validity of thermographic methods by using different operative conditions in a controlled environment. The results obtained by different IR methods in a Guarded Hot Box have been compared with heat flux meter measurements and theoretical values.

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1. Introduction

The knowledge of the thermal transmittance of a building envelope is mandatory for the quantification of losses through it. This parameter, commonly referred to as *U*-value, can be determined by a theoretical approach (using the electrical analogy) or by using the heat flow meter method (HFMM).

To apply the first method, it is possible to refer to ISO 6946 [1] that requires the knowledge of the thickness and thermal conductivity of each layer of the wall structure. This information is often missing, especially for ancient buildings; in these cases, it can be retrieved by comparison with several stratigraphies and by referring to values provided by norms, as for example UNI 10551 [2].

As an alternative, the heat flow meter method allows to determine the thermal transmittance directly on the wall, complying with ISO 9869 [3]. This method requires specific operating conditions (as for instance, a minimum temperature gradient between indoor and outdoor, which might affect the results and their relative uncertainty as proved in Ref. [4]); and the absence of thermal bridges or anomalies, humidity, mould, partial adhesion between sensors and wall. Furthermore, results might depend on the considered analysis method, as demonstrated by Cesaratto et al. [5]; who applied different methods and tools to process data acquired by HFMM on real buildings; even the wall exposure might affect the final result, as shown in Ref. [7], where results of the HFMM method applied both to a North and to an East facing wall have been compared after different surveys; the effect probes location, as examined in Ref. [1], where the influence of different probe pasting angle has been examined through a validated model.

Besides these two approaches, in the last years new methodologies based on the use of Infrared Thermography (ITT) have been proposed in literature to evaluate the thermal transmittance. It is well known that a correct interpretation of an IR image for *U*-value measurement is complex, mainly because of the many parameters involved in an IR image reading: emissivity, whose variation against temperature and evaluation method is discussed in Ref. [8]; reflected radiation, which influences the accuracy of infrared thermography temperature measurements, but can be compensated using a reflective mirror (i.e. an aluminium foil), as explained in Ref. [1], where laboratory tests and evaluations on a real building have been performed, showing the better agreement between corrected temperature gathered from a thermogram and the temperature read on the same surfaces by a thermocouple; climatic factors: the effects, on an IR image, of air and sky temperatures

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 doi:10.1016/j.enb.2016.03.007

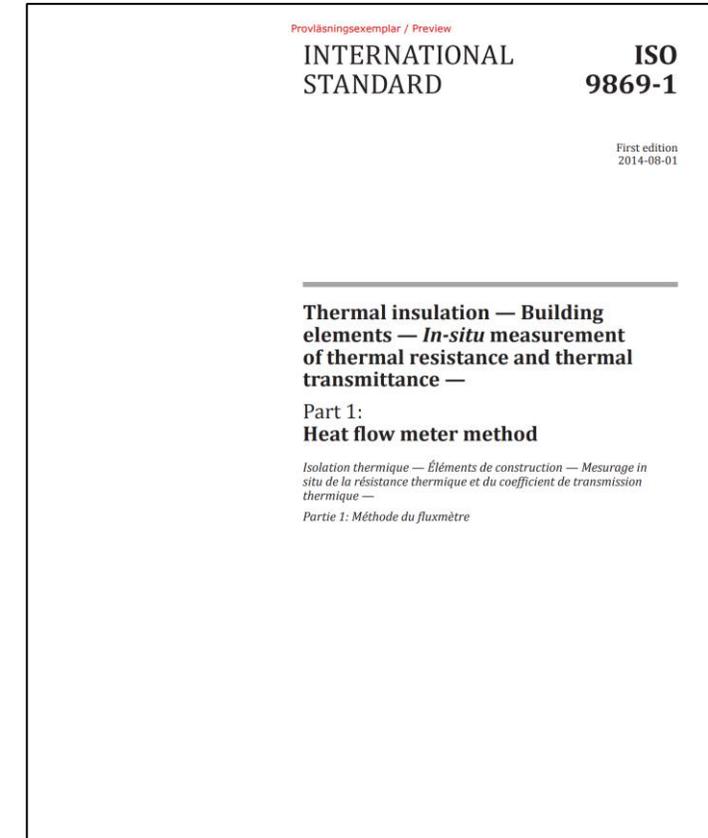
Nardi et al., 2016



RELATED WORK: QUANTITATIVE MEASUREMENT



Direct Contact Methods:
Heat Flux Sensors and Thermocouples





RESEARCH CONTRIBUTIONS

Future work called for within these assessments includes real-world deployments with professional users

This work contributes the design of such a system, and evaluations with both professional and non-professionals

TALK OVERVIEW



Introduction

Background

System Overview

Field Deployment

Expert Review

Conclusion

TALK OVERVIEW



Introduction

Background

System Overview

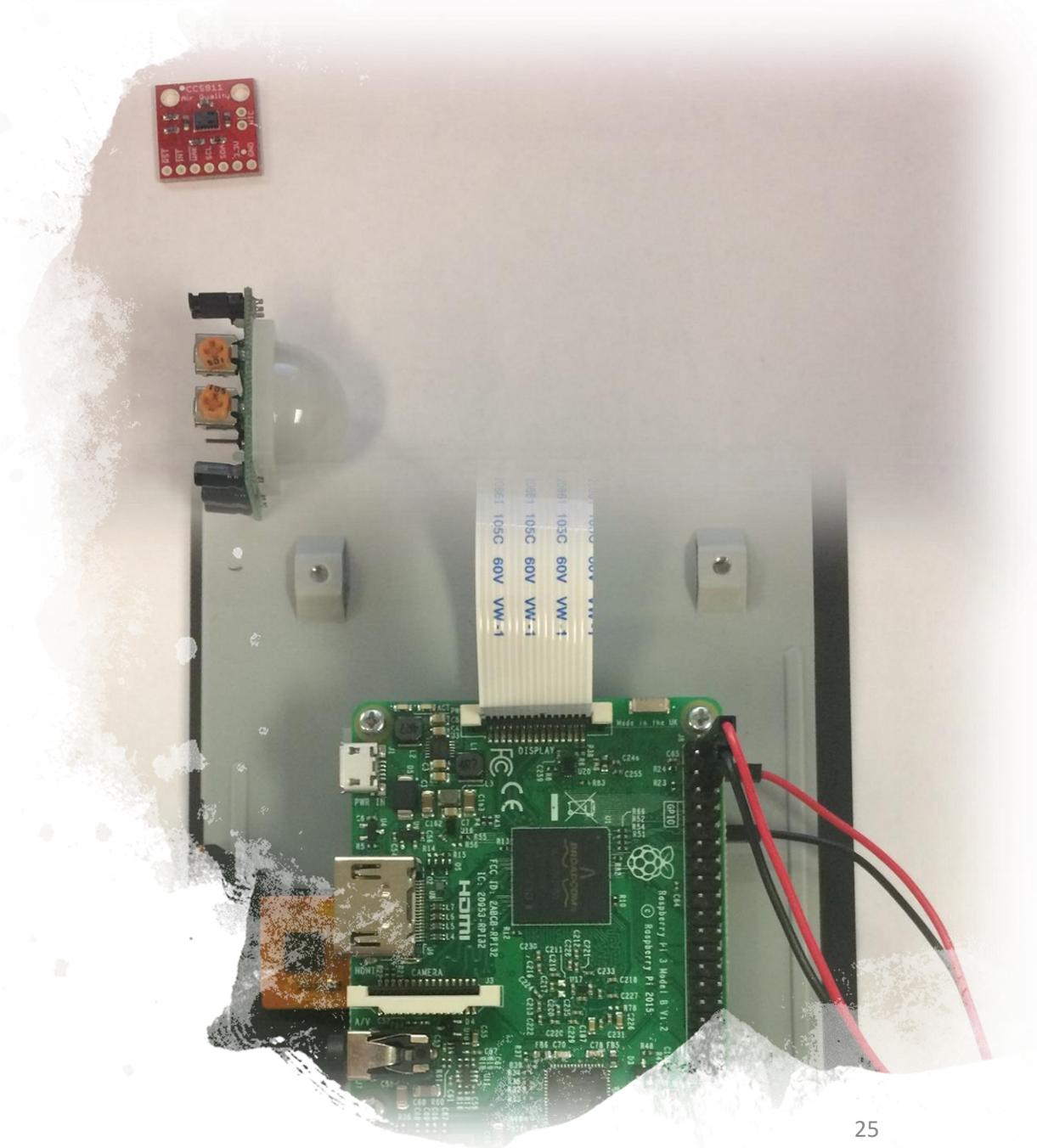
Field Deployment

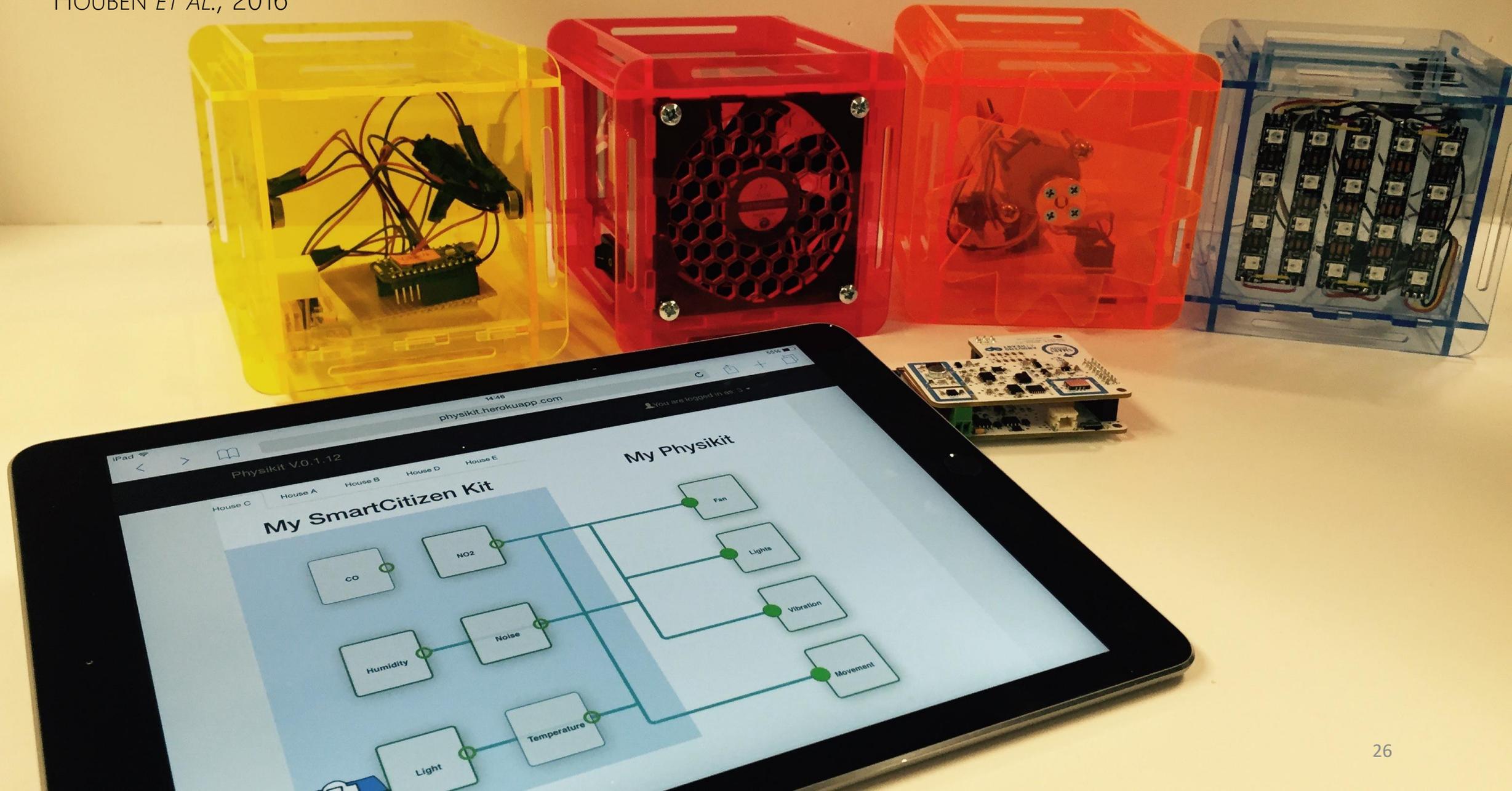
Expert Review

Conclusion

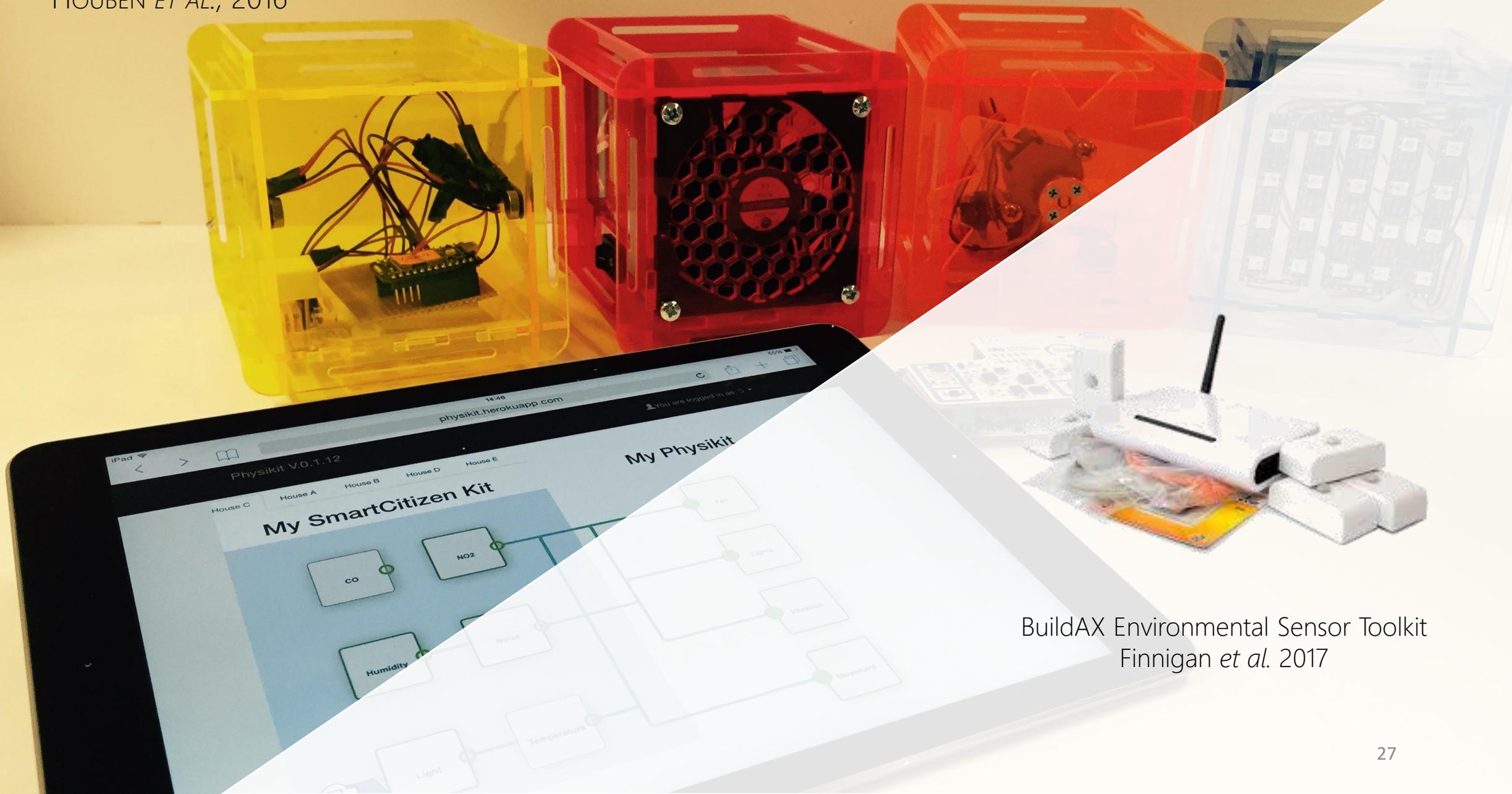
DEVELOPMENT: DESIGN GOALS

- Easy-to-Deploy
- Non-intrusive
- Provide Rapid Analysis
- Help with Severity Estimation
- Holistic Report



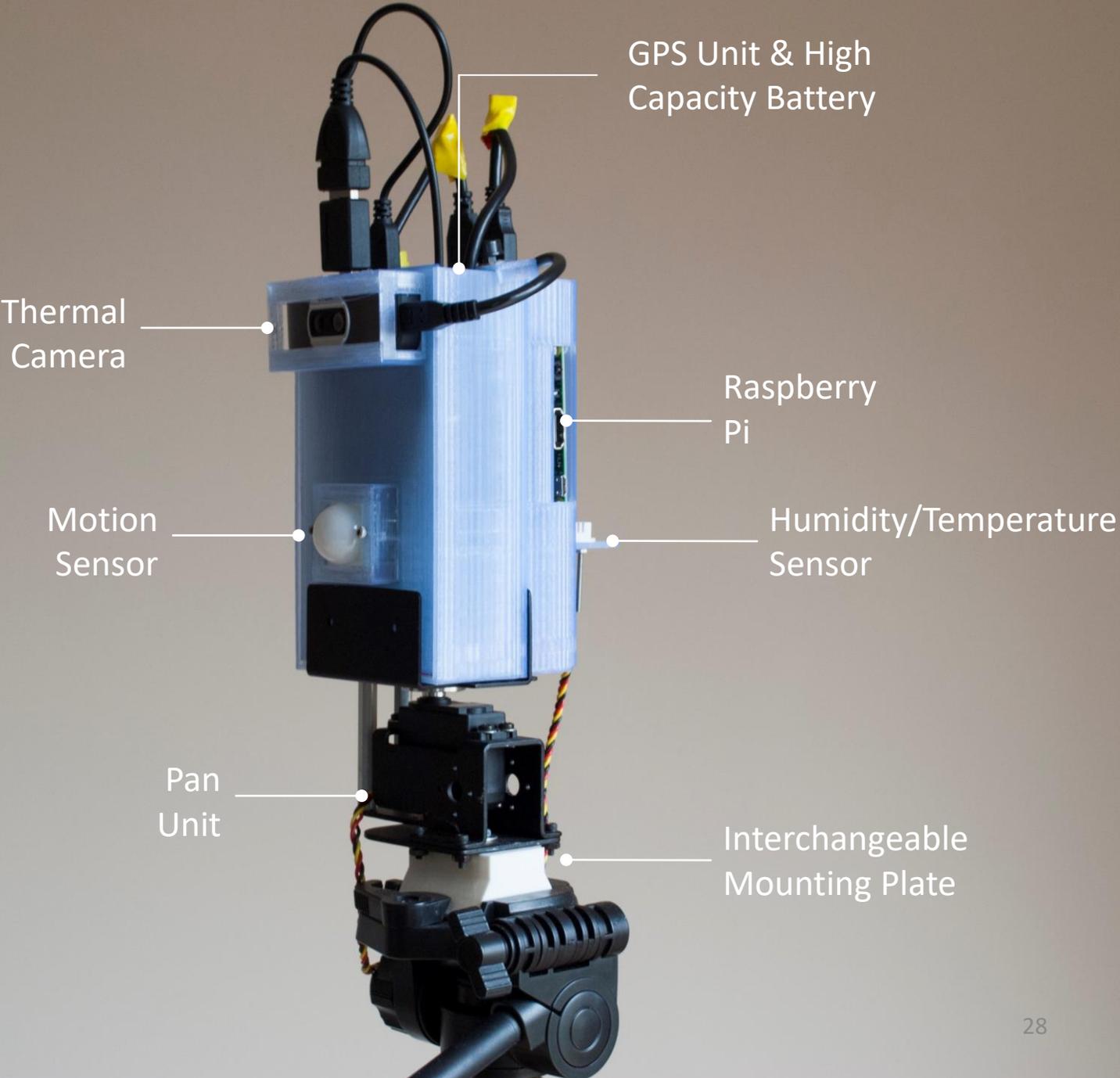


PHYSIKIT
HOUBEN *ET AL.*, 2016



BuildAX Environmental Sensor Toolkit
Finnigan *et al.* 2017

EASY-TO-DEPLOY THERMOGRAPHIC
SENSOR SYSTEM
(v3.0)



Dataset Information:

Start Date:
2017-03-12 14:53

Schedule:
Every 30 Minutes (Approx)

Iterations:
106 / 2.21 Days (Approx)

Survey Description:
Wall Insulation & Discharge
Air Temperature

Settings:

Toggle View

Patch Size

Time Window:

 +1.58 Hours

Temp Scale

Include Unselected

Reset

Sensors:

Internal Temp

External Temp

Tools:

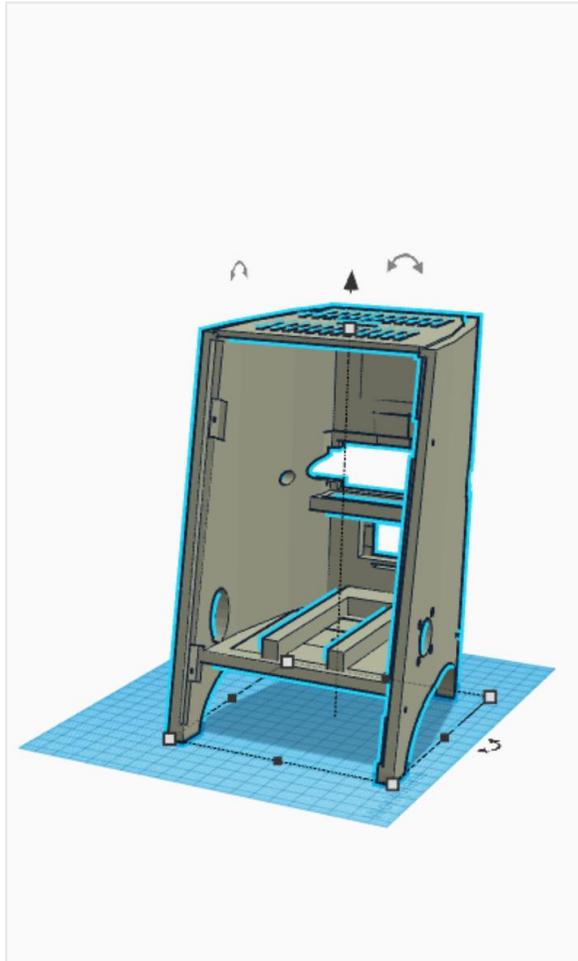
Select

Point

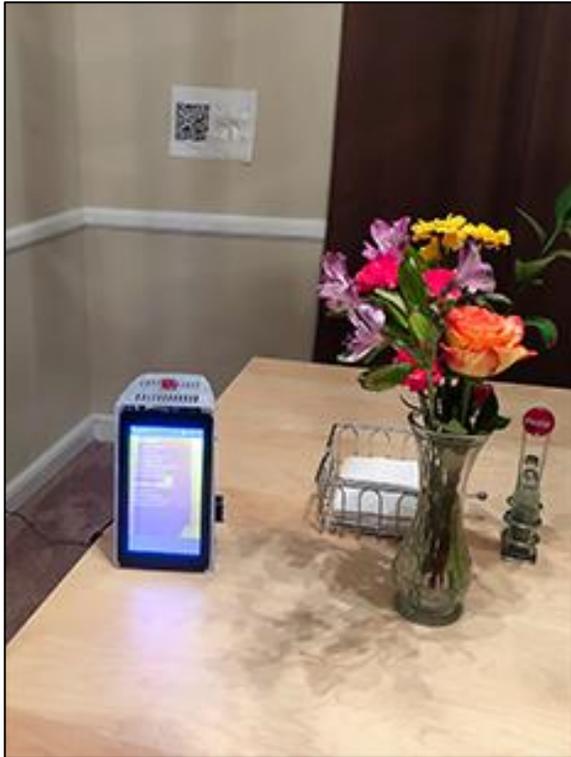
Box



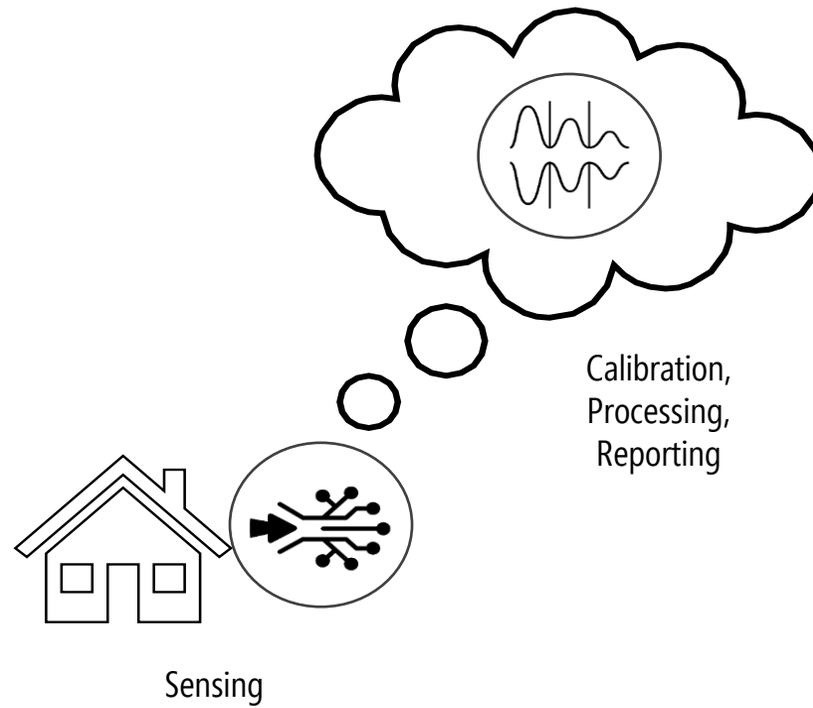
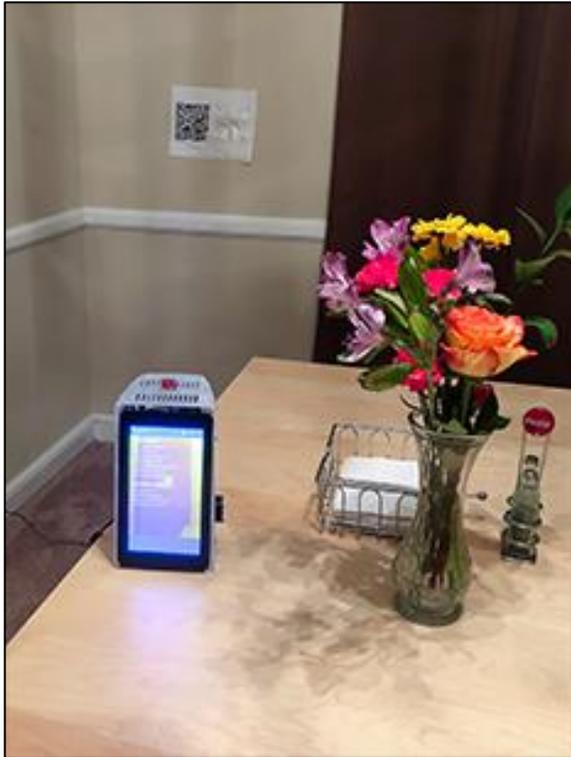
DEVELOPMENT: EASY-TO-DEPLOY THERMOGRAPHIC SENSOR KIT (v4.0)



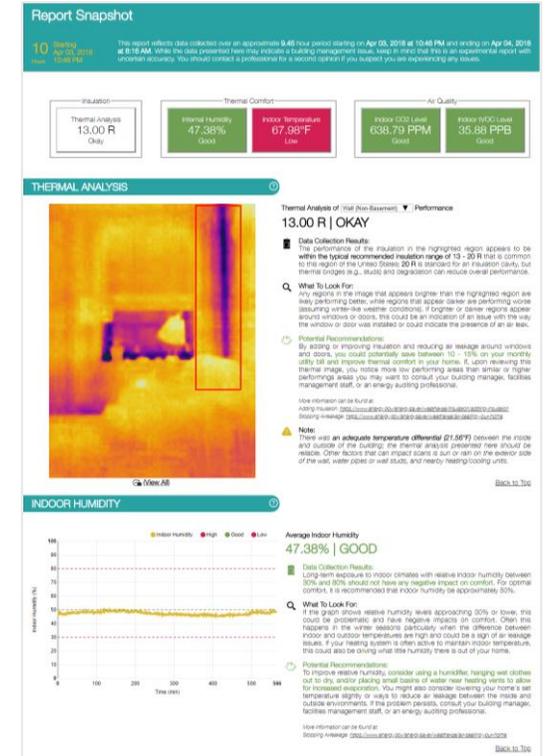
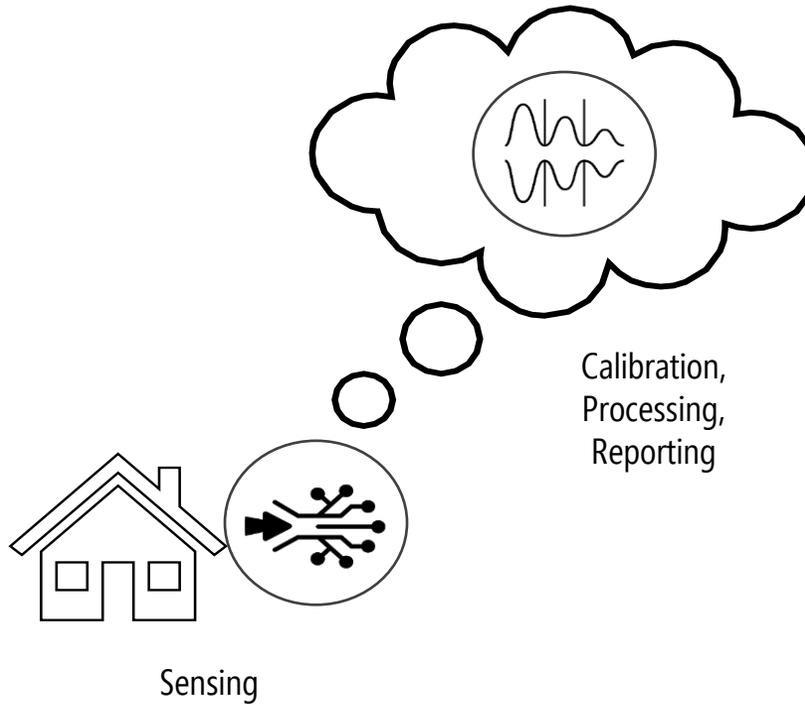
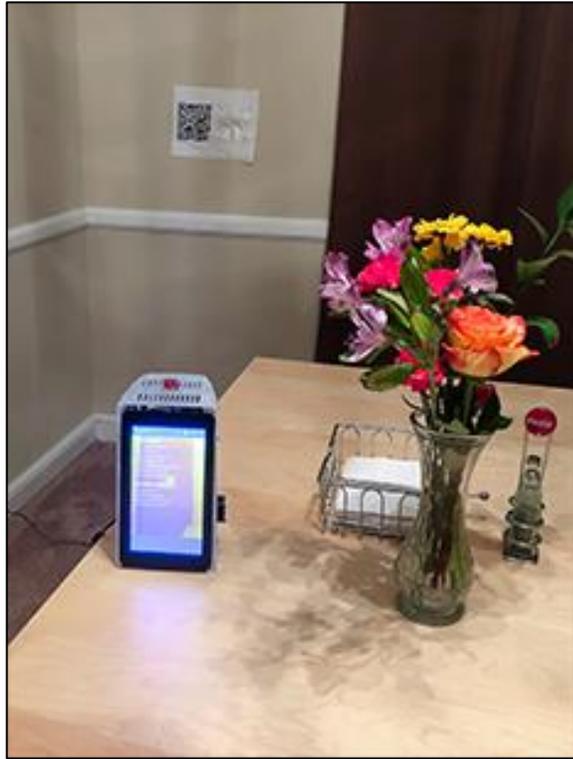
DEVELOPMENT: SYSTEM OVERVIEW



DEVELOPMENT: SYSTEM OVERVIEW



DEVELOPMENT: SYSTEM OVERVIEW



DEVELOPMENT: REVISED VISUALIZATION

Report Snapshot

10 Energy Points
13.00 R

Thermal Analysis: 13.00 R | OKAY

Indoor Humidity: 47.58% | GOOD

Indoor Temperature: 67.98°F | LOW

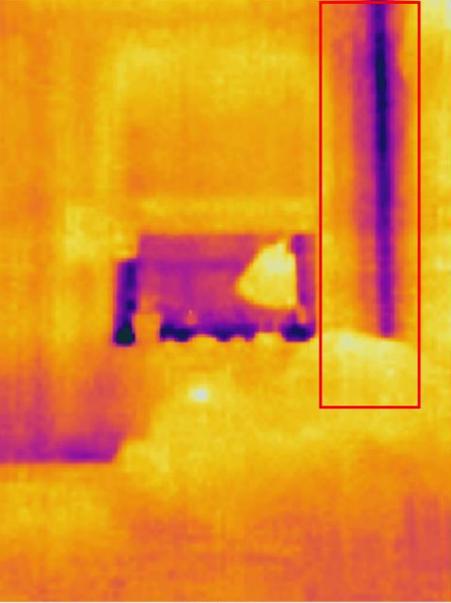
Indoor CO2 Level: 838.79 PPM | GOOD

Indoor VOC Level: 35.88 PPB | GOOD

THERMAL ANALYSIS

Thermal Analysis of Wall (Non-Basement) Performance

13.00 R | OKAY



Data Collection Results:
The performance of the insulation in the highlighted region appears to be within the typical recommended insulation range of 13 - 20 R that is common to this region of the United States; 20 R is standard for an insulation cavity, but thermal bridges (e.g., studs) and degradation can reduce overall performance.

What To Look For:
Any regions in the image that appears brighter than the highlighted region are likely performing better, while regions that appear darker are performing worse (assuming winter-like weather conditions). If brighter or darker regions appear around windows or doors, this could be an indication of an issue with the way the window or door was installed or could indicate the presence of an air leak.

Potential Recommendations:
By adding or improving insulation and reducing air leakage around windows and doors, you could potentially save between 10 - 15% on your monthly utility bill and improve thermal comfort in your home. If, upon reviewing this thermal image, you notice more low performing areas than similar or higher performing areas you may want to consult your building manager, facilities management staff, or an energy auditing professional.

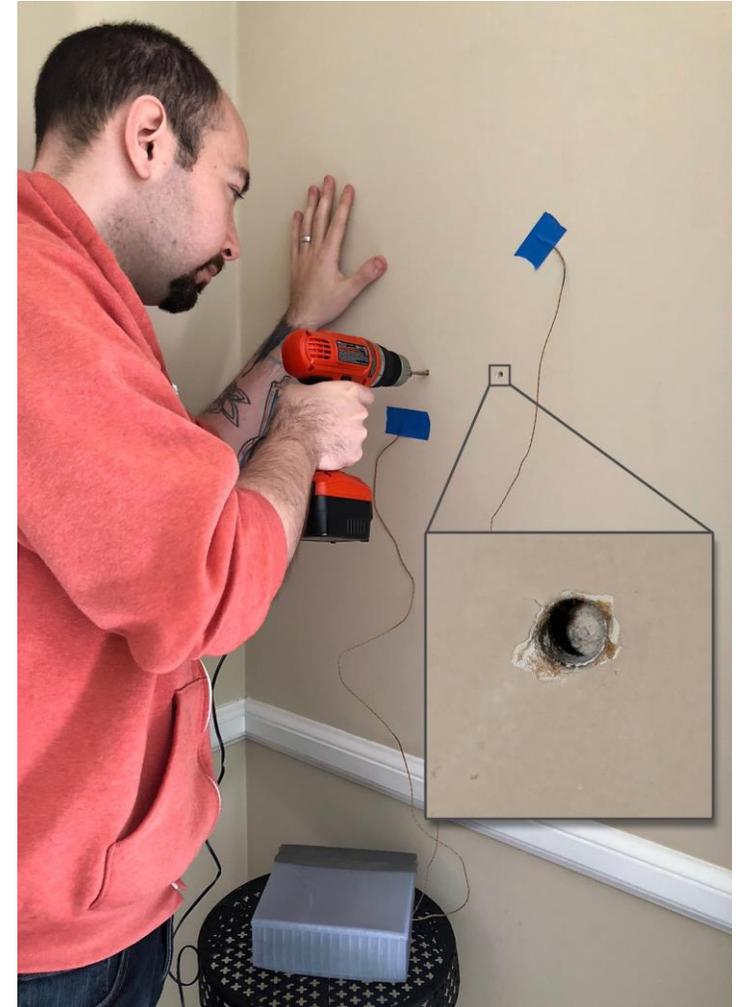
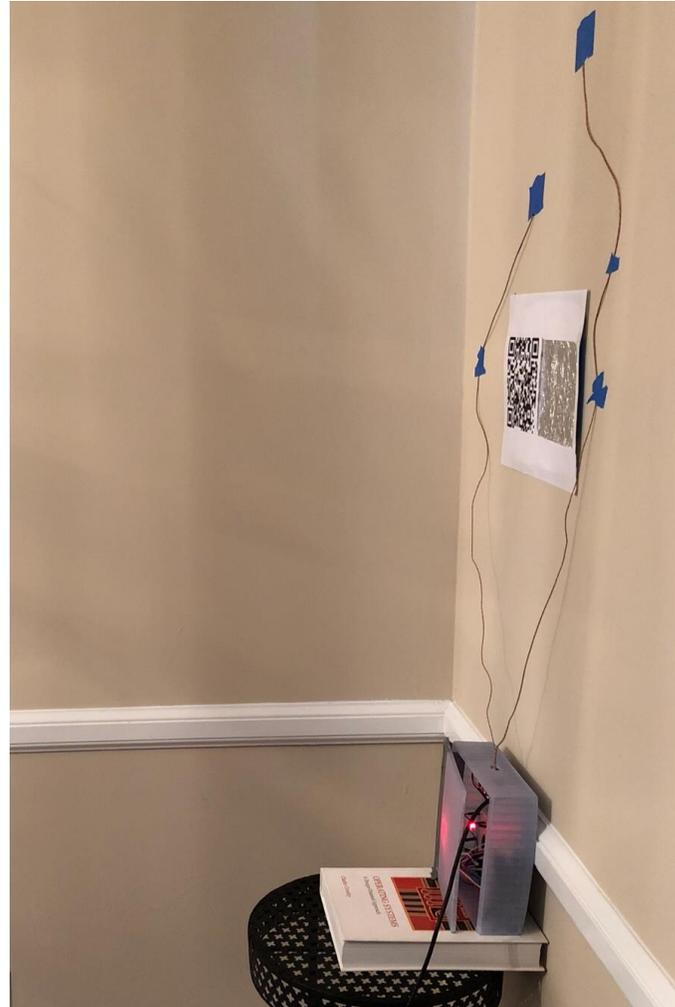
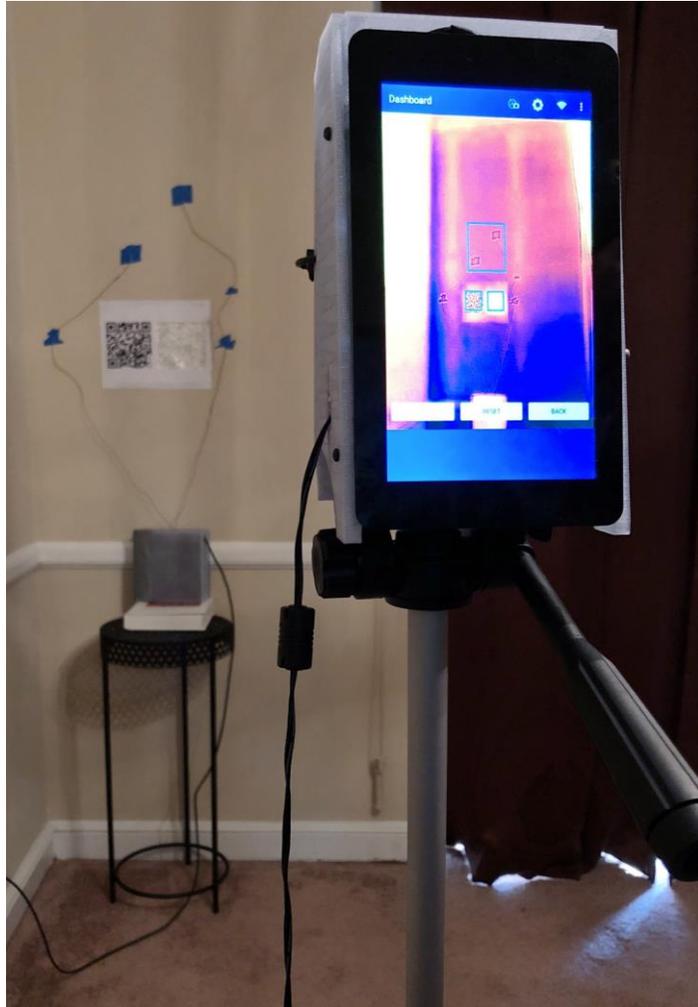
More information can be found at:
Adding Insulation: <https://www.energy.gov/energy-saver/weatherize/insulation/adding-insulation>
Stopping Airleakage: <https://www.energy.gov/energy-saver/weatherize/air-sealing-your-home>

Note:
There was an adequate temperature differential (21.56°F) between the inside and outside of the building; the thermal analysis presented here should be reliable. Other factors that can impact scans is sun or rain on the exterior side of the wall, water pipes or wall studs, and nearby heating/cooling units.

[View All](#)

[Back to Top](#)

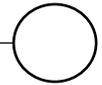
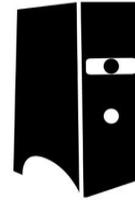
DEVELOPMENT: VALIDATION EXPERIMENTS



DEVELOPMENT: VALIDATION RESULTS

Data Segment	Notional	THM (deviation)	IRT (deviation)	Average Temp. Delta
Day 1	R-6.50	R-7.54 (16.00%)	R-7.67 (18.00%)	27.47°C
Day 2	R-6.50	R-6.67 (2.61%)	R-6.29 (3.23%)	20.96°C
Full Campaign	R-6.50	R-6.30 (3.07%)	R-6.39 (1.69%)	22.85°C

TALK OVERVIEW



Introduction

Background

System Overview

Field Deployment

Expert Review

Conclusion

TALK OVERVIEW



Introduction

Background

System Overview

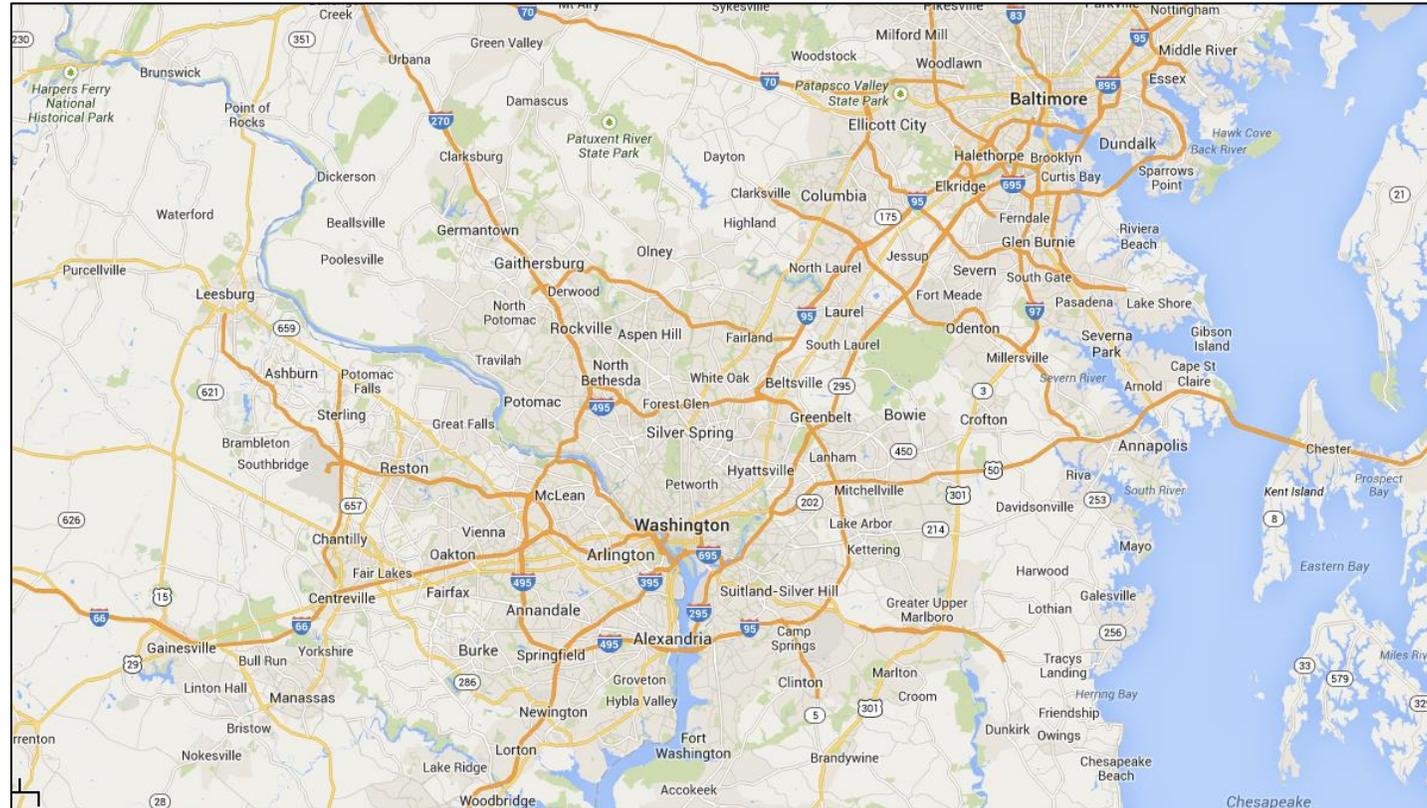
Field Deployment

Expert Review

Conclusion



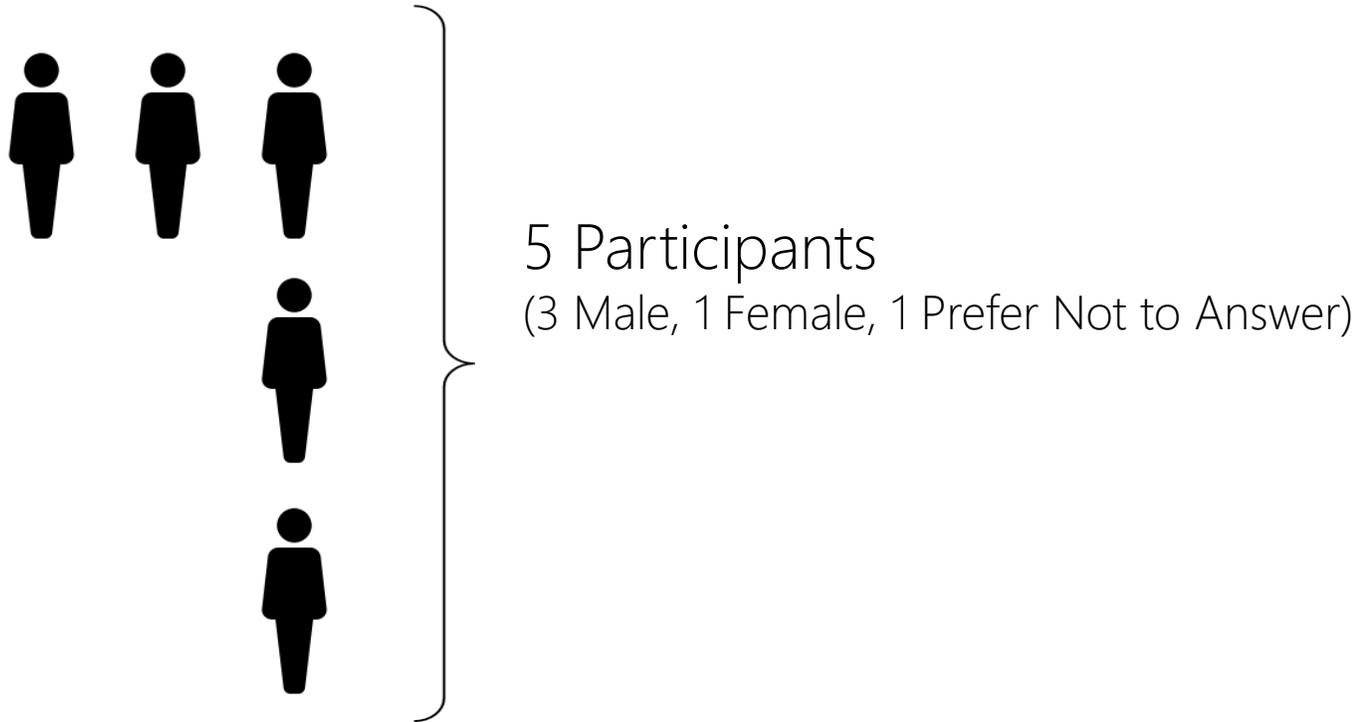
FIELD DEPLOYMENT: RECRUITMENT



We recruited local participants using listserv, community message boards, and word-of-mouth in the Washington D.C. metro area.



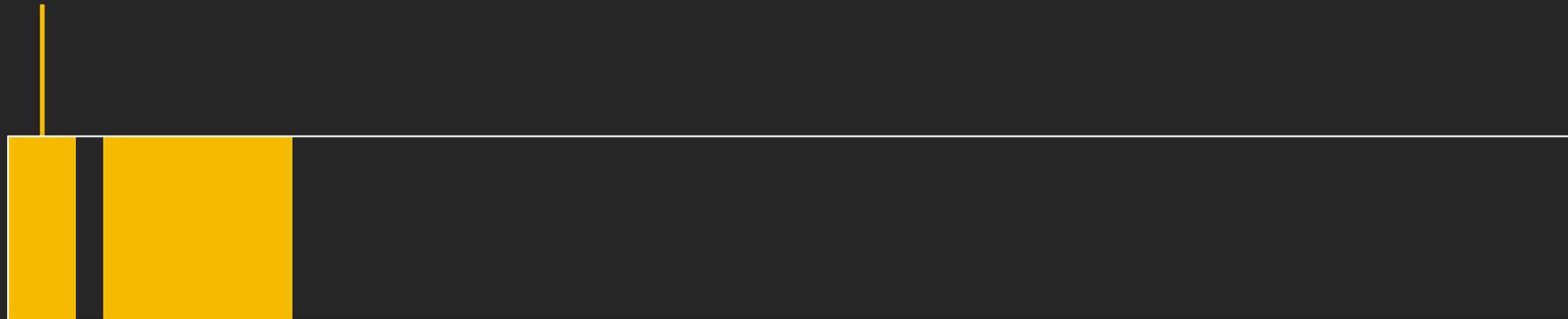
FIELD DEPLOYMENT: PARTICIPANTS





FIELD DEPLOYMENT: PROCEDURE

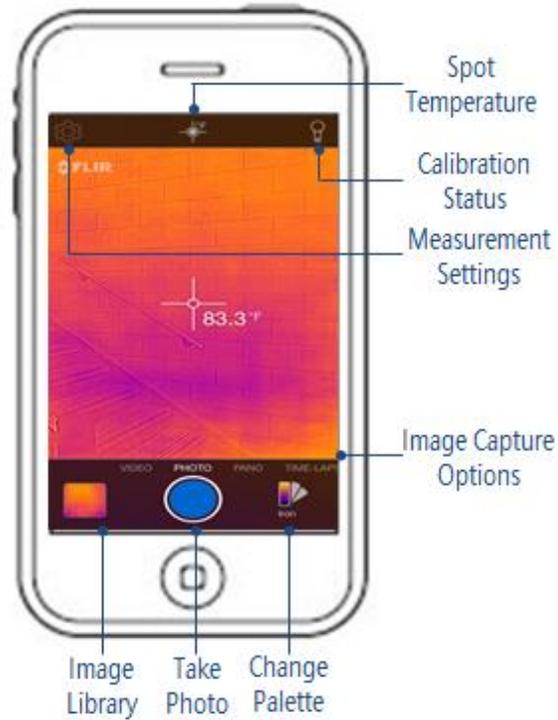
Pre-Study
Questionnaire



Introduction
Meeting



FIELD DEPLOYMENT: TRAINING



Hardware/Software Overview

What Does the System Do?

The system collects data about wall insulation, thermal comfort, thermal comfort, and air quality. Once WiFi is connected, the system constantly collects: Outdoor Weather, Outdoor Temperature, Indoor Temperature, Indoor Relative Humidity, Motion, and Air Quality Data (e.g., CO₂, IVOC).

Once calibrated, the system will begin collecting thermal readings with the forward-looking camera; pictures are not stored. **While a time-lapse is running, pictures are being stored.**

Powering the System On

1. First, turn on the camera by pressing the power button on the right side (assuming you're looking at the touchscreen) and give it a moment to turn on. **Very important!**
2. Next, plug in the power cord for the housing to any regular wall outlet—the system should boot up to a blue and white application screen.
3. After a few minutes, the display should synchronize with the thermal camera and you should see a thermal image overlaid with text. After a few more minutes the display should start displaying data from the sensors. *If the camera doesn't synchronize then the system may restart, this is normal.*

Note: If the system continually reboots itself then pull the micro USB cable out from the opposite side of the camera, wait for the housing to boot up to a blue and white application screen, turn on the camera and, after a moment, plug in the micro USB cable. Hopefully this doesn't happen!

Sensor Menu Overview

The top menu is laid out to be used from the left to right:

The 'WiFi' icon allows you to add the sensor to your home network. The system will remember your WiFi settings.	The 'Thermostat' icon allows you to change the temperature scale; it is set to Fahrenheit by default. This setting will not be remembered if the system is rebooted.	The 'Cog' icon allows you to set up the system before an inspection.	The 'Clock' icon allows you to set up a time-lapse data collection session.	The 'Cloud' icon allows you to upload your data to our server which will analyze your data and generate a report for you.	The dropdown menu on the right is for power options including: 'Restart' and 'Shutdown'. Please use the shutdown option before pulling the power and moving the device.

Set-Up and Calibration

To begin a data collection session, perform the following steps:

1. In the early evening (after sundown or close to it), select a room with good WiFi connectivity that contains a blank area of EXTERIOR wall you wish to scan, perhaps with a window or door to look for air leakage issues. *Note: We recommend that you do this in common/vacant rooms (non-bedroom)—light from the screen dims but doesn't go dark and the LEDs could be very distracting.*

How-to Thermoporal Guide

makeability lab FLIR One Thermal Camera A guide to assembling and using HCFL

Common Uses

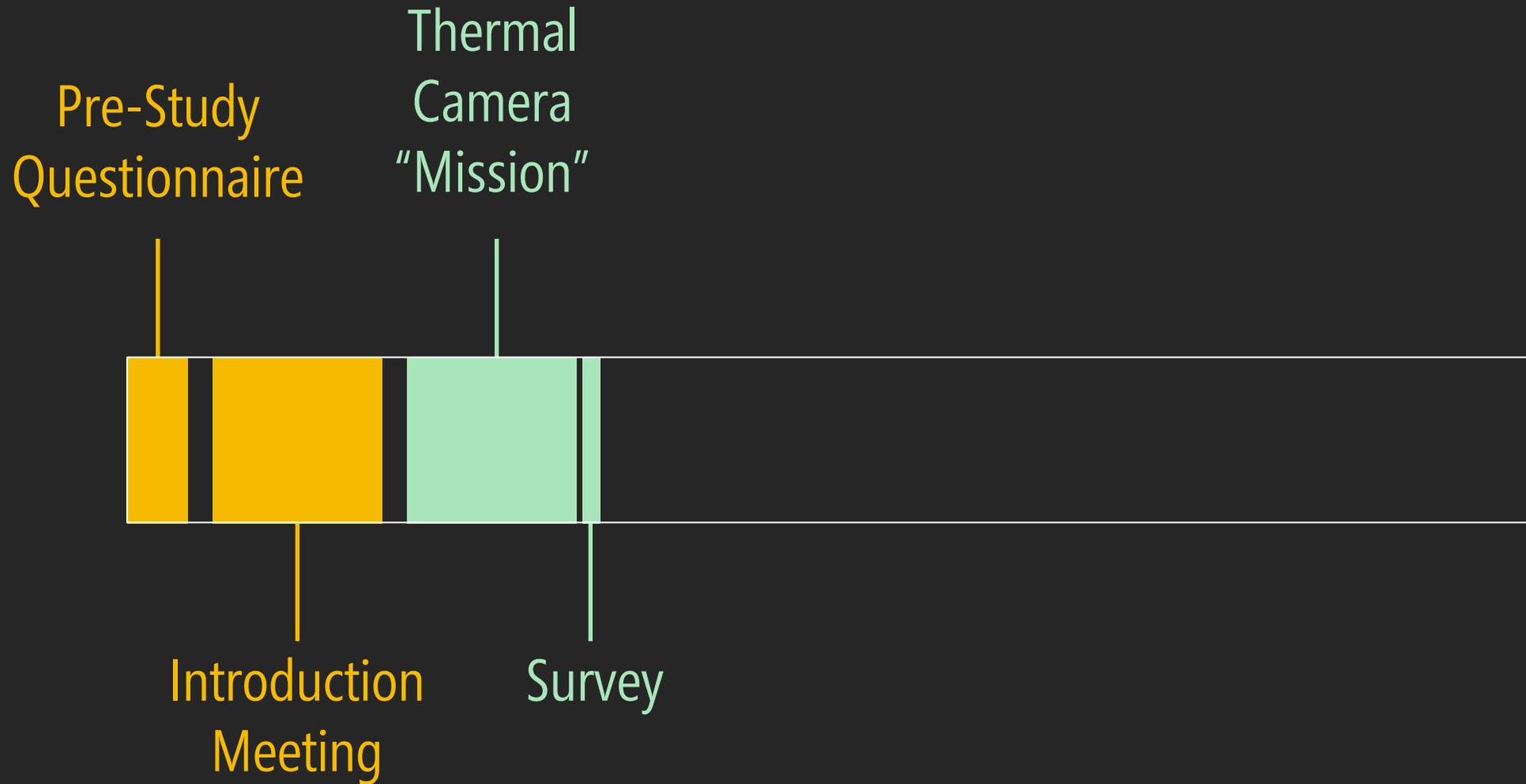
	Missing Insulation: In these two photos you can see a typical example of missing insulation in a wall cavity. What this picture likely demonstrates is that the insulation has "settled" over time (i.e., gravity has pulled the insulation down the wall) leaving the upper cavity empty, which the camera sees as dark patches on the wall.
	Internal Structure: In these photos we can see a new well insulated wall, but because the studs conduct heat differently than the insulation they show up slightly darker; however, this is normal.
	Leaking Windows (and Doors): In this photo we can see the heating pattern that results from hot air leaking out around a window; we are seeing the results of a weakened window seal on the exterior wall. On the interior we would likely see cold air leaking in around the window on the interior wall.
	Moisture Damage: Leaking pipes in between walls and the resulting damage from moisture build up is shown as dark splotches on warm walls and can indicate a problem long before there is visual signs of a problem. Note the inconsistent patterns on the ceiling and walls, which should look different from a case of missing wall insulation.
	Electrical Inspection: Another common use of thermal cameras is to inspect electrical equipment. In this image we can see that one of the connections to the power transformers is potentially damaged or degraded.

While this is a list of some of the common uses of thermal cameras, you should feel free to explore other potential applications (e.g., cooking food) that might exist using your FLIR ONE camera.

Thermographic Inspection Guide

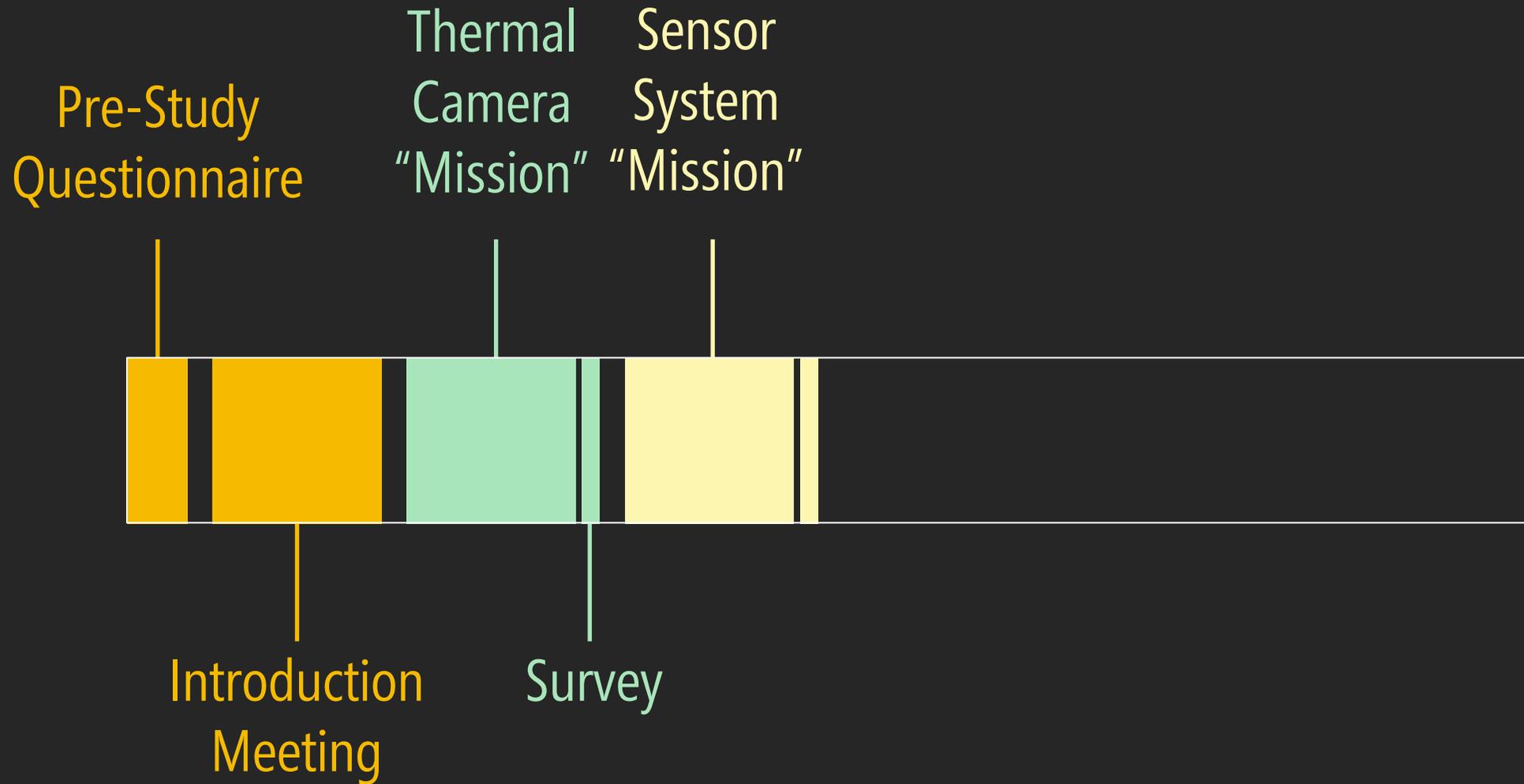


FIELD DEPLOYMENT: PROCEDURE



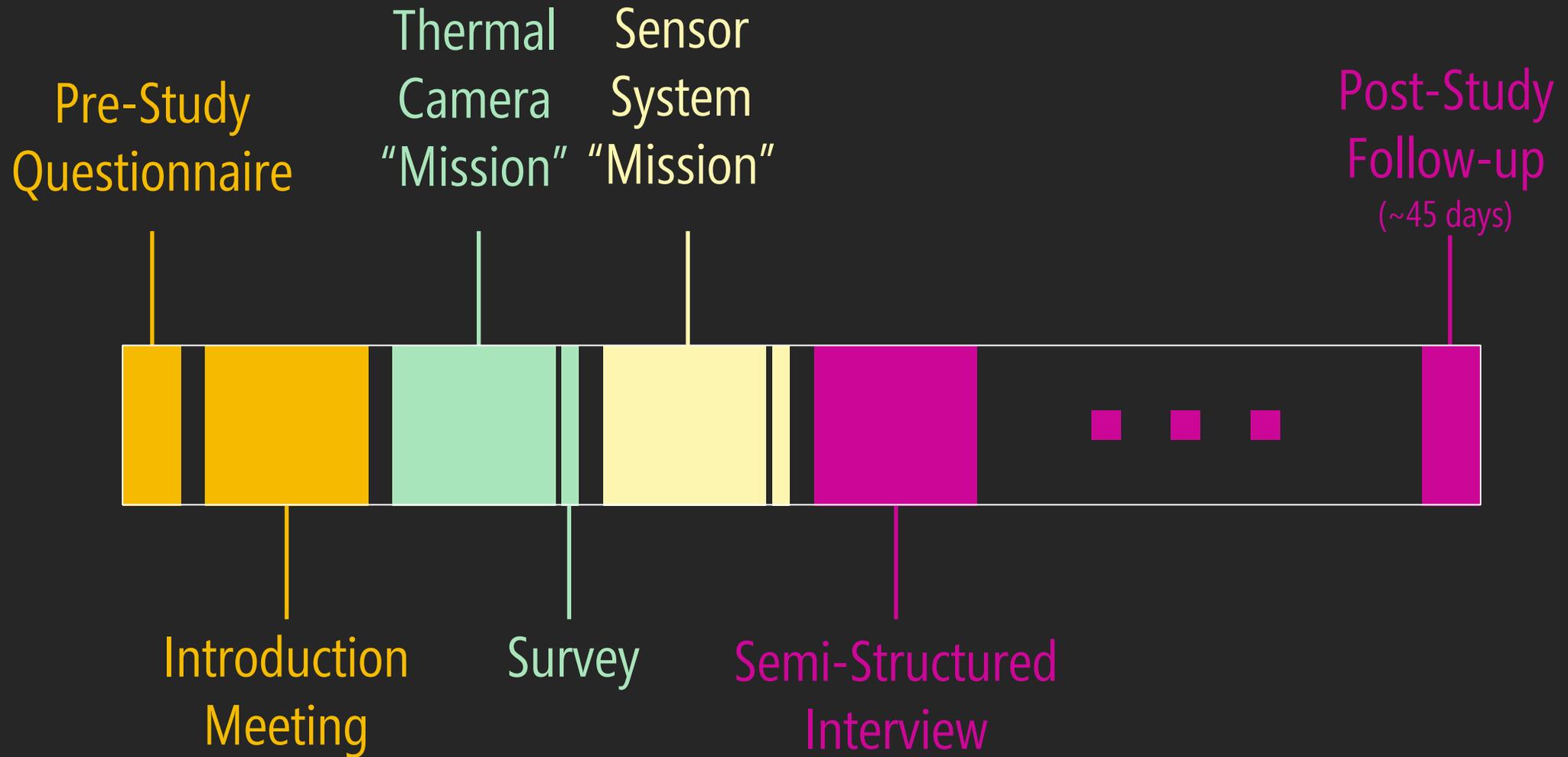


FIELD DEPLOYMENT: PROCEDURE





FIELD DEPLOYMENT: PROCEDURE





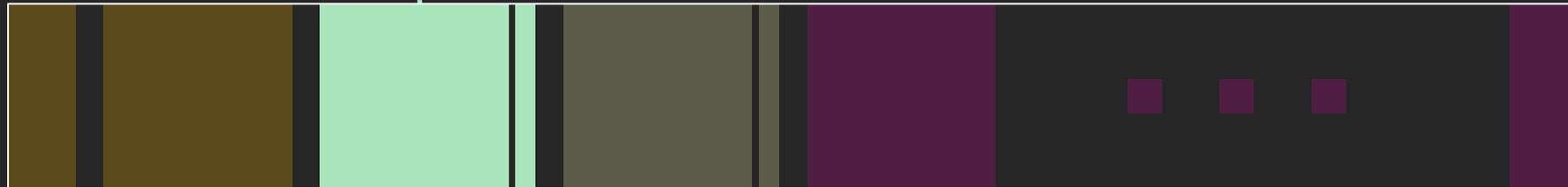
FIELD DEPLOYMENT: ANALYSIS

We **qualitatively coded** the survey and interview data to uncover themes.



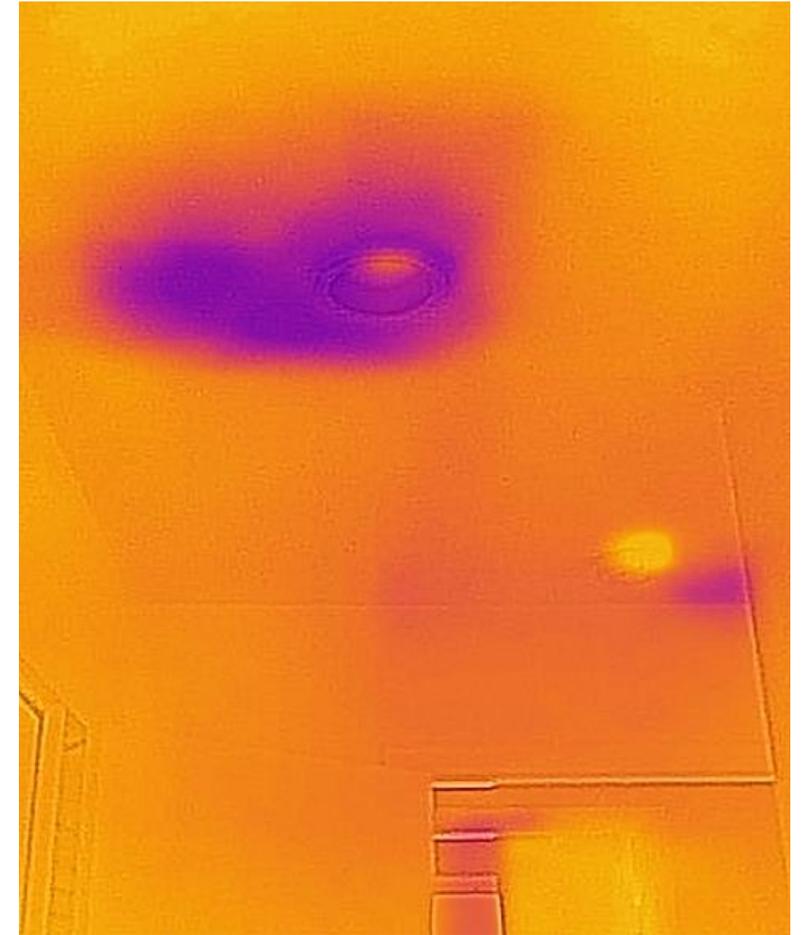
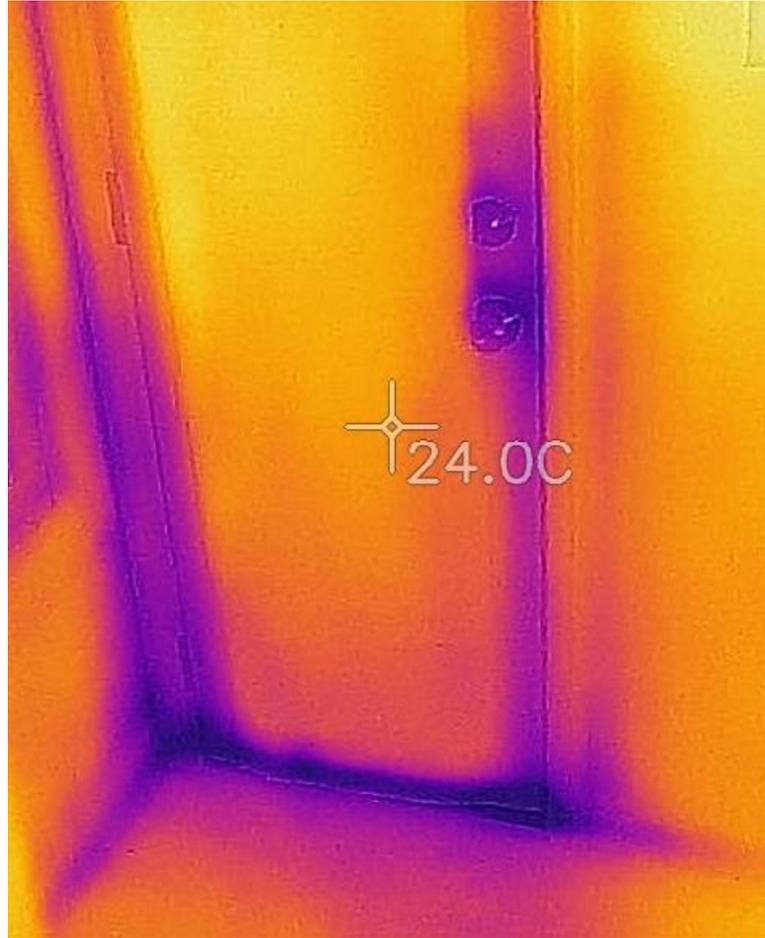
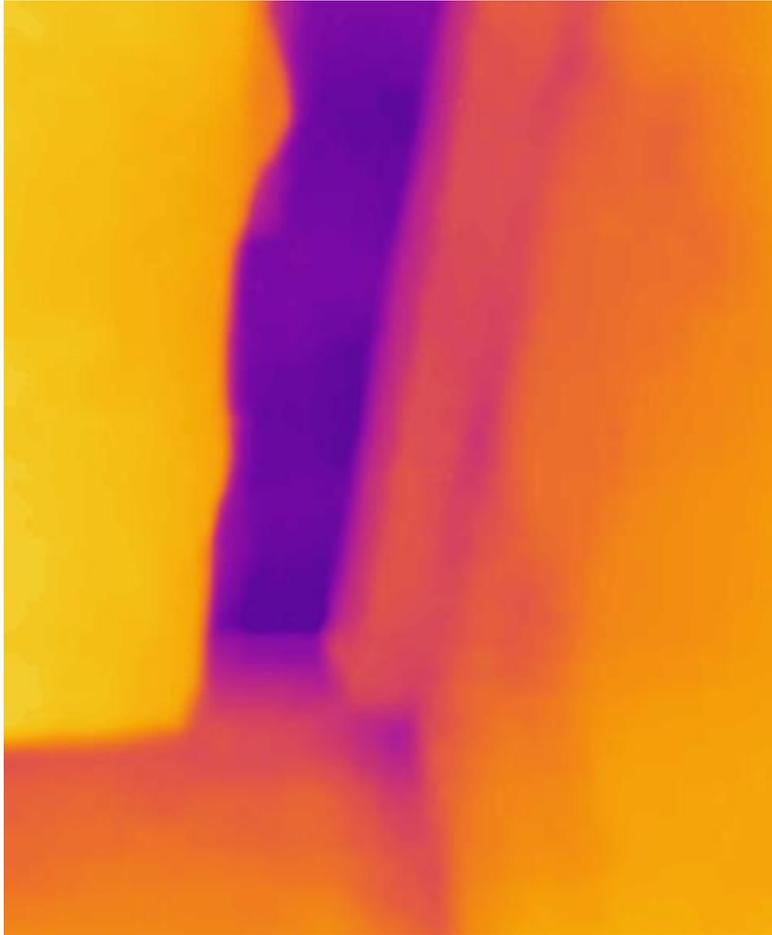
FIELD DEPLOYMENT: RESULTS

Thermal
Camera
"Mission"



Survey

FIELD DEPLOYMENT: THERMAL CAMERA RESULTS





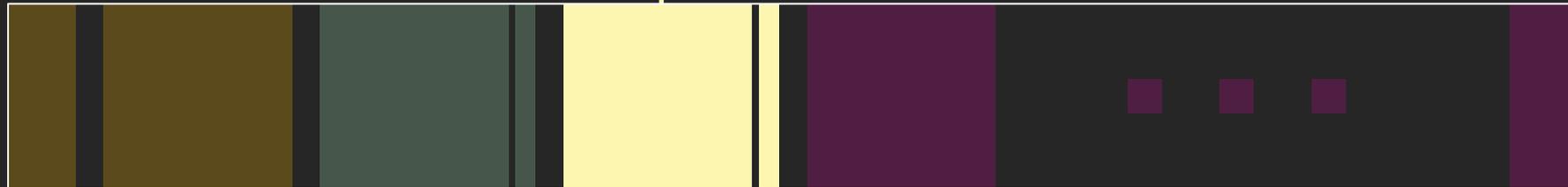
FIELD DEPLOYMENT: THERMAL CAMERA RESULTS

"There are some very cold spots in the office, but it's hard to tell if they are just because it's unheated or that there's some big gaps in the insulation." –NS2



FIELD DEPLOYMENT: RESULTS

Sensor
System
"Mission"



Survey



FIELD DEPLOYMENT: SENSOR SYSTEM RESULTS

Participant ID	Sensor Kit Aimed at Suspected Issue	Issue was Found
P1	No	No
P2	Yes	Yes <i>Less severe than anticipated</i>
P3	Yes	Yes
P4	No	Yes
P5	Yes <i>Based on intuition, not thermal camera mission</i>	No



FIELD DEPLOYMENT: SENSOR SYSTEM RESULTS

Participant ID	Sensor Kit Aimed at Suspected Issue	Issue was Found
P1	No	No
P2	Yes	Yes <i>Less severe than anticipated</i>
P3	Yes	Yes
P4	No	Yes
P5	Yes <i>Based on intuition, not thermal camera mission</i>	No

THERMAL ANALYSIS ⓘ

Thermal Analysis of [Wall (Non-Baseament)] Performance

13.00 R | OKAY

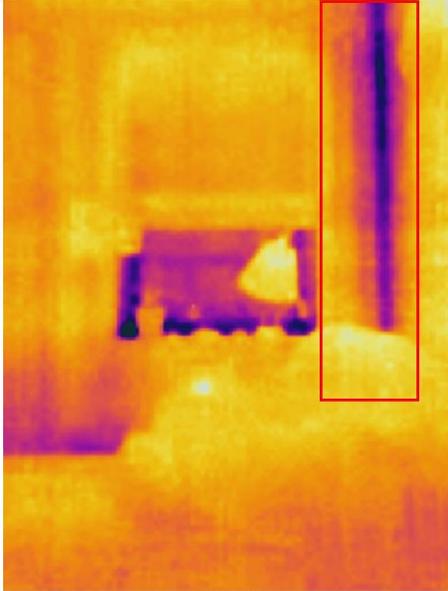
Data Collection Results:
The performance of the insulation in the highlighted region appears to be **within the typical recommended insulation range of 13 - 20 R** that is common to this region of the United States; **20 R** is standard for an insulation cavity, but thermal bridges (e.g., studs) and degradation can reduce overall performance.

What To Look For:
Any regions in the image that appears brighter than the highlighted region are likely performing better, while regions that appear darker are performing worse (assuming winter-like weather conditions). If brighter or darker regions appear around windows or doors, this could be an indication of an issue with the way the window or door was installed or could indicate the presence of an air leak.

Potential Recommendations:
By adding or improving insulation and reducing air leakage around windows and doors, you could potentially save between 10 - 15% on your monthly utility bill and improve thermal comfort in your home. If, upon reviewing this thermal image, you notice more low performing areas than similar or higher performing areas you may want to consult your building manager, facilities management staff, or an energy auditing professional.

More information can be found at:
Adding Insulation: <https://www.energy.gov/energy-saver/weatherize/insulation/adding-insulation>
Stopping Airleakage: <https://www.energy.gov/energy-saver/weatherize/airsealing-your-home>

Note:
There was **an adequate temperature differential (21.56°F)** between the inside and outside of the building; the thermal analysis presented here should be reliable. Other factors that can impact scans is sun or rain on the exterior side of the wall, water pipes or wall studs, and nearby heating/cooling units.

 A thermal image showing a wall with a highlighted rectangular region. The image uses a color scale from purple (cooler) to yellow (warmer). The highlighted region is a vertical strip on the right side of the wall, showing a mix of colors. To the left, there is a window or door opening. The overall scene is dimly lit, with some light reflecting off the wall.

[\(View All\)](#) [Back to Top](#)

"It kind of gave me a why. **It's real cold here and it is below code.** Here's some further information you can look at. That was super helpful. **I can decide if I agree that this is a problem,** and it's telling me something I can do."
-NI2



FIELD DEPLOYMENT: SENSOR SYSTEM RESULTS

Participant ID	Sensor Kit Aimed at Suspected Issue	Issue was Found
P1	No	No
P2	Yes	Yes <i>Less severe than anticipated</i>
P3	Yes	Yes
P4	No	Yes
P5	Yes <i>Based on intuition, not thermal camera mission</i>	No



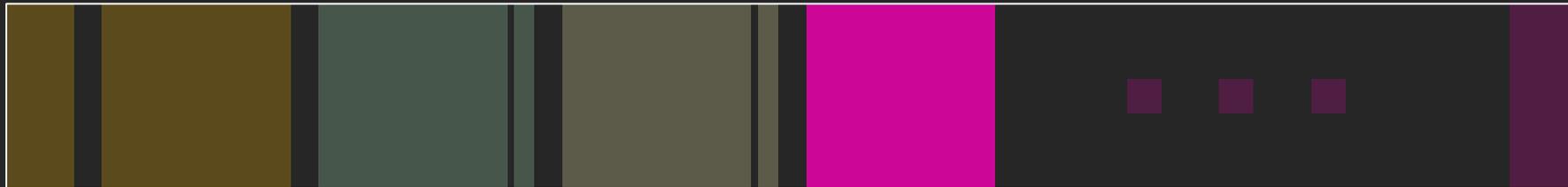
FIELD DEPLOYMENT: SENSOR SYSTEM RESULTS

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“My reports were negative, so I am not sure what else to glean from them.” –NS5



FIELD DEPLOYMENT: RESULTS



Semi-Structured
Interview



FIELD DEPLOYMENT: SEMI-STRUCTURED INTERVIEW RESULTS

Interactive Reporting

Data Privacy

Personal Confidence

Post-Mission Attitudes



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FIELD DEPLOYMENT: SEMI-STRUCTURED INTERVIEW RESULTS

Interactive Reporting

Participants described the interactive report in several ways:

- 4 of 5 were positive about receiving the easy-to-read, automatically generated report.



FIELD DEPLOYMENT: SEMI-STRUCTURED INTERVIEW RESULTS

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- 4 of 5 liked having longitudinal data and the additional depth the report provided by comparison to thermograms alone.



Interactive Reporting

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"I like the idea of having a report that I can refer to again afterward. You get that with pictures too, obviously. But the reporting aspect gives you more detail, [...] the fact that you had the environmental and air quality readings also gave you something more to look at." –NI3

- 4 of 5 were positive about receiving the easy-to-read, automatically generated report.

- 4 of 5 liked having longitudinal data and the additional depth the report provided by comparison to thermograms alone.



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- 3 of 5 envisioned using this data as a tool to communicate with professionals



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- 4 of 5 liked having longitudinal data and the additional depth the report provided by comparison to thermograms alone.
- 3 of 5 envisioned using this data as a tool to communicate with professionals

“If there's a big problem, that's the thing I want to fix, but I don't trust that some guy is coming in and not trying to sell me.” –NI2



FIELD DEPLOYMENT: SEMI-STRUCTURED INTERVIEW RESULTS

Interactive Reporting

Data Privacy

Personal Confidence

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FIELD DEPLOYMENT: SEMI-STRUCTURED INTERVIEW RESULTS

Data Privacy

Participants were largely homogenous when it came to the privacy of their data:

- 4 of 5 desired explicit control over all data collected about/in their home.



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- 4 of 5 desired explicit control over all data collected about/in their home.

“If it were not an internet connected device, if it were just a local network thing that I used in my house, that would be fine. If information is going out, then I have a big problem with technology like that.” –NI2



FIELD DEPLOYMENT: SEMI-STRUCTURED INTERVIEW RESULTS

Data Privacy

Participants were largely homogenous when it came to the privacy of their data:

- 4 of 5 desired explicit control over all data collected about/in their home.
- 1 of 5 desired aggregated data about their neighborhood and advocated that local policy makers should have access.



FIELD DEPLOYMENT: SEMI-STRUCTURED INTERVIEW RESULTS

Interactive Reporting

Data Privacy

Personal Confidence

Post-Mission Attitudes

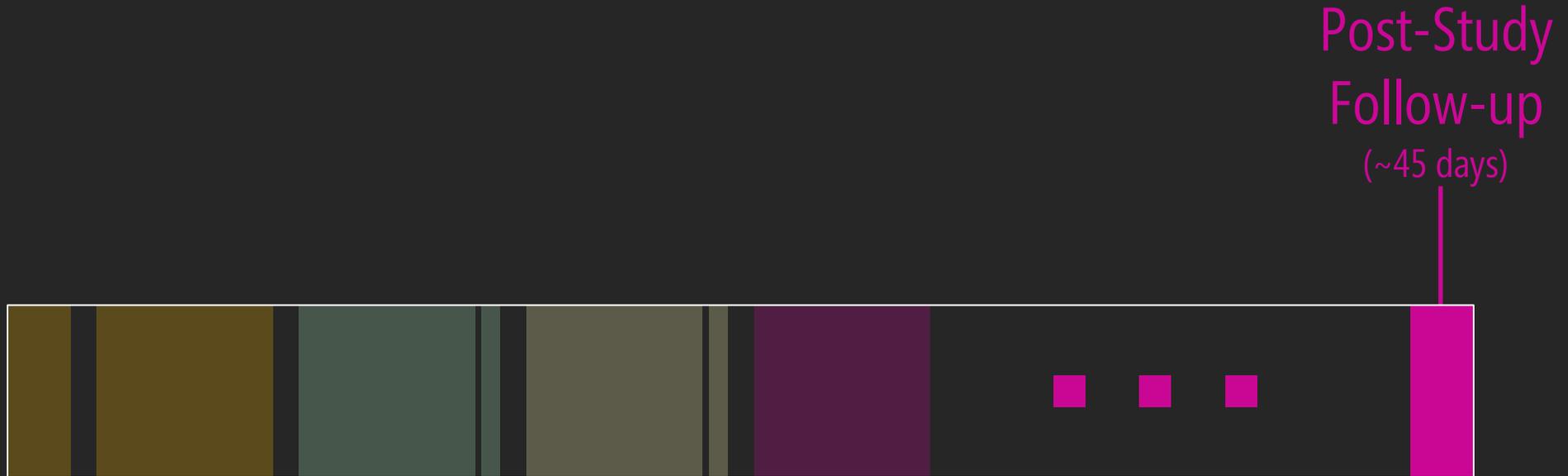


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FIELD DEPLOYMENT: RESULTS





FIELD DEPLOYMENT: FOLLOW-UP SURVEY

Follow-up Findings

- 5 of 5 reported thinking more about energy efficiency issues in their home since participation had ended.



Follow-up Findings

Participants were largely homogenous when it came to the privacy of their data:

- 5 of 5 reported thinking more about energy efficiency issues in their home since participation had ended.

“It has made me generally more aware of where there might be issues and why.” –NS3



FIELD DEPLOYMENT: FOLLOW-UP SURVEY

Follow-up Findings

Participants were largely homogenous when it came to the privacy of their data:

- 5 of 5 reported thinking more about energy efficiency issues in their home since participation had ended.
- 2 of 5 reported making some repairs for air leakage issues; however, all reported that insulation issues required more savings and planning.



Follow-up Findings

Participants were largely homogenous when it came to the privacy of their data:

- 5 of 5 reported thinking more about energy efficiency issues in their home since participation had ended.
- 2 of 5 reported making some repairs for air leakage issues; however, all reported that insulation issues required more savings and planning.

“I'd say it's kind of too late for a homeowner, unless you're about to do a renovation.” –NI3

TALK OVERVIEW



Introduction

Background

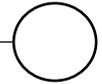
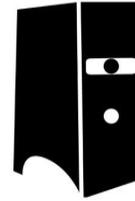
System Overview

Field Deployment

Expert Review

Conclusion

TALK OVERVIEW



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EXPERT REVIEW: PARTICIPANTS



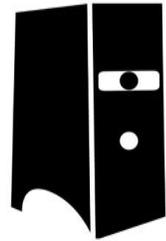
5 Participants
(All male)



EXPERT REVIEW: PRESENTATION OF DESIGN PROBES



Scenario 1
(Text)



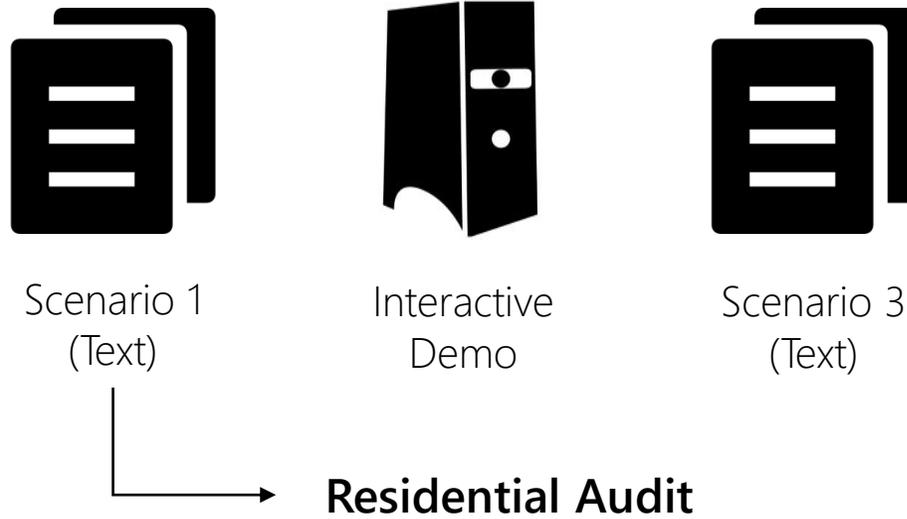
Interactive
Demo



Scenario 3
(Text)



EXPERT REVIEW: PRESENTATION OF DESIGN PROBES

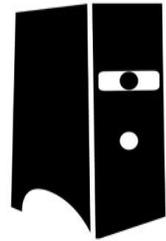




EXPERT REVIEW: PRESENTATION OF DESIGN PROBES



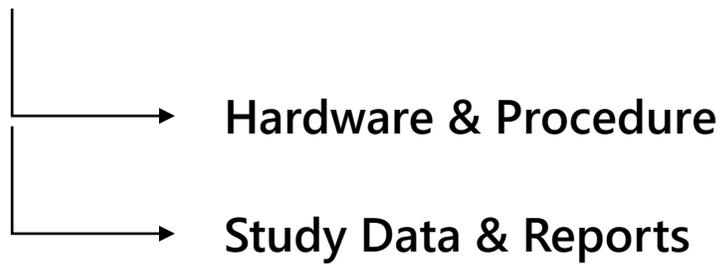
Scenario 1
(Text)



Interactive
Demo



Scenario 3
(Text)

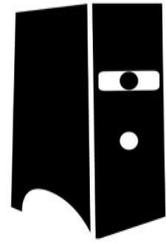




EXPERT REVIEW: PRESENTATION OF DESIGN PROBES



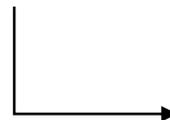
Scenario 1
(Text)



Interactive
Demo



Scenario 3
(Text)



Audits-at-Scale



EXPERT REVIEW: DESIGN PROBE RESULTS





EXPERT REVIEW: DESIGN PROBE RESULTS

Raising Awareness



EXPERT REVIEW: DESIGN PROBE RESULTS

Raising Awareness

Providing Reliable Data



EXPERT REVIEW: DESIGN PROBE RESULTS

Raising Awareness

Providing Reliable Data

Relationship Building



EXPERT REVIEW: DESIGN PROBE RESULTS





EXPERT REVIEW: DESIGN PROBE RESULTS

Installation and Coverage

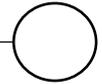


EXPERT REVIEW: DESIGN PROBE RESULTS

Installation and Coverage

Motivating Action

TALK OVERVIEW



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Background

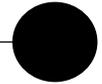
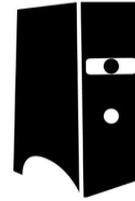
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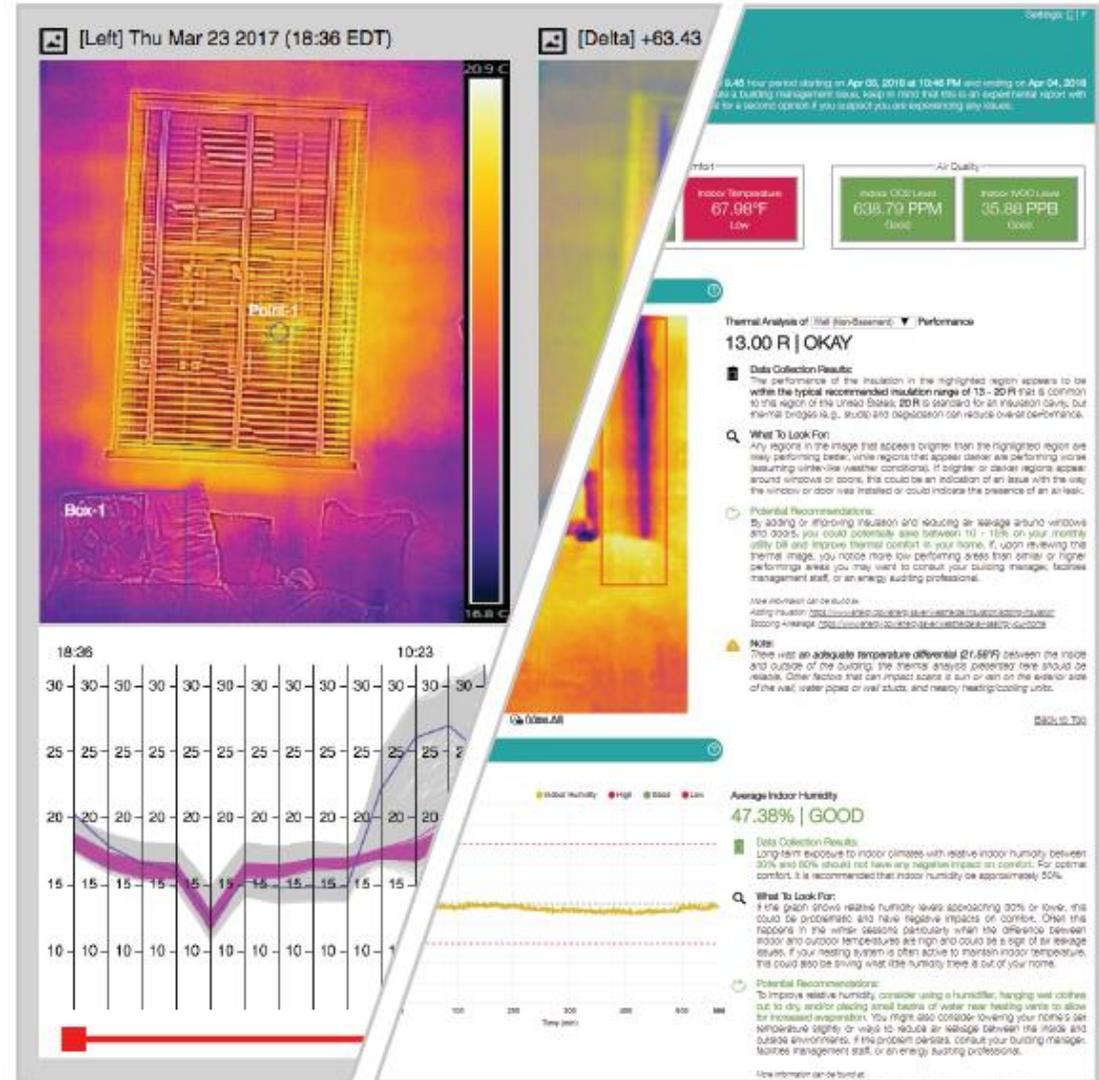
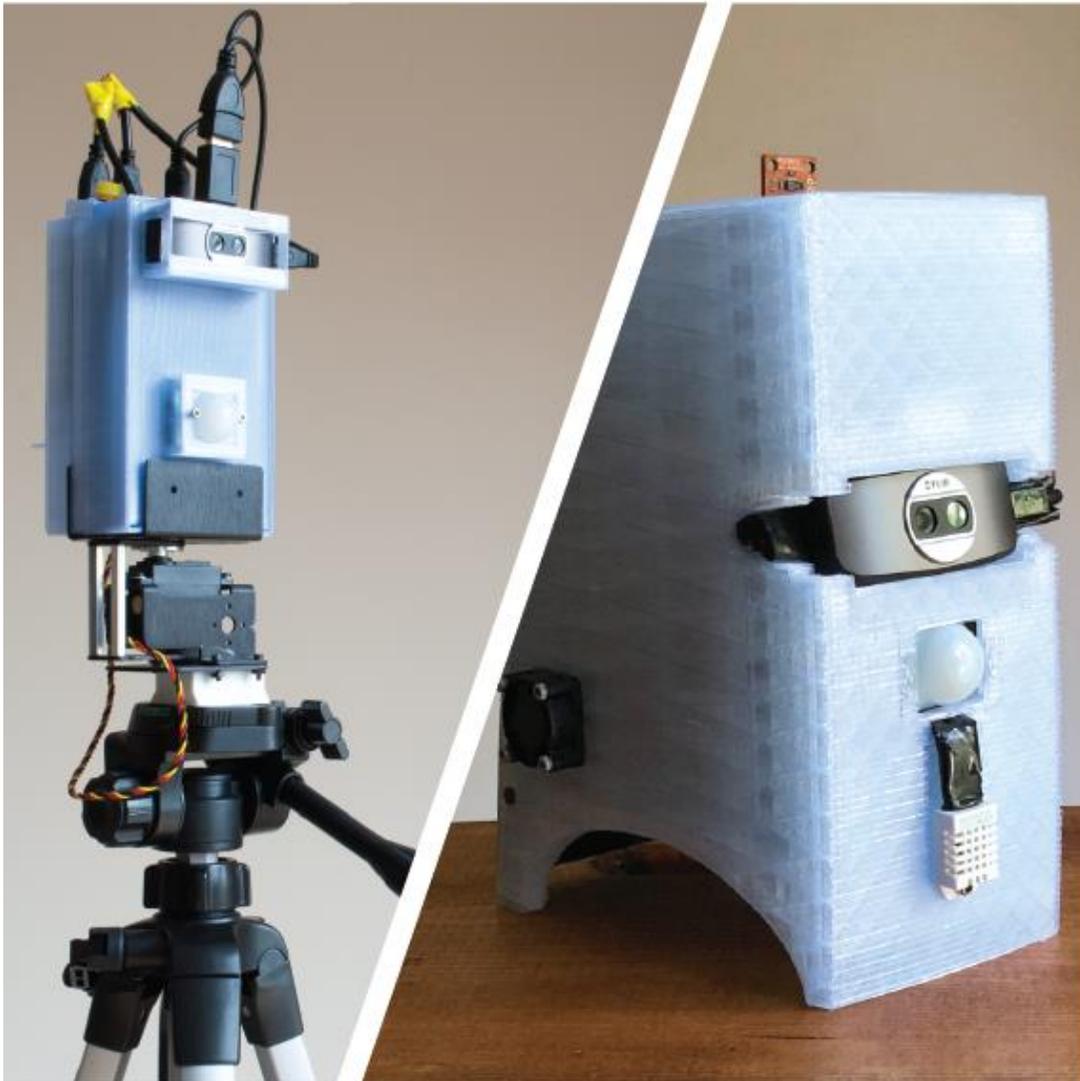
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🕒 CONCLUSION



CONCLUSION: DESIGN RECOMMENDATIONS

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Framing efficiency recommendations with the right motivations and delivering them with the right timing is critical.

🕒 CONCLUSION: DESIGN RECOMMENDATIONS

Framing efficiency recommendations with the right motivations and delivering them with the right timing is critical.

Permanently deployed sensor system that provide increased coverage are preferred to overnight scanning

CONCLUSION: LIMITATIONS

Small N for both studies

Homogeneous weather conditions and construction types

Professional participants only evaluated the results of deployments

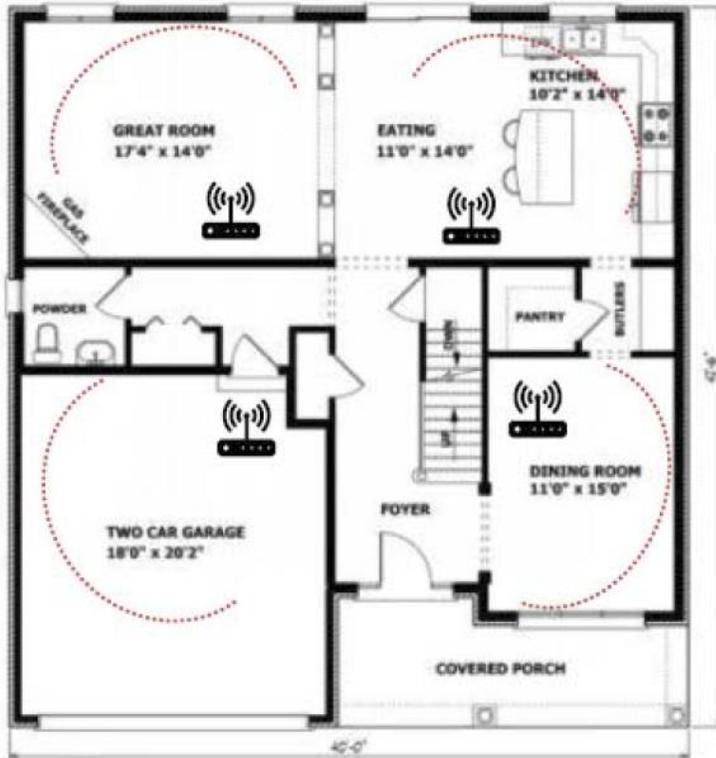
CONCLUSION: SUMMARY

Temporal/Quantitative analysis provides more specific insights in the case of insulation performance.

Increasing homeowner agency opens new opportunities for professional auditor and homeowner relations.

While we saw DIY solutions enacted, motivating larger-scale structural changes remains challenging.

🕒 CONCLUSION: FUTURE WORK



Multi-Sensor Deployments



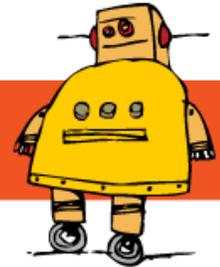
Standard for Temporal Thermography

🕒 CONCLUSION: FUTURE WORK



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CONCLUSION: ACKNOWLEDGEMENTS

Students

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Simran Chawla

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Erica Brown

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University of Maryland's Office of Sustainability

Thermporal: An Easy-to-Deploy Temporal Thermographic Sensor System to Support Residential Energy Audits

CHI 2019 | May 9th
Session on Sustainable HCI

Matthew Louis Mauriello
@mattm401

Brenna McNally
Jon E. Froehlich

