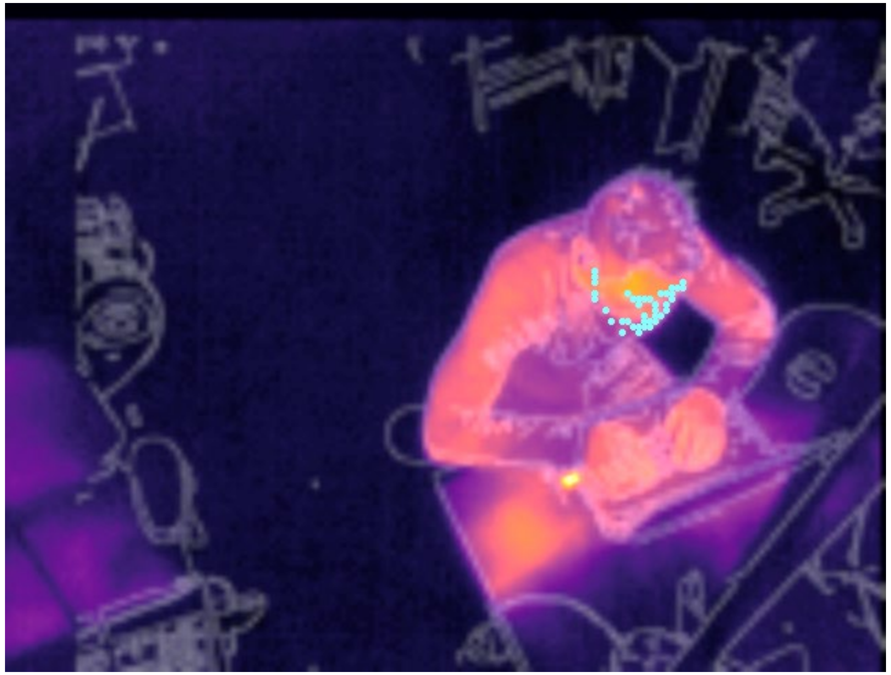
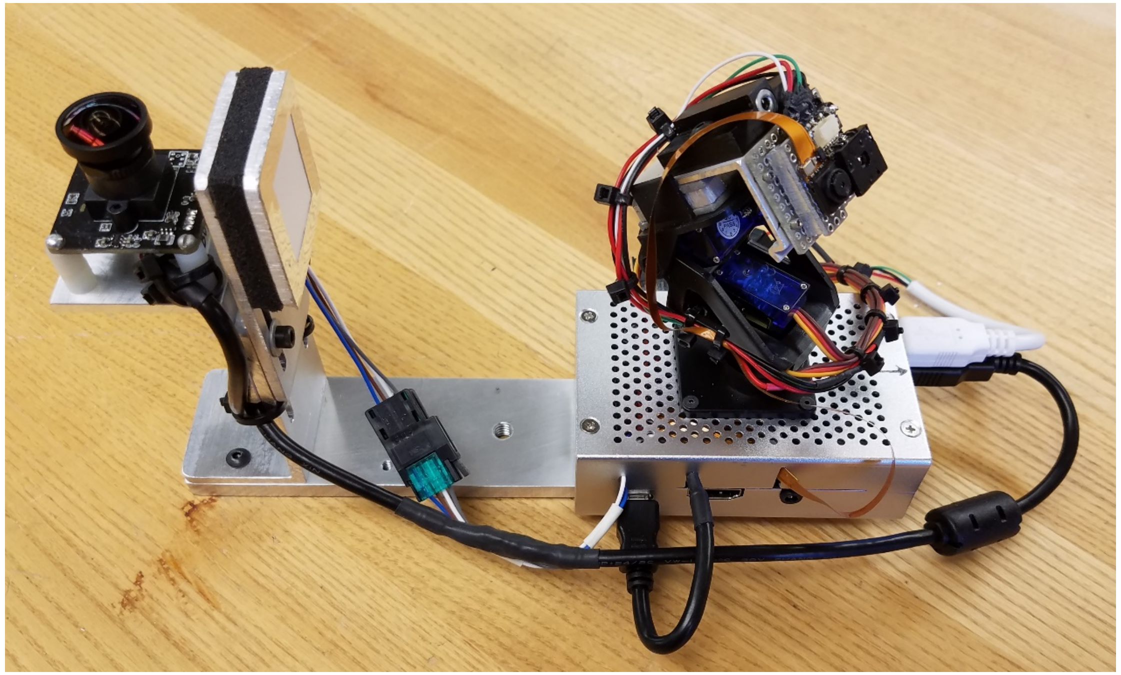
Hot, Cold, or Just Right?

Using a Wide-View Infrared Biometric Sensor to Improve Occupant Comfort and Reduce Overcooling in Buildings via Closed-loop Control





Lawrence Berkeley National Laboratory (prime), UC Berkeley, Daikin, and MoviTHERM
Dr. Ronnen Levinson, Staff Scientist, LBNL
Tel. 510-486-7494 / RMLevinson@LBL.gov

Project Summary

Timeline

Start date: 2019-05-01

Planned end date: 2022-04-30

Key Milestones

1. Lab test comfort prediction accuracy based on skin temperature measurements above 90%, with less than 5% false negatives; 2020-04
2. Prototype sensor/controller can measure occupant facet skin temperature differences to within 0.2 K; 2021-04

Budget (at end of project year 2)

Total Project $ to Date:

- DOE: $1,200K
- Cost Share: $281K

Total Project $:

- DOE: $1,500K
- Cost Share: $408K

Key Partners

Center for the Built Environment at UC Berkeley	CBE
Daikin Silicon Valley (Santa Clara, CA)	DAIKIN
MoviTHERM (Irvine, CA)	moviTHERM advanced thermography solutions

Project Outcome

We will improve occupant comfort and save cooling energy by implementing a closed-loop HVAC sensor/controller that radiatively detects occupants, occupant comfort, and room surface temperature distribution, then uses this information to reduce overcooling (cooling-energy overuse that discomforts occupants) by regulating HVAC output.

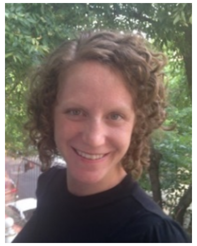
Use of our sensor/controller could decrease commercial-building overcooling by at least 50%, potentially saving up to 0.5 Quad/y in U.S. commercial buildings. It could also save a comparable amount in U.S. residential buildings.

Team

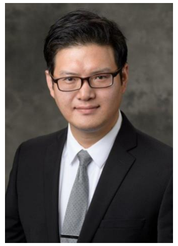
BERKELEY LAB


Ronnen Levinson


Sharon Chen


Haley Gilbert


Howdy Goudey


Donghun Kim


Alexander Merritt

① **LBNL** builds the sensor/controller (cameras + MPC)

④ **MoviTHERM** guides infrared thermography and machine vision


Chun-cheng Piao

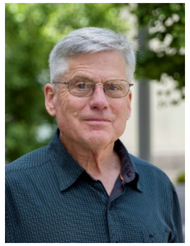

Robert Prickett


Kevin Nimomiya

③ **Daikin** provides AC control expertise, hosts real-world trials

CBE
CENTER FOR THE BUILT ENVIRONMENT


Hui Zhang


Ed Arens


Ali Ghahramani


Yingdong He

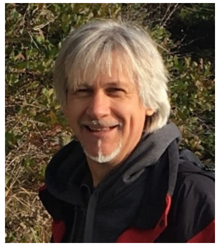

Charlie Huizenga

② **CBE** (UC Berkeley) leads machine vision and comfort algorithm/software development

moviTHERM
advanced thermography solutions


Markus Tarin

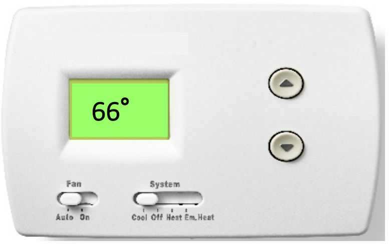

Ana Alvarez


David Ritter

④ **MoviTHERM** guides infrared thermography and machine vision

Challenge

- Cooling-energy overuse that discomforts occupants, or "overcooling", wastes about 0.5 Quads of primary energy annually in U.S. commercial buildings†, and may waste a comparable amount of energy in U.S. homes
- Conventional thermostats regulate air temperature, rather than comfort
- **We seek a passive (non-invasive, non-participatory) solution that provides closed-loop comfort control of air conditioning to avoid overcooling and save energy**




nytimes.com

Chilly at Work? Office Formula Was Devised for Men (Published 2015)

By Pam Belluck | Aug. 3rd, 2015   Send to Kindle

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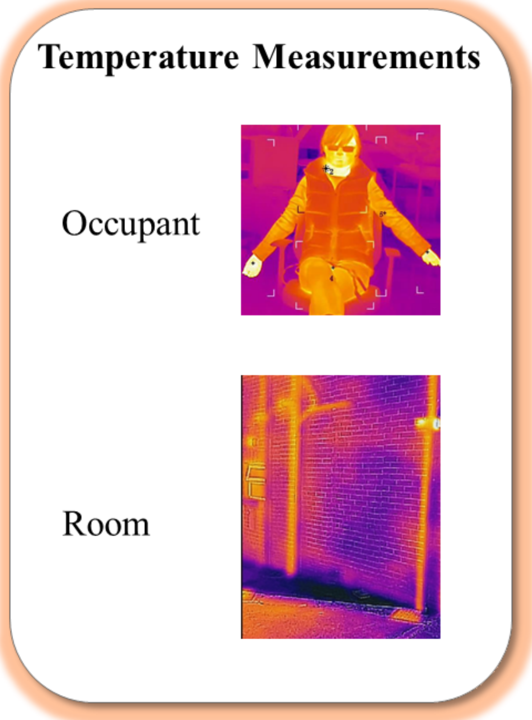
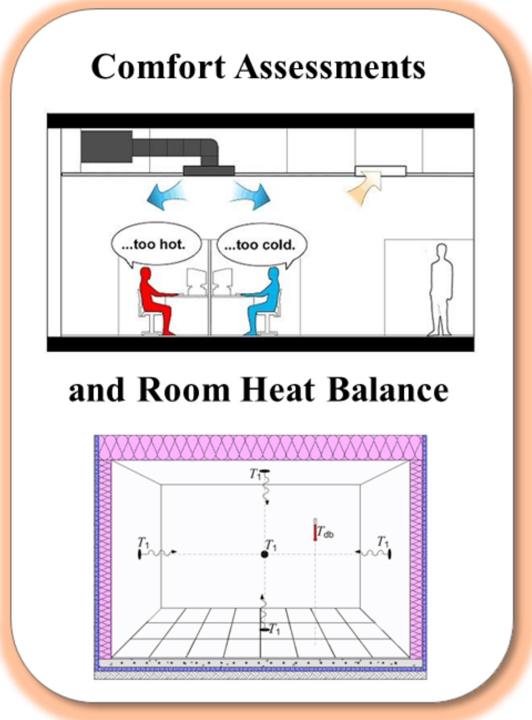
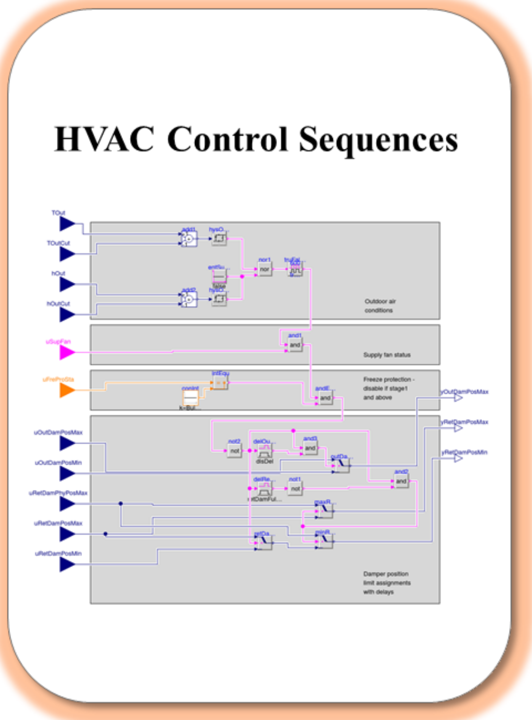
† Derrible et al. (2015). https://doi.org/10.1016/j.enbuild.2015.09.022

Approach

Create a closed-loop HVAC sensor/controller that radiatively detects occupants, occupant comfort, and room surface temperature, and reduces overcooling by regulating HVAC output





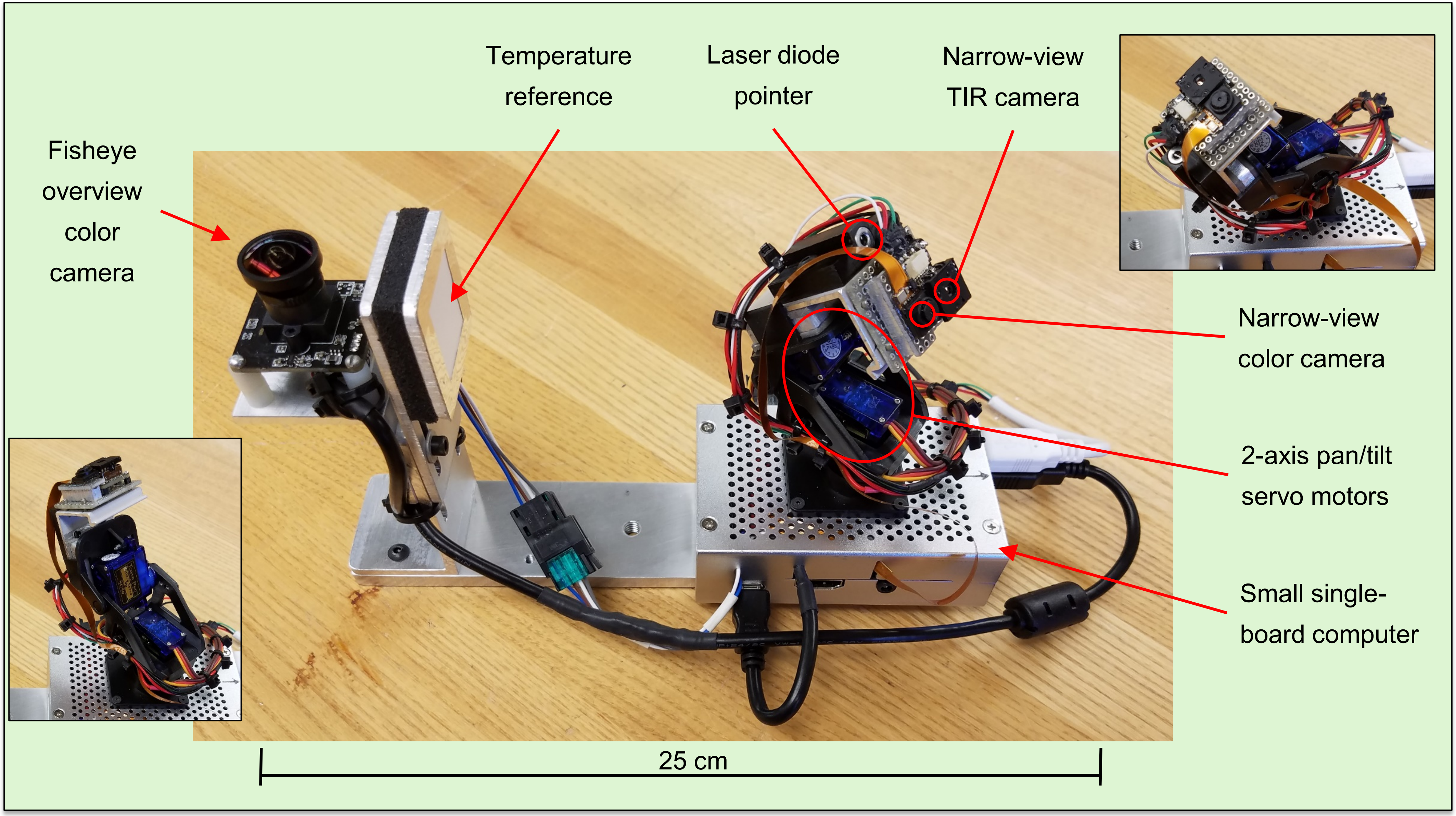


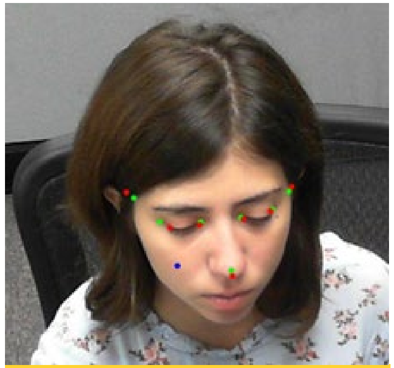
① Machine vision + thermography

② Physiology + physics

③ Model predictive control

SENSING: Our sensor includes color and thermal infrared (TIR) cameras used to detect occupants and measure skin temperatures



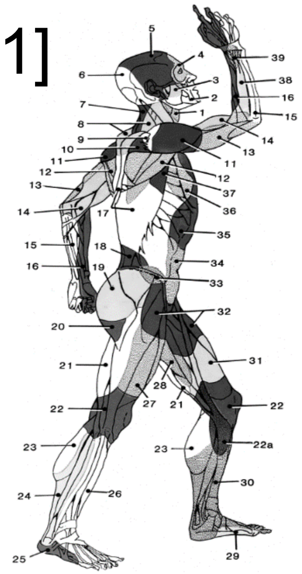

Landmarks in face

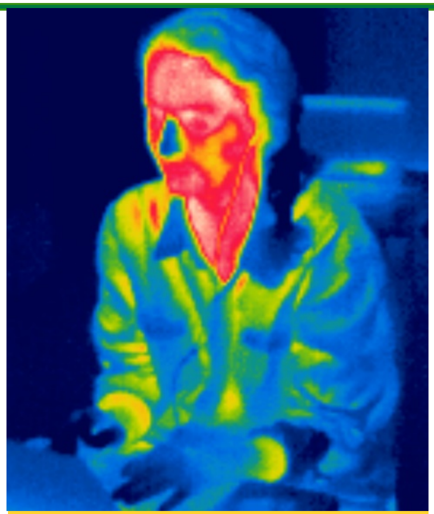

Landmarks in hands

COMFORT: Skin temperature serves as a proxy for thermoregulation performance

- **Thermal comfort state is closely tied to thermoregulation performance**
- **Thermoregulation system uses**
  - Vasoconstriction and shivering to warm the body
  - Vasodilation and sweating to cool the body
- **Cardiovascular territories[1] blood flow rates vary when exposed to hot or cold (e.g., that in nose is reduced when exposed to cold)**
- **This results in temperature variations on the skin in regions with high skin blood density[2]**

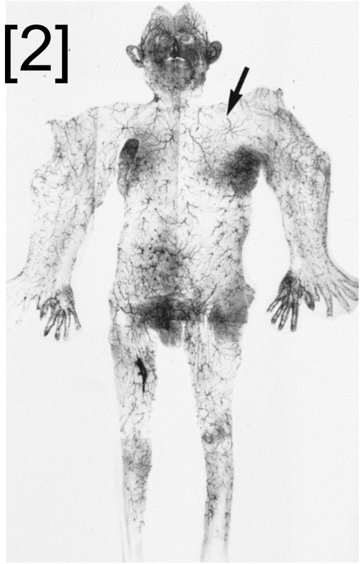
[1]

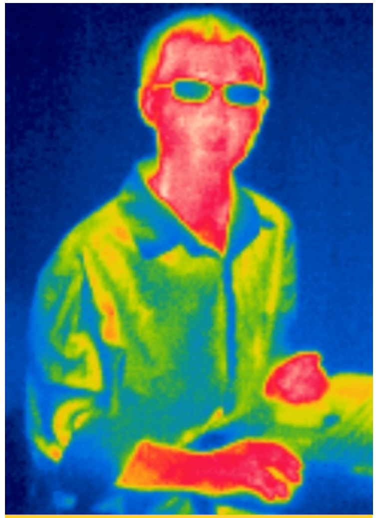




Cold: nose and hand temperatures low

[2]



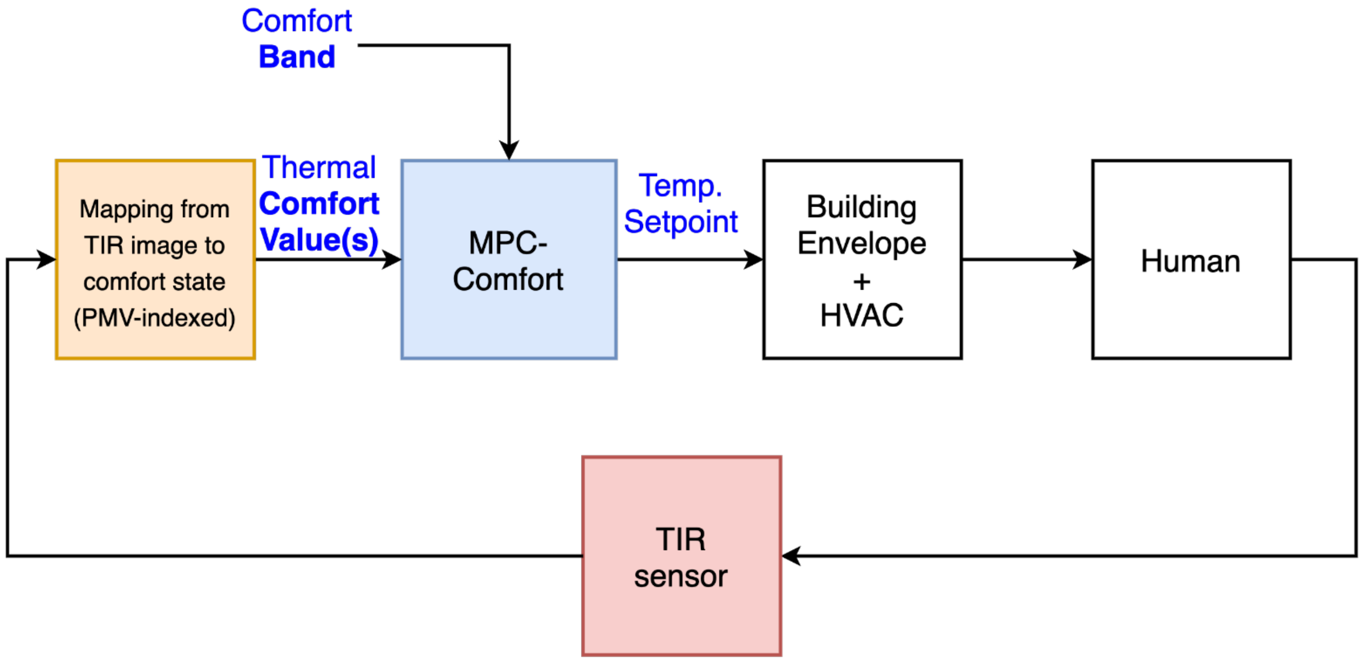


Warm: more uniform skin temperature

CONTROL: The control loop regulates AC operation to provide the minimum cooling output that maintains occupant comfort

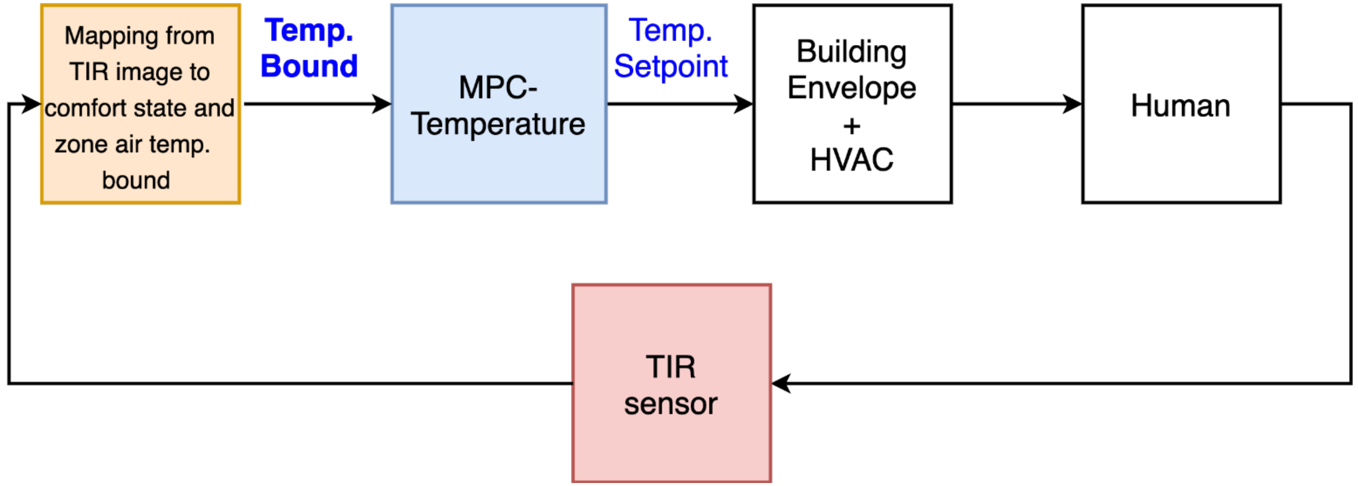
MPC-Comfort:

Determine the right thermostat temperature setpoint which minimizes HVAC energy cost while maintaining comfort within a **comfort band.**



MPC-Temperature:

Determine a zone air temperature range first, and then optimize AC operation within the **temperature band.**



Our human-in-the-loop approach streams continuous comfort information to the controller without requiring occupant instrumentation or participation

- Today's *closed-loop* alternatives are invasive or may fatigue occupants
  - Wearable wireless sensors that measure core and skin temperatures
  - Smartphone applications that ask occupants to rate their comfort
  - Wearables unsuitable in nearly all spaces, including offices
  - Smartphone applications impractical where people often come and go (e.g., meeting rooms, stores, and restaurants)
- Today's *open-loop* alternatives lack feedback to prevent overcooling
  - Occupant counters (door switch, motion detector, CO_2 detector)

No thermocouples taped to skin

No IR sensors on eyeglasses

No smartphone polls

Impact

- Occupant-centric control strategy will deliver both energy efficiency and occupant comfort
- Large U.S. technical potential for energy savings by minimizing overcooling in U.S. buildings
  - About 0.5 Quad/year in 2030
  - 2 - 4 year payback period based on unit price of $300 - $600
- Could be integrated with smart home energy management and home security systems
- Allows a natural extension to Grid-interactive Efficient Buildings by taking time-varying utility price signal to MPC formulation
- We will demonstrate our passive closed-loop radiative sensor/controller in project year 3
- **To maintain privacy, our final system will not identify occupants and will not retain photos**

Elephants may never forget...
but our sensor
will discard images

Progress

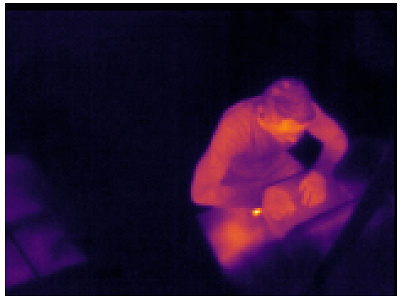
A COVID-19 adaptation: carport trials!

- **Administrative**
  - Began final year of 3-year project on 2021-05-01
  - Spending rate in first two years slightly higher than planned (79% vs. 70%), but we will finish on time and on budget
  - **Now current on all milestones and deliverables**
    - ✓Completed laboratory work & human subject tests delayed by COVID-19 controls
    - ✓Satisfied all Go/No-Go milestones (comfort model accuracy, sensor accuracy)
- **Technical**
  - Built prototype sensor/controller (hardware + software)
  - Completed human subject tests relating comfort to skin temperature differences
  - Acquired real-building test sites for summer/fall 2021 trials
  - Began laboratory and real-building trials of sensor/controller

SENSING: Patent-pending iEye hardware/software system captures real-time temperatures of facial segments, computes comfort indices

Client (Pi): captures, compresses and transmits images

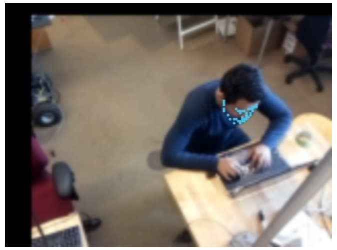
Color Image



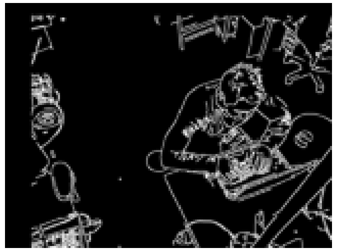
Infrared Image

Server (laptop + GPU): calculates comfort indices

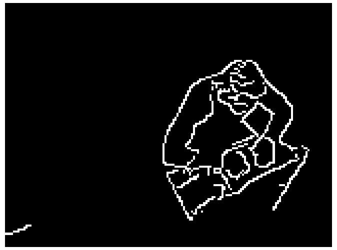
Facial-part detection

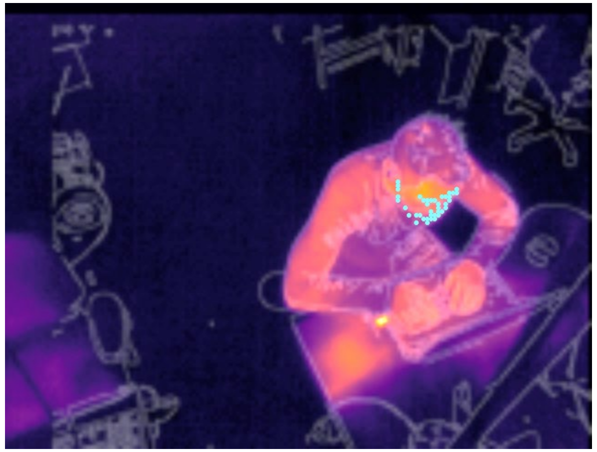


Color image edge detection



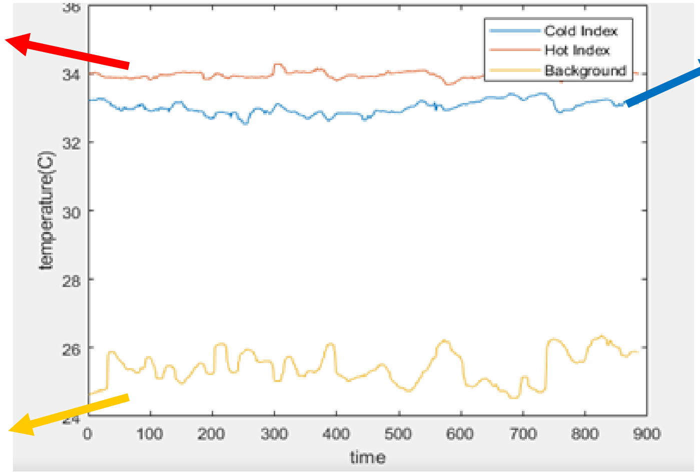
IR image edge detection





Registered image with facial components identified

Hot index: Median of 10 warmest points in areas around face



Cold index: Median of 3 coldest points around nose

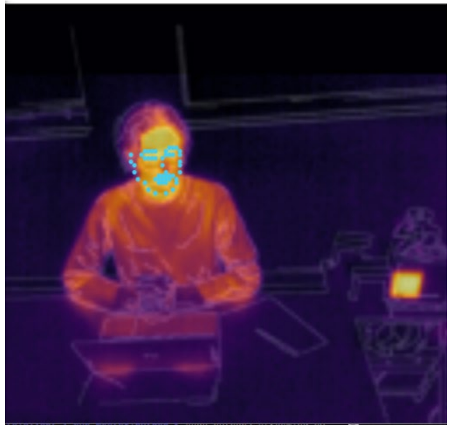
We use the background temperature to eliminate the sensor drift

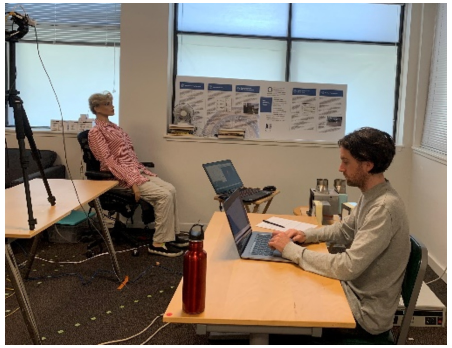
COMFORT: Comfort-driven setpoint constraints guide the HVAC controller to provide heating and cooling when needed

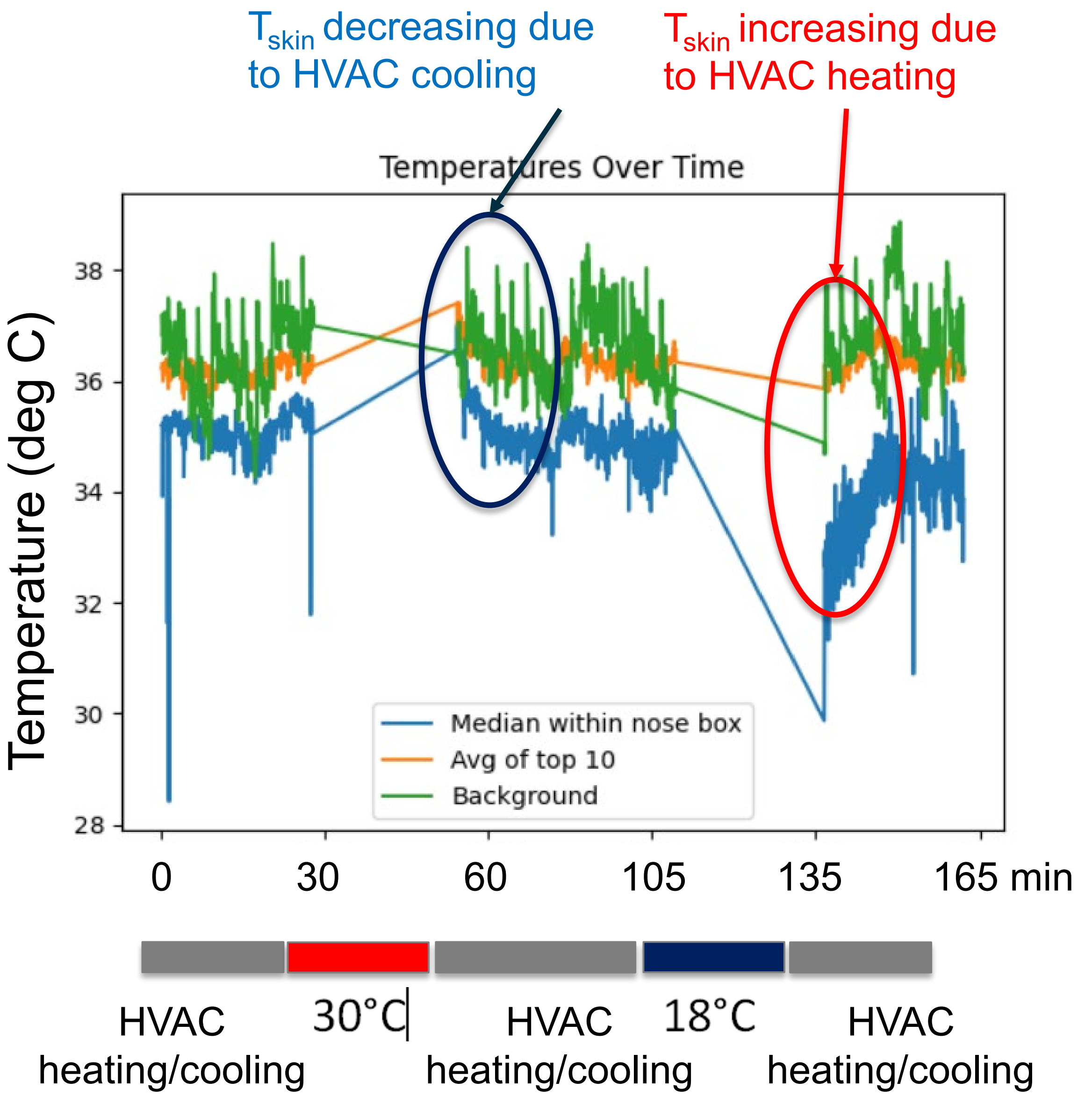
1) A decision-tree infers comfort state and assigns setpoint constraints

2) Generalized Gaussian Mixture Models detect steady states

- **Trials:**
  - Simulated outdoor commutes: cold (18 °C) and hot (30 °C) conditions
  - 13 subjects

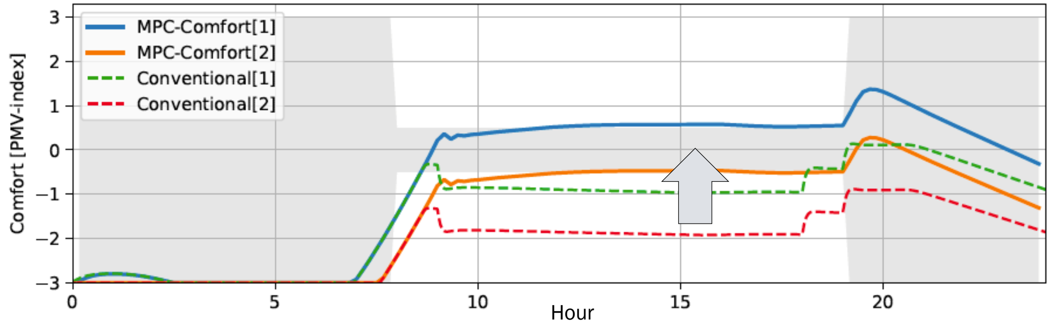


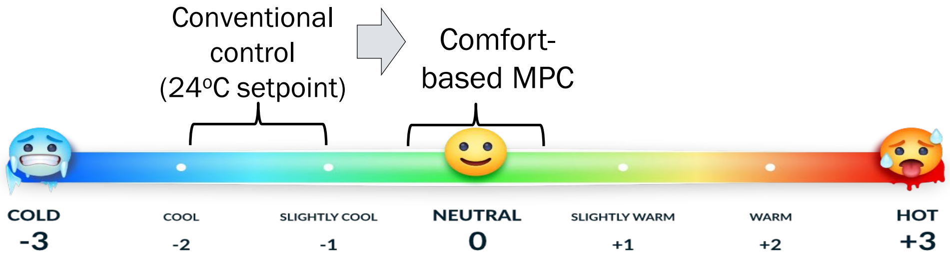




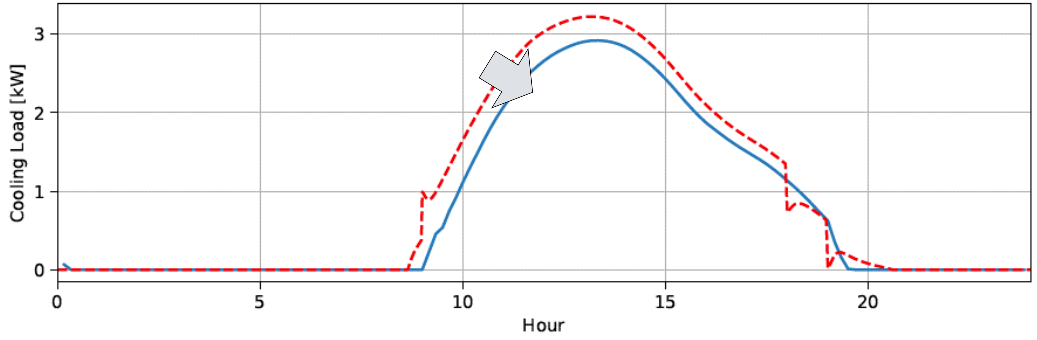
CONTROL: Comfort-based sensor and control diminishes overcooling, improving comfort and saving energy

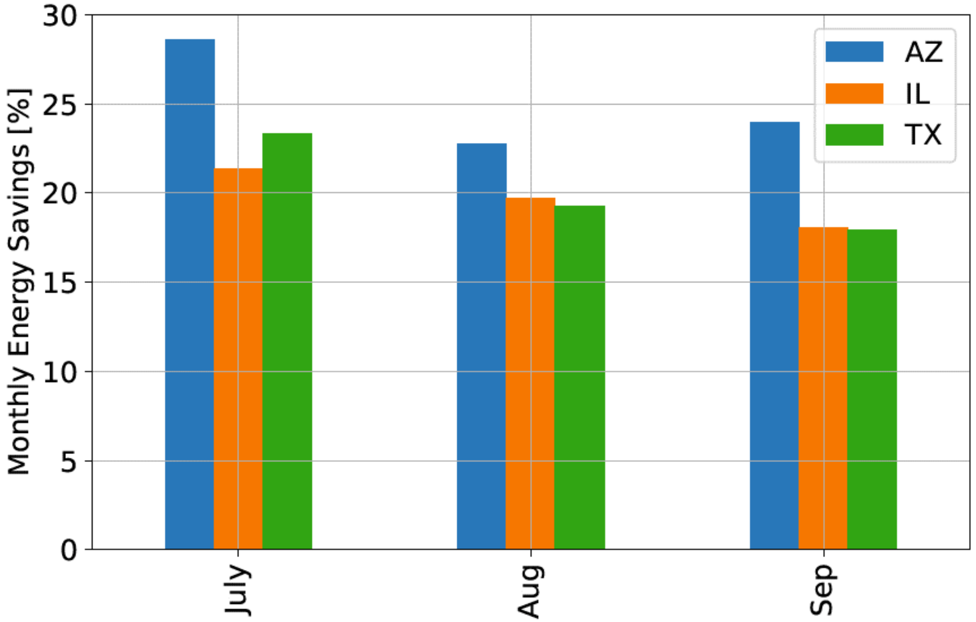
Comfort improvement





Energy savings

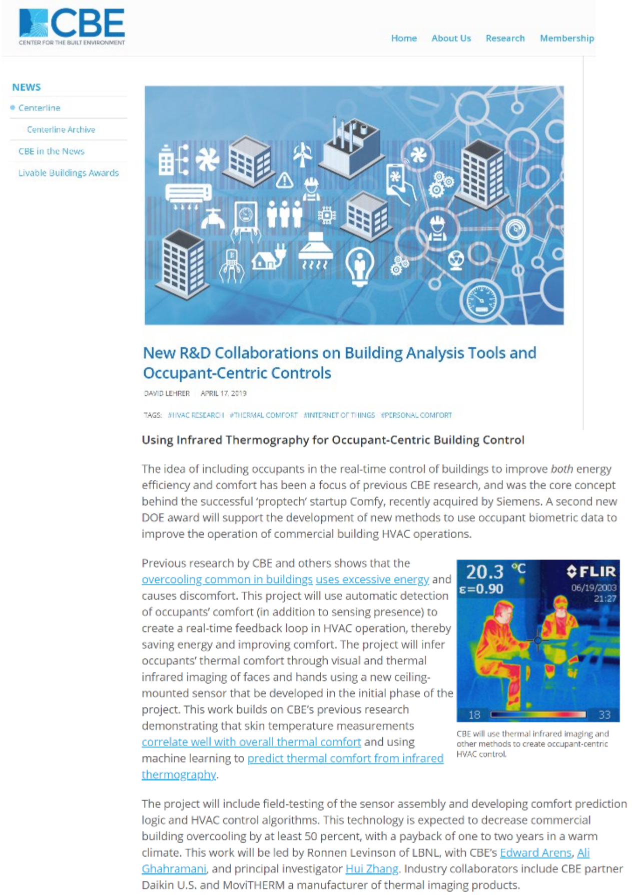




HVAC energy savings of the comfort-based sensor and control strategy for each cooling month for different climates (AZ: hot & dry; IL: cool & humid; TX: hot & humid)

Stakeholder Engagement

- **Project partner Daikin is potential licensee**
  - Top U.S. & global AC manufacturer
  - Develops HVAC sensor and control systems
  - Will host demonstration in Houston, TX (Sep 2021)
- **Our late-stage project (3 Qs remaining) has engaged with the building industry since its inception**
  - April 2021: Presented comfort prediction results at the CBE's Partner Advisory Board (about 50 building-industry & government organizations); plan to present demonstration results at fall 2021 meeting
  - April 2019: Published news release in CBE *Centerline*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New R&D Collaborations on Building Analysis Tools and Occupant-Centric Controls

DAVID LEHRER | APRIL 17, 2019

TAGS: #HVAC RESEARCH #THERMAL COMFORT #INTERNET OF THINGS #PERSONAL COMFORT

Using Infrared Thermography for Occupant-Centric Building Control

The idea of including occupants in the real-time control of buildings to improve *both* energy efficiency and comfort has been a focus of previous CBE research, and was the core concept behind the successful 'proptech' startup Comfy, recently acquired by Siemens. A second new DOE award will support the development of new methods to use occupant biometric data to improve the operation of commercial building HVAC operations.

Previous research by CBE and others shows that the overcooling common in buildings uses excessive energy and causes discomfort. This project will use automatic detection of occupants' comfort (in addition to sensing presence) to create a real-time feedback loop in HVAC operation, thereby saving energy and improving comfort. The project will infer occupants' thermal comfort through visual and thermal infrared imaging of faces and hands using a new ceiling-mounted sensor that be developed in the initial phase of the project. This work builds on CBE's previous research demonstrating that skin temperature measurements correlate well with overall thermal comfort and using machine learning to predict thermal comfort from infrared thermography.

CBE will use thermal infrared imaging and other methods to create occupant-centric HVAC control.

The project will include field-testing of the sensor assembly and developing comfort prediction logic and HVAC control algorithms. This technology is expected to decrease commercial building overcooling by at least 50 percent, with a payback of one to two years in a warm climate. This work will be led by Ronnen Levinson of LBNL, with CBE's Edward Arens, Ali Ghahramani, and principal investigator Hui Zhang. Industry collaborators include CBE partner Daikin U.S. and MoviTHERM a manufacturer of thermal imaging products.

https://cbe.berkeley.edu/centerline/new-building-analysis-tools-and-occupant-centric-controls/

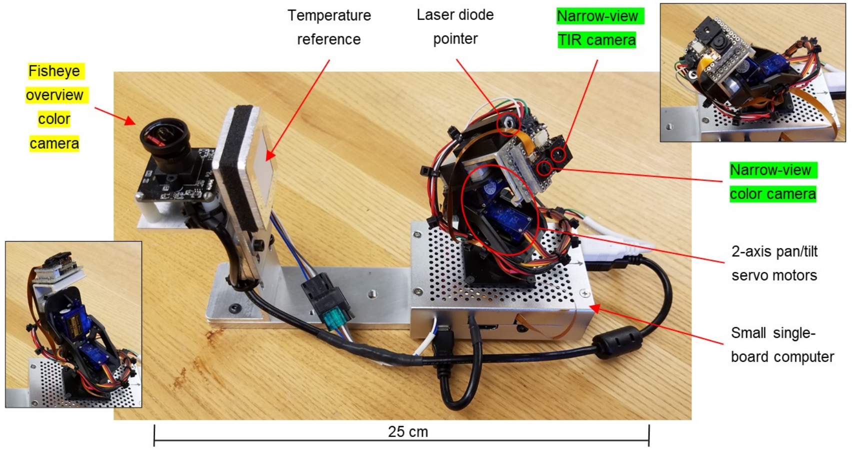
Remaining Project Work

- **We are now in the integration, demonstration, and refinement stage of the project (3 quarters left)**
  - SENSING: implement anonymous occupant tracking to improve efficiency of occupant detection and comfort assessment
  - CONTROL: test and improve control algorithm with single-occupant field trials at Daikin Silicon Valley (Santa Clara, CA) to prepare for demonstration
  - DEMONSTRATION: test sensor/controller with multi-occupant field trials at Daikin facility (Houston, TX)
  - REFINEMENT: improve sensor/controller during and after demonstration
- **Technology Transition Planning**
  - Daikin may license technology if successful
  - Daikin will assess market demand

SENSING: Will improve ability of sensor/controller to assess comfort of multiple occupants by adding anonymous occupant detection & tracking

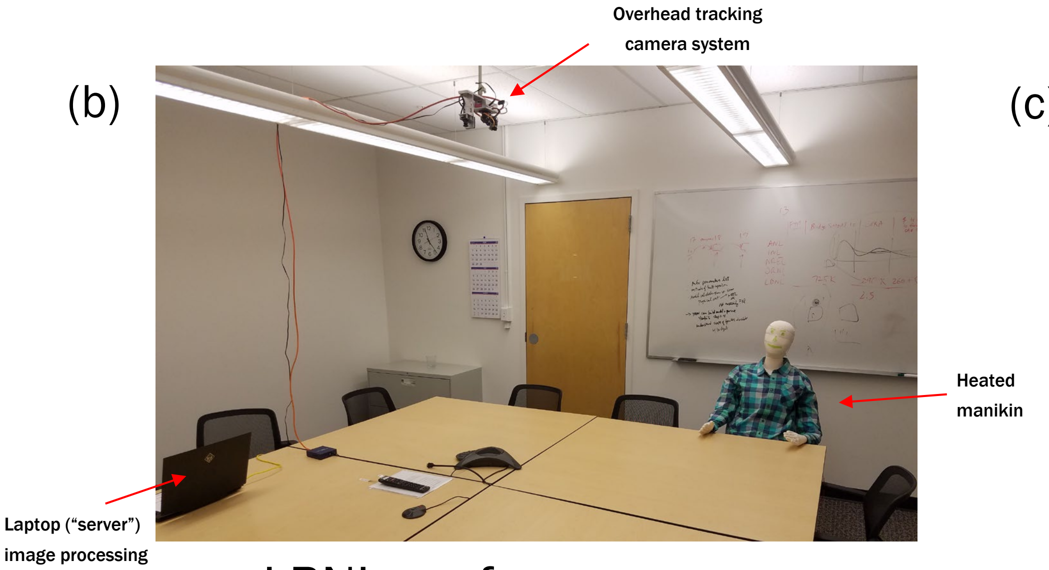
Will program sensor to point narrow-view cameras at occupants after finding them in wide-view overhead image

(a)



Prototype sensor

(b)

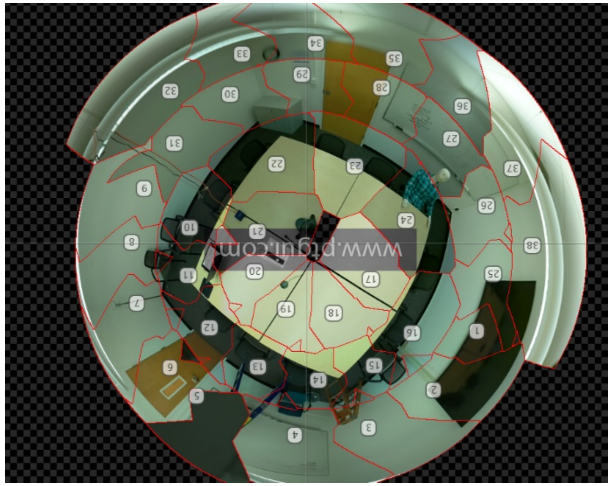


LBNL conference room

(c)

Wide-view overhead image

(d)

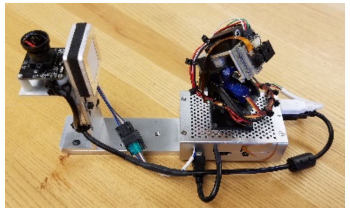


Narrow-view panorama

CONTROL: We're preparing hardware & software to link our sensor/controller to AC systems in our demonstration sites, and to monitor outcomes

Devices for the sensor/control loop

Wireless interface to AC



TIR camera

Local computer for image processing, comfort sensing and MPC

Conference room in Daikin Texas Technology Park (Houston, TX)

Devices for analytics

Cloud-connected temp/RH loggers

Air velocity logger

Gateway for data loggers

Touchscreen for comfort survey

INTEGRATION & DEMONSTRATION: We are testing the sensor/controller in stages, from laboratory trials to a multi-occupant demonstration

① Laboratory trials (July 2021)

② Single-occupant field trials (August 2021)

③ Multi-occupant demonstration (September 2021)

CBE environmental chamber (Berkeley, CA)

Daikin Open Innovation Lab (Santa Clara, CA)

Daikin Texas Technology Park (Houston, TX)

Thank You

Lawrence Berkeley National Laboratory
Center for the Built Environment at UC Berkeley

Daikin Silicon Valley

MoviTHERM

Ronnen Levinson, Staff Scientist, LBNL

Tel. (510) 486-7494 / RMLevinson@LBL.gov

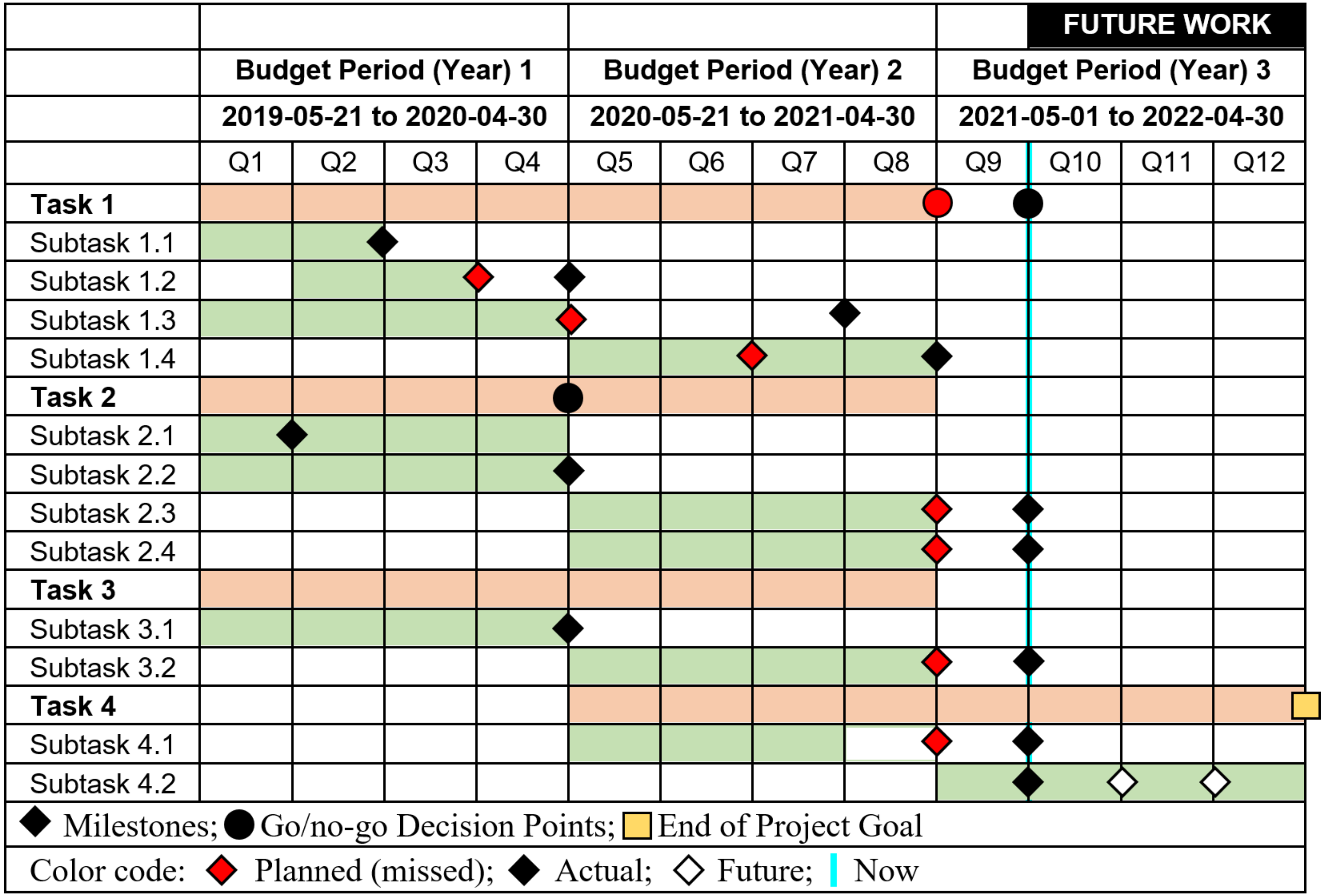
REFERENCE SLIDES

Project Budget

Project Budget: $1,500,000 (DOE) + $408,254 (cost share) over three years
Variances: Year 2 spending higher than planned, but the project will be completed on budget/time
Cost to Date: 79% by end of Year 2 (originally planned 70%)
Additional Funding: None

Budget History					
Project Year 1 (2019-05-01 to 2020-04-30)		Project Year 2 (2020-05-01 to 2021-04-30)		Project Year 3 (2021-05-01 to 2022-04-30)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$499,718	$179,901	$700,309	$101,295	$299,273	$127,650

Project Plan and Schedule



- **Period of performance**
  - 2019-05-21 to 2022-04-30
  - 3 quarters remaining
- **Tasks**
  - 1 = Sensing
  - 2 = Comfort
  - 3 = Control
  - 4 = Integration & demo
- **Some milestones were delayed by COVID-19 controls limiting lab access & human subject tests**
- **All milestones now current**