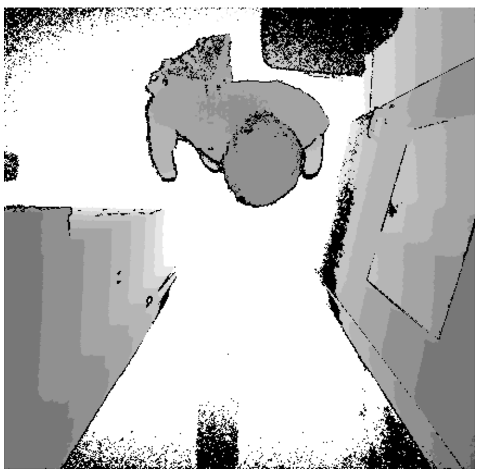
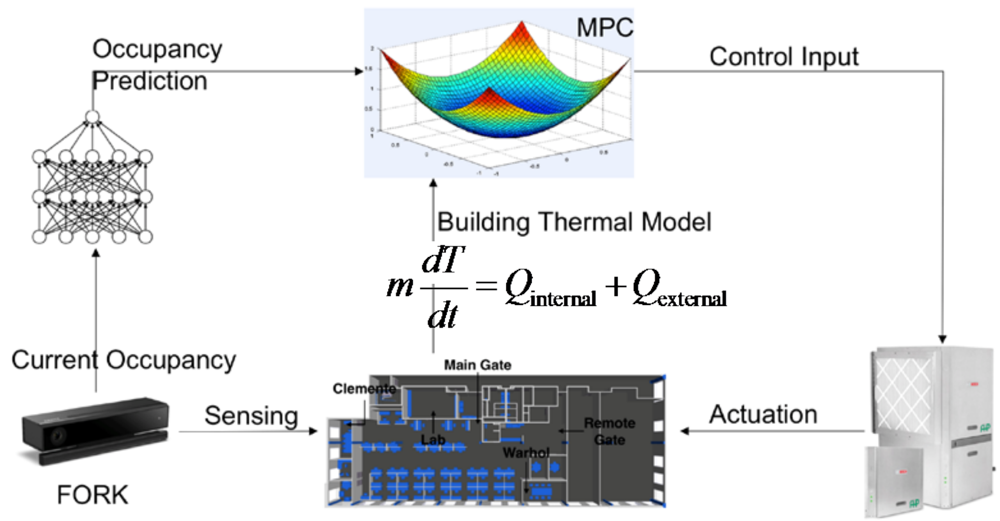
Human-in-the-loop Sensing and Control for Commercial Building Energy Efficiency and Occupant Comfort





Carnegie Mellon University, Stony Brook University, Robert Bosch Research and Technology Center

PI: Mario Bergés, Associate Professor

(412) 268-4572, marioberges@cmu.edu

Presented by:
Anthony Rowe, Associate Professor
agr@ece.cmu.edu

Project Summary

Timeline:

Start date: January 1st, 2017

Planned end date: December 31st, 2019

Key Milestones

1. 95% Accuracy in Occupancy Estimation (Dec. 2017)
2. Cost-optimized sensing prototype BOM < $300 and a 3-month long control study shows 10% energy reduction compared to EnergyPlus baseline (Dec. 2018)
3. Sensing prototype BOM < $300 and a 6-month long control study shows 20% energy reduction (Dec. 2019)

Budget:

Total Project $ to Date:

- DOE: $381,325
- Cost Share: $45,300

Total Project $:

- DOE: $1,223,986
- Cost Share: $139,741

Key Partners:

Carnegie Mellon Univ.
Stoney Brook Univ.
Robert Bosch RTC

Project Outcome:

- A novel human-in-the-loop sensing and control system for energy efficiency of HVAC and lighting systems.
- Provide estimates number of occupants in a thermal zone and their thermal comfort sensitivity
- Incorporation of occupancy/comfort information into a model-predictive control (MPC) framework for HVAC set-point adjustment.

Team

Mario Bergés (CEE), Anthony Rowe (ECE), Alex Davis (EPP)
Carnegie Mellon University

Sirajum Munir, Jon Francis and Charles Shelton
Bosch RTC

Shan Lin
Stony Brook University

CMU:
- Hardware prototype dev./testing
- Thermal Comfort Model
- Machine Learning Models

Bosch RTC:
- Sensing Solution
- Commercialization

Stony Brook:
- Controls

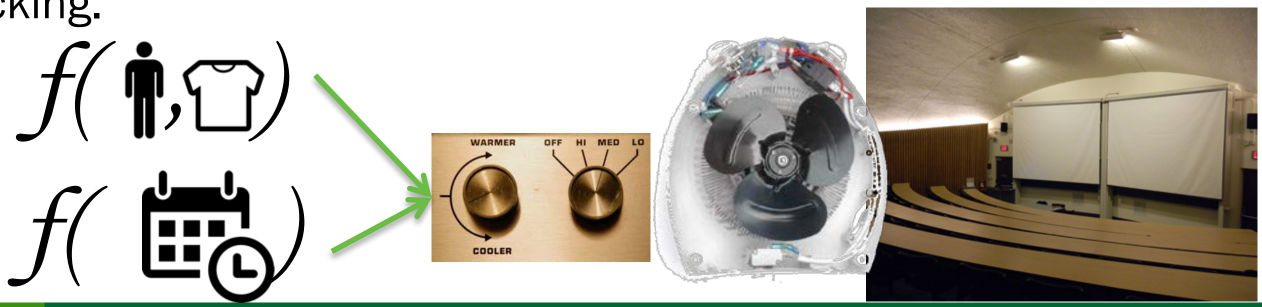
Challenge

Problem Definition: HVAC systems consume 35% of all energy in commercial buildings, yet they are operated by assuming maximum occupancy for each thermal zone and average thermal comfort sensitivity for each occupant. This problem permeates all current HVAC controls, and leads to significant energy waste and occupant dissatisfaction, estimated to be as high as 20% and 49%, respectively.

Current solutions to this problem rely on presence detectors for each thermal zone which, though inexpensive, cannot provide occupancy counts or estimates of individual comfort preferences. Current comfort models estimate average comfort, require detailed inputs (e.g., mean radiant temperature) and exhibit bias.

Moreover, even when all these inputs are available, incorporating them into a control solution is far from trivial. Model-predictive control solutions can assist with this but require a simplified (e.g., linear) model of the building's thermodynamics leading to plant-model mismatch.

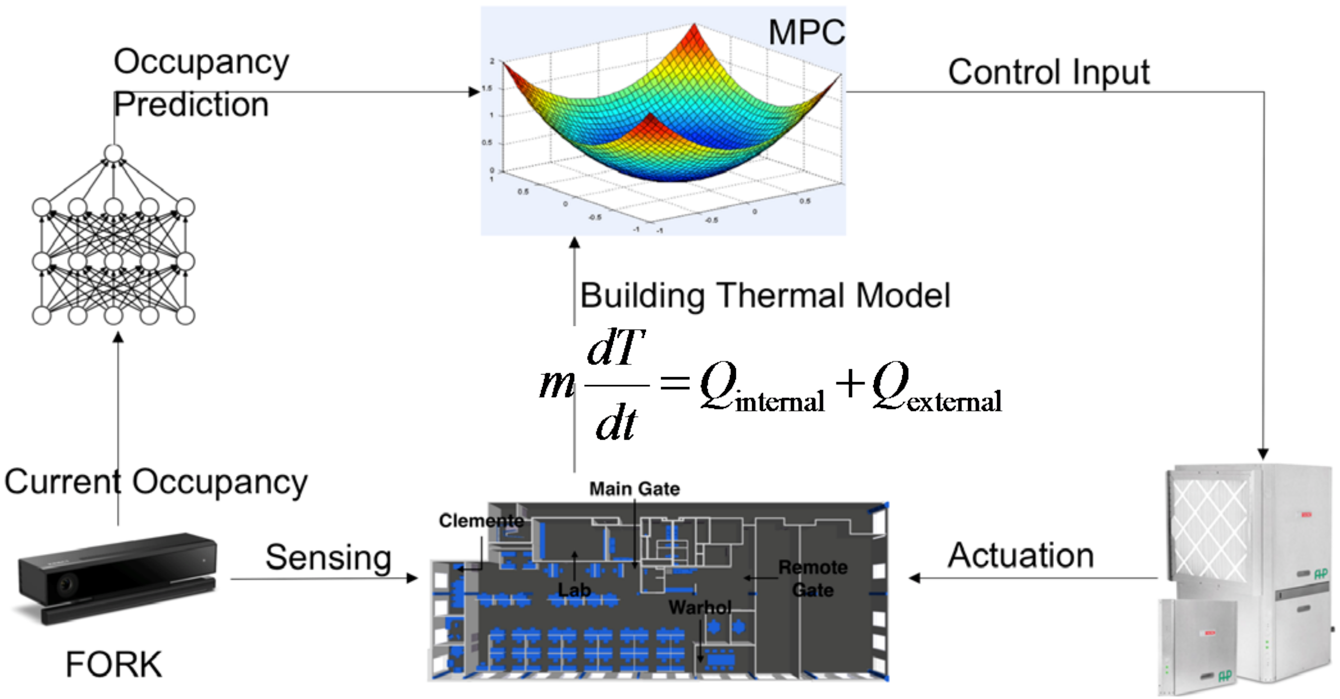
A solution that can address these challenges inexpensively and in a privacy-preserving manner is lacking.



Approach

A human-in-the-loop controller for HVAC systems leveraging:

- Depth-imaging sensors for granular estimates of occupancy counts and comfort
- A novel data-driven comfort model
- Data-driven models of building thermodynamics
- Open-standards for integrating with building automation systems.

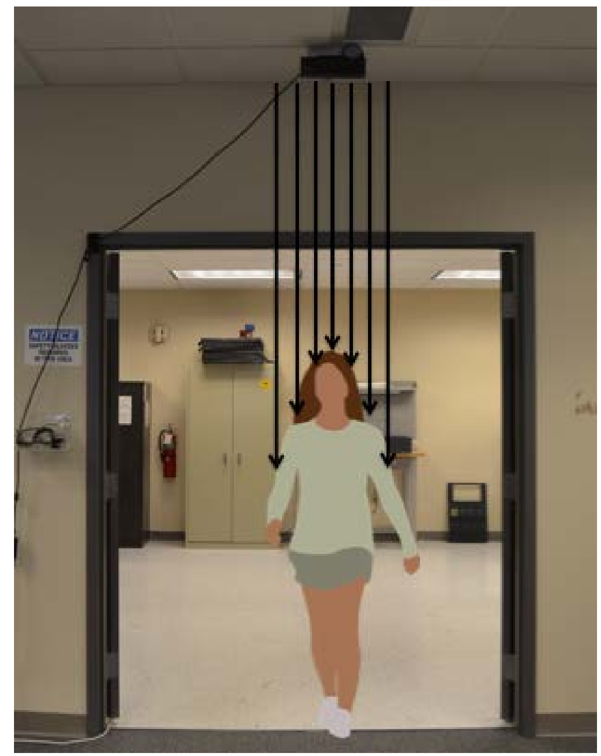


Highlights:

1. Privacy-preserving estimates of occupancy count and comfort preferences.
2. Novel personalized thermal comfort model based on biometrics
3. Data-driven thermal and occupancy models
4. Control actions computed by jointly optimizing comfort and energy objectives.

Impact

- Our solution extracts more information about occupant loads than the state-of-the-art approaches
- Higher accuracy than existing solutions (including cameras) due to the use of depth-imaging sensors.
- Privacy-preserving approach: depth-image only, and processing done at the edge device.
- Closed-loop control by directly modeling the thermal behavior of the space being controlled and integrating with the existing BAS systems
- Targeting a BOM cost of $200/unit
- Targeting 20% energy reduction via HVAC and lighting scheduling optimization, with no significant difference in perceived comfort.
- In line with BTO goals for occupant-centric sensors/controls of 25% reduction in primary energy savings, and $40-100 per-occupant installed cost.



Progress

Project began in January of 2017, and is in its early stages.

Overview of progress:

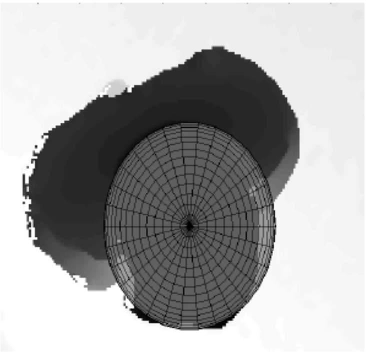
- Prototype has been running in 12 rooms for over a year
- Demonstrated a 95% accuracy in people counting with 4 weeks of ground truth data
- Developed an improved estimator using deep neural-networks
- Conducted a thermal comfort study with 80 participants (3-hours per study session) and are currently analyzing the data to develop comfort models
- Developed a T2M plan in collaboration with Bosch and its business units.
- Compared the accuracy of our solution to other commercial solutions: ours outperforms.
- Demonstrated energy savings using occupancy estimates in simulation.

Progress

Sensing system development:

- Developed 1st prototype system (device and software)
  - Depth-imaging sensor (Microsoft Kinect)
  - Embedded Linux computer (Odroid)
  - Occupancy estimation algorithm (FORK)
- Installed in 12 rooms across different bulidings
- Collected data for > 1 year
- Developed system checks for improving uptime, monitoring

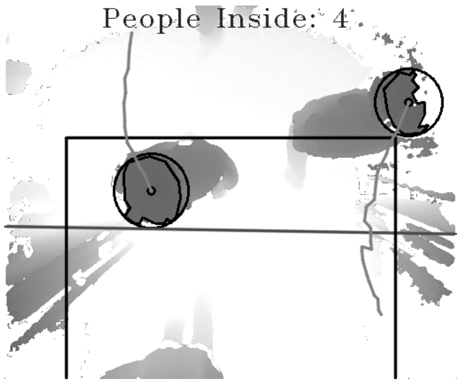
Head verification



Multi-level scanning

Shoulder verification

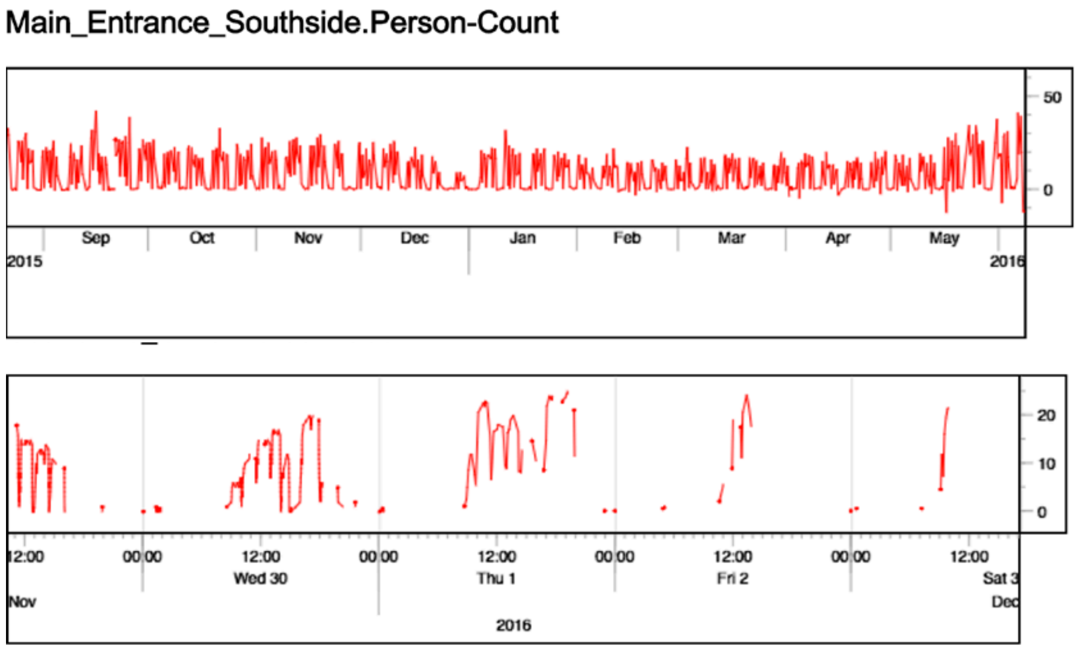
Occupant Tracking/Counting



Progress

Sensing system validation:

- Collected 1 week of data in 4 rooms for ground truth (16 TB)
- Finished hand-annotation of every frame
- Tested algorithm on these data (Table 1), showing >95% accuracy
- Publically released 6-months of occupancy traces for an office building (COD Dataset)*



Category	Number
Ground Truth instances	764
Detected events	760
True Positives	727
False Positives	37
False Negatives	37
Recall	**0.9515**
F1-score	0.9515

* https://doi.org/10.5281/zenodo.996587

Progress

Thermal Comfort Study and Modeling:

- Conducted an 80-participant study for comfort data collection:
  - 3 hour sessions, 6 temperature set points
  - Experience sampling via mobile app, reporting comfort on a 5-point scale
  - Sensor data: wearables, building automation system, depth-imaging
- Preliminary data analysis shows a correlation between biometrics and comfort response.

Timeline:

1) Neutral – Hot – Neutral - Cold experiment

22^{0}C	28^{0}C	33^{0}C	22^{0}C	17^{0}C	15^{0}C
40 mins	30 mins	30 mins	30 mins	30 mins	30 mins

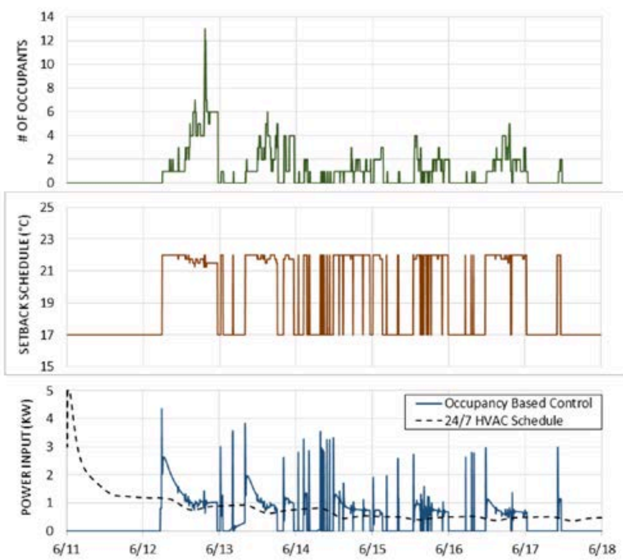
2) Neutral – Cold – Neutral – Hot experiment

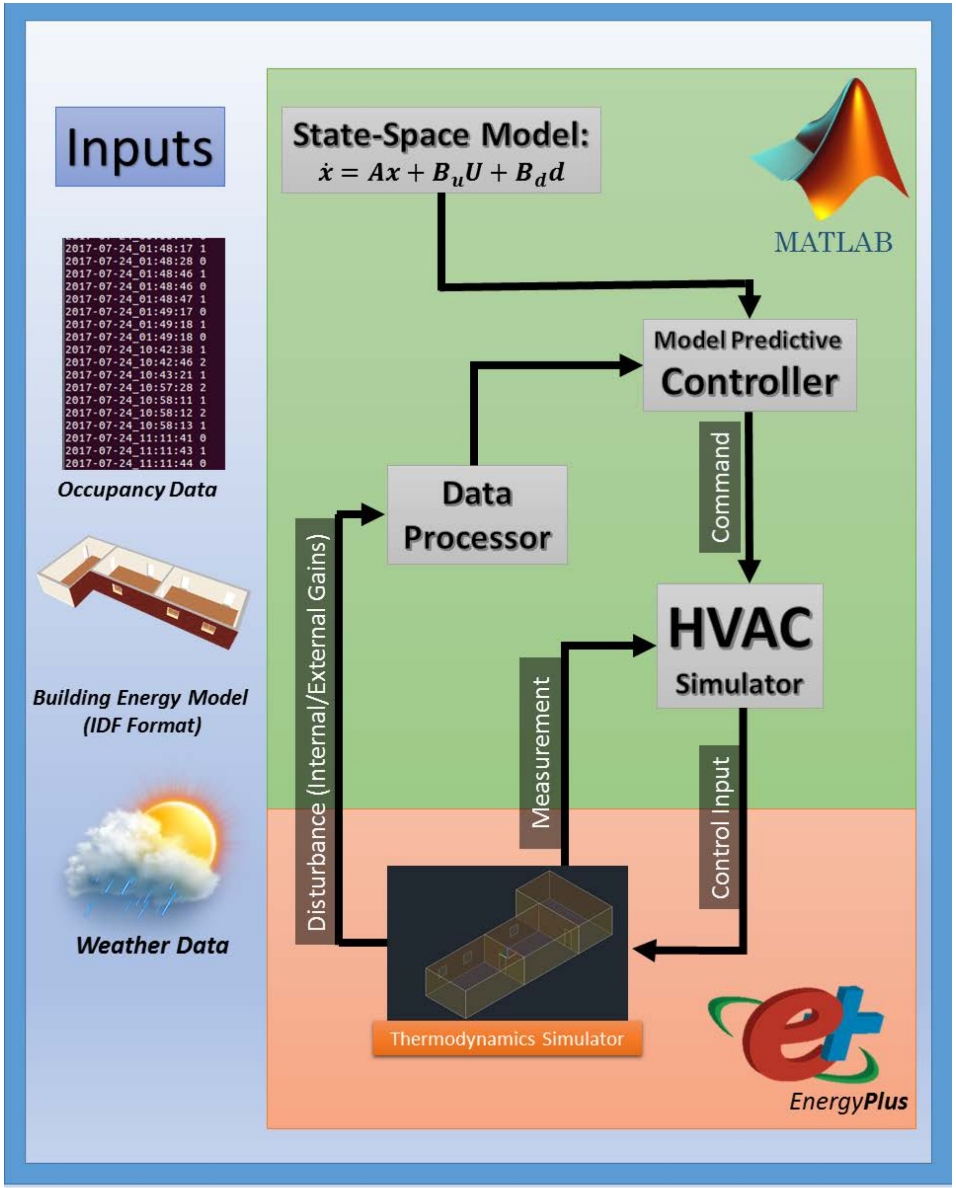
22^{0}C	17^{0}C	15^{0}C	22^{0}C	28^{0}C	33^{0}C
40 mins	30 mins	30 mins	30 mins	30 mins	30 mins

Progress

Model Predictive Control progress:

- Developed EnergyPlus and OpenBuild models of three zones in field experiments
- Implemented an MPC solution and co-simulated it with EnergyPlus using OpenBuild.
- Tested the solution using real occupancy traces for dynamic setpoint setback assignments.





Stakeholder Engagement

- Market research and commercialization planning lead by Bosch
  - Initial market discovery process completed including more than 75 interviews with facility managers, owners and operators of commercial buildings.
  - Identified two Bosch employees from the Bosch Climatec division to serve as the T2M leads for the project.
  - Business units within Bosch considering inclusion of the technology as part of their portfolio.
- Field demonstrations lead by Carnegie Mellon University
  - Main field partner: Facility Management Services office at Carnegie Mellon University in Pittsburgh, PA,
  - 12 prototype units already deployed
  - Obtained approval for the installation of 25 new units in BP2 that will allow for thermostat set-point control.

Remaining Project Work

Milestones	*2018*				*2019*			
	Q1	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q1*	*Q2*
Install 25 new prototype units		x						
* Achieve 97% accuracy in detection and estimation				x				
Determine effectiveness of thermal comfort model		x						
Demonstrate remote control of setpoints in testbed			x					
T2M Plan Updated	x							
Preliminary Cost Performance Model	x							
Refined Cost Performance Model			x					
Preliminary post-project financing/transiton plan				x				
Go/No-Go: <$300 BOM and <30W Power Usage				x				
Go/No-Go: 10% energy reduction on testbed rooms				x				
Install 30 new prototype units						x		
<$250 BOM and <25W Power Usage								x
20% energy reduction on testbed w/o comfort problems								x
Production level cost model						x		
Refined post-project financing/transition plan					x			
Transition progress report						x		
Final transition report								x

* *Occupancy detection accuracy will be improved by using modern computer vision techniques (deep neural nets)*

Remaining Project Work

Milestones	*2018*				*2019*			
	Q1	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q1*	*Q2*
Install 25 new prototype units		x						
Achieve 97% accuracy in detection and estimation				x				
Determine effectiveness of thermal comfort model		x						
* Demonstrate remote control of setpoints in testbed			x					
T2M Plan Updated	x							
Preliminary Cost Performance Model	x							
Refined Cost Performance Model			x					
Preliminary post-project financing/transiton plan				x				
Go/No-Go: <$300 BOM and <30W Power Usage				x				
Go/No-Go: 10% energy reduction on testbed rooms				x				
Install 30 new prototype units						x		
<$250 BOM and <25W Power Usage								x
20% energy reduction on testbed w/o comfort problems								x
Production level cost model						x		
Refined post-project financing/transition plan					x			
Transition progress report						x		
Final transition report								x

* *We will test two type of controllers: MPC with a data-driven model, and Deep Reinforcement Learning*

Remaining Project Work

	Milestones	2018				2019			
		Q1	Q2	Q3	Q4	Q1	Q2	Q1	Q2
	Install 25 new prototype units		x						
	Achieve 97% accuracy in detection and estimation				x				
*	Determine effectiveness of thermal comfort model		x						
	Demonstrate remote control of setpoints in testbed			x					
	T2M Plan Updated	x							
	Preliminary Cost Performance Model	x							
	Refined Cost Performance Model			x					
	Preliminary post-project financing/transiton plan				x				
	Go/No-Go: <$300 BOM and <30W Power Usage				x				
	Go/No-Go: 10% energy reduction on testbed rooms				x				
	Install 30 new prototype units						x		
	<$250 BOM and <25W Power Usage								x
	20% energy reduction on testbed w/o comfort problems								x
	Production level cost model						x		
	Refined post-project financing/transition plan					x			
	Transition progress report						x		
	Final transition report								x

* *New thermal comfort model based on biometrics. Will be incorporated into control objective using different formulations (e.g., mean or ind. comfort)*

Thank You

Carnegie Mellon University, Stoney Brook University, Robert Bosch RTC

Mario Berges, Associate Professor

(412) 268-4572

marioberges@cmu.edu

REFERENCE SLIDES

Project Budget

SUMMARY OF BUDGET CATEGORY COSTS PROPOSED/APPROVED											
				Federal			Cost Share			Total Costs	Cost Share %
	BP1			$342,887			$41,928			$384,815	10.90%
	BP2			$428,997			$47,924			$476,921	10.05%
	BP3			$452,102			$49,889			$501,991	9.94%
	Total			$1,223,986			$139,741			$1,363,727	10.25%
	01/01/2017 - 12/31/2017			01/01/2018 - 12/31/2018			01/01/2019 - 12/31/2019			Cumulative	
CATEGORY	Revised/Actuals BP1	Original BP1	BP1 Variance (%)	Revised/Approved BP2	Original BP2	BP2 Variance (%)	Revised BP3	Original BP3	BP3 Variance (%)	Total Project Costs	% of Project
a. Personnel	$66,219	$52,565	26%	$68,572	$54,141	27%	$70,880	$55,767	27%	$205,671	15.08%
b. Fringe Benefits	$9,183	$4,819	91%	$7,745	$4,964	56%	$8,036	$5,113	57%	$24,965	1.83%
c. Travel	$1,730	$4,914	-65%	$3,155	$5,061	-38%	$3,240	$5,213	-38%	$8,125	0.60%
d. Equipment	$0	$0	0%	$0	$0	0%	$0	$0	0%	$0	0.00%
e. Supplies	$11,386	$8,380	36%	$21,855	$20,425	7%	$33,720	$32,250	5%	$66,961	4.91%
f. Contractual										$0	
Sub-recipient	$175,023	$227,851	-23%	$218,716	$218,716	0%	$225,345	$225,345	0%	$619,084	45.40%
Vendor	$10,537	$16,800	-37%	$30,955	$35,000	-12%	$27,000	$22,700	19%	$68,492	5.02%
FFRDC	$0	$0	0%	$0	$0	0%	$0	$0	0%	$0	0.00%
Total Contractual	$185,560	$244,651	-24%	$249,671	$253,716	-2%	$252,345	$248,045	2%	$687,576	50.42%
g. Construction	$0	$0	0%	$0	$0	0%	$0	$0	0%	$0	0.00%
h. Other Direct Costs	$19,293	$44,794	-57%	$44,702	$46,138	-3%	$46,043	$47,522	-3%	$110,038	8.07%
Total Direct Costs	$293,371	$360,123	-19%	$395,700	$384,446	3%	$414,265	$393,911	5%	$1,103,336	80.91%
i. Indirect Charges	$91,444	$81,796	12%	$81,221	$71,256	14%	$87,726	$72,195	22%	$260,391	19.09%
Total Costs	$384,815	$441,919	-13%	$476,921	$455,702	5%	$501,991	$466,106	8%	$1,363,727	100.00%

Project Budget

Budget History					
1/1/2017 – FY 2017 (past)		FY 2018 (current)		FY 2019 – 12/31/2019 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$342,887	$41,928	$428,997	$47,924	$452,102	$49,889

Project Plan and Schedule

Describe the project plan including:

- Project original initiation date & Project planned completion date
- Schedule and Milestones
- Explanation for slipped milestones and slips in schedule
- Go/no-go decision points
- Current and future work

Project Schedule												
Project Start: 01/01/2017		Completed Work										
Projected End: 12/31/2019		Active Task (in progress work)										
		Milestone/Deliverable (Originally Planned)										
		Milestone/Deliverable (Actual)										
	FY2017				FY2018				FY2019			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Q1 Milestone: Sensor Deployment in 12 rooms												
Q2 Milestone: 95% Detection Accuracy												
Q3 Milestone: Example 3												
Q4 Milestone: Example 4												
Q1 Milestone: Example 5												
Current/Future Work												
Q3 Milestone: Example 6												
Q4 Milestone: Example 7												