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

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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%.

Norberg-Bohm, V. and White, C. Building America Program Evaluation. 2004
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.
Energy auditors may use thermography — or infrared scanning — to detect thermal defects and air leakage in building envelopes.
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

- Missing Insulation
- Air Leakage
- Moisture Intrusion
FLIR ONE Gen 3

MODEL: FLIR ONE GEN 3 - IOS

Go to Support Page »

There's an invisible world right next to the one you see every day, just waiting for you to explore it with the FLIR ONE. Whether you're seeing the world in a whole new way or just finding problems around the house, FLIR ONE's thermal camera gives you a new view of your everyday world. Discover what's been around you all the time, with FLIR ONE. The FLIR ONE app requires sign in, which enables automatic warranty registration and access to all the latest updates from FLIR.

PRODUCT VARIATIONS:

FLIR ONE Gen 3 - IOS

$199.99

BUY NOW

Thermal Imaging Camera Attachment

THE DIY'ERS BEST FRIEND
Find problems around the home fast, like where you're losing heat, how your insulation's holding up.

EXPLORE THE GREAT OUTDOORS
See in the dark and explore the natural world safely with the FLIR ONE. Watch animals in their natural habitat.

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.
• 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?
RELATED WORK: TEMPORAL DATA COLLECTION

Fox et al., Energy and Buildings '14
Related Work: Temporal Data Collection

Fox et al., Energy and Buildings '14

Thermal image recorded every 30 minutes

Thermal camera. On tripod and housed in protective hide. Located with minimal obstruction between facade and camera
**RELATED WORK:** TEMPORAL DATA COLLECTION

Fox et al., *Energy and Buildings* '14

- **Weather station (external)** collecting data on external temperature, humidity and wind
- **Internal temperature and humidity detector**
**RELATED WORK: TEMPORAL VISUALIZATIONS**

[Images of thermal imaging data showing temperature variations over time]

Fox et al., *Energy and Buildings* ’14

Danese et al., *Archaeometry* ’08
RELATED WORK: QUANTITATIVE THERMOGRAPHY

\[
R - \text{Value} = \frac{\Delta T_{\text{io}}}{4 \varepsilon \sigma T_m^3 \Delta T_r + h_c \Delta T_a}
\]
**RELATED WORK: QUANTITATIVE TEMPORAL THERMOGRAPHY**

Fokaides & Kalogirou, 2011

Dall'O et al., 2013

Albatici et al., 2015

Nardi et al., 2016
Direct Contact Methods: Heat Flux Sensors and Thermocouples
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
**Development: Design Goals**

- Easy-to-Deploy
- Non-intrusive
- Provide Rapid Analysis
- Help with Severity Estimation
- Holistic Report
PHYSIKIT
HOUNBEN ET AL., 2016
PHYSIKIT
HOUBEN ET AL., 2016

BUILDAX Environmental Sensor Toolkit
Finnigan et al. 2017
Thermal Camera
Motion Sensor
Pan Unit
Raspberry Pi
Humidity/Temperature Sensor
Interchangeable Mounting Plate
GPS Unit & High Capacity Battery

EASY-TO-DEPLOY THERMOGRAPHIC SENSOR SYSTEM
(V3.0)
DEVELOPMENT: EASY-TO-DEPLOY THERMOGRAPHIC SENSOR KIT (v4.0)
DEVELOPMENT: SYSTEM OVERVIEW
Development: System Overview

Sensing, Calibration, Processing, Reporting
**DEVELOPMENT:** SYSTEM OVERVIEW

Sensing

Calibration, Processing, Reporting
**DEVELOPMENT:** REVISED VISUALIZATION

**Thermal Analysis**

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 for this region of the United States. 20 R is ideal for an insulation cavity, but thermal bridges (e.g., studs) and degradation can reduce overall performance.

- **What to Look For:**
  Any region in the image that appears brighter than the highlighted region is likely performing better, while regions that appear darker are performing worse (assuming similar 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 optimizing and 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 you’re seeing a mismatch between lower performing areas and an energy audit results in 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:

- [rating disclaimer](https://www.earthybuildings.com/rating-disclaimer)

**Note:**

There was an adequate temperature differential (0.58°F) between the inside and outside of the building. The thermal analysis presented here should be reliable. Other factors that can impact results include: sun or shade on the exterior side of the wall, water damage or wall studs, and nearby heating/cooling units.
DEVELOPMENT: VALIDATION EXPERIMENTS
### Development: Validation Results

<table>
<thead>
<tr>
<th>Data Segment</th>
<th>Notional</th>
<th>THM (deviation)</th>
<th>IRT (deviation)</th>
<th>Average Temp. Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>R-6.50</td>
<td>R-7.54 (16.00%)</td>
<td>R-7.67 (18.00%)</td>
<td>27.47°C</td>
</tr>
<tr>
<td>Day 2</td>
<td>R-6.50</td>
<td>R-6.67 (2.61%)</td>
<td>R-6.29 (3.23%)</td>
<td>20.96°C</td>
</tr>
<tr>
<td>Full Campaign</td>
<td>R-6.50</td>
<td>R-6.30 (3.07%)</td>
<td>R-6.39 (1.69%)</td>
<td>22.85°C</td>
</tr>
</tbody>
</table>
TALK OVERVIEW

- Introduction
- Background
- System Overview
- Field Deployment
- Expert Review
- Conclusion
TALK OVERVIEW

Introduction  Background  System Overview  Field Deployment  Expert Review  Conclusion
We recruited local participants using listserv, community message boards, and word-of-mouth in the Washington D.C. metro area.
FIELD DEPLOYMENT: PARTICIPANTS

5 Participants
(3 Male, 1 Female, 1 Prefer Not to Answer)
Pre-Study Questionnaire

Introduction Meeting
FIELD DEPLOYMENT: TRAINING

Hardware/Software Overview

How-to Thermoral Guide

Thermographic Inspection Guide
**FIELD DEPLOYMENT: PROCEDURE**

- Pre-Study Questionnaire
- Introduction Meeting
- Thermal Camera "Mission"
- Survey
FIELD DEPLOYMENT: PROCEDURE

Pre-Study Questionnaire

Introduction Meeting

Thermal Camera “Mission”

Sensor System “Mission”

Survey
FIELD DEPLOYMENT: PROCEDURE

Pre-Study Questionnaire
Thermal Camera “Mission”
Sensor System “Mission”
Introduction Meeting
Survey
Semi-Structured Interview
Post-Study Follow-up (~45 days)
We qualitatively coded the survey and interview data to uncover themes.
Thermal Camera
“Mission”

Survey
FIELD DEPLOYMENT: THERMAL CAMERA RESULTS

24.0°C
“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

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<td>Yes</td>
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<td></td>
<td><em>Less severe than anticipated</em></td>
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<td>P3</td>
<td>Yes</td>
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### FIELD DEPLOYMENT: SENSOR SYSTEM RESULTS

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“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

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“My reports were negative, so I am not sure what else to glean from them.” –NS5
Semi-Structured Interview
Interactive Reporting
Data Privacy
Personal Confidence
Post-Mission Attitudes
Interactive Reporting
Data Privacy
Personal Confidence
Post-Mission Attitudes
Interactive Reporting

Data Privacy

Personal Confidence

Post-Mission Attitudes
Interactive Reporting

Participants described the interactive report in several ways:

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

“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
Interactive Reporting

Participants described the interactive report in several ways:

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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
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“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
Interactive Reporting

Data Privacy

Personal Confidence

Post-Mission Attitudes
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.
Data Privacy

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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
**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.
Interactive Reporting

Data Privacy

Personal Confidence

Post-Mission Attitudes
## Field Deployment: Sensor System Results

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*Based on intuition, not thermal camera mission*
Post-Study Follow-up
(≈45 days)
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
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
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

Scenario 1
(Text)

Interactive Demo

Scenario 3
(Text)

Residential Audit
EXPERT REVIEW: PRESENTATION OF DESIGN PROBES

Scenario 1 (Text)
Interactive Demo
Scenario 3 (Text)

Hardware & Procedure
Study Data & Reports
EXPERT REVIEW: PRESENTATION OF DESIGN PROBES

Scenario 1 (Text)

Interactive Demo

Scenario 3 (Text)

Audits-at-Scale
Raising Awareness
Raising Awareness

Providing Reliable Data
Raising Awareness

Providing Reliable Data

Relationship Building
Installation and Coverage
Installation and Coverage

Motivating Action
TALK OVERVIEW

Introduction  Background  System Overview  Field Deployment  Expert Review  Conclusion
CONCLUSION
CONCLUSION: DESIGN RECOMMENDATIONS
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
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.
Multi-Sensor Deployments

CONCLUSION: FUTURE WORK

Standard for Temporal Thermography
CONCLUSION: FUTURE WORK
<table>
<thead>
<tr>
<th><strong>Students</strong></th>
<th><strong>Funding</strong></th>
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<tbody>
<tr>
<td>Noa Chazan</td>
<td>University of Maryland’s Office of Sustainability</td>
</tr>
<tr>
<td>Simran Chawla</td>
<td></td>
</tr>
<tr>
<td>Jamie Gilkeson</td>
<td></td>
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<td>Erica Brown</td>
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CHI 2019 | May 9th
Session on Sustainable HCI

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