Quantification of HVAC Energy Savings for Occupancy Sensing in Buildings through an Innovative Testing Methodology

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November 9th 2018
Outline

• Introduction and Overview
• Methodology
• Preliminary Results
• Ongoing and Future work: Community Engagement
Overview of the Proposed Work

- A novel protocol with an eight-level diversity and a simulation suite to investigate various types of occupancy sensors for detection failure rates and energy saving potentials in real-world retrofit scenarios.
- Controlled lab testing and system-level field testing.
Testing and Validation **Challenges**: Complexity and uncertainty due to diversity of types of occupant sensors, deployment topologies, software, installations, and HVAC control strategies

**Novelty:**

- Testing protocol with eight-level diversity
  - 1) occupant profile diversity, 2) building type and floor plan diversity, 3) sensor diversity, 4) HVAC controls and mode diversity, 5) Functional testing diversity, 6) deployment location diversity, 7) software diversity, and 8) diagnostic diversity
- Simulation suite with uncertainty quantifications of sensor errors
- Integration with Well Building Standard concept
- Testing data analytics with advanced Machine Learning algorithms
- Market transition through proactive engagements with HVAC standards committees, control consulting and building automation companies
a. Testing Protocol with Eight-level Diversity

Occupant Profiles

- Density
- Skin color
- Body type
- Physical ability levels

Building Types and Layout

- Commercial (different sub-market)
- Residential (different floor plans)

HVAC control and mode

- Heating mode
- Cooling mode

Wired Sensors

1) Analog
2) Digital
3) USB
4) Ethernet

Wireless Occupancy Sensors

1) Bluetooth
2) Zigbee
3) f.8.G

Sensor Deployment

- Local location (door, wall, etc.)
- Sensor density
- Deployment topology (chain, mesh, grid, start, etc.)

Building HVAC and Control System

- Local controller
- Network controller

Occupancy-based Control for Ventilation/Temperature

1) Follow ASHRAE GPC 36
2) ASHRAE Standard 90.1, 90.2, 62.1 and 62.2
3) Functional testing scripts
4) Run functional testing

Wireless Occupancy Sensors

- A variety of homes (old & new)
- With different floor plans
- Very open-plan home

Software Diversity

- Computational algorithms
- Local computation
- Hub (aggregator) computation

Diagnostics

- Missing data
- Counting delay, inaccuracy
- Sensing-control time

Sensor Power

- Sensing
- Computing
- Communication

RF Communication Power

- 1-hop transmission
- Multi-hop commu.

Building Perform.

- HVAC Energy
- Thermal Comfort, IAQ

Total Cost

- Material
- Installation
- Commissioning

Sensor Performance (e.g., failure rate)

Energy, Cost, Uncertainty and Other Data Analysis

Impact of sensor reliability and capability on energy savings & cost
Sensor Integration with Building Automation System

- Sensor communication with Building automation system
  - BACnet gate way
  - Lonworks, Modbus
  - Wired sensors vs. wireless sensors
- Volttron
- sMAP (Simple Measurement and Actuation Profile)
b. Energy Saving Assessment Using a Novel Simulation Suite

Use EnergyPlus EMS module to simulate controls and sensor faults

- 16 climate zones
- Nationwide energy savings

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Ideal impact with ground truth sensed (zero sensor error)</th>
<th>Impact with deterministic sensor error</th>
<th>Impact with stochastic sensor error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole building EnergyPlus simulation (thousands)</td>
<td>Step 1 Step 2 Step 3 Step 4</td>
<td>Outputs from each sample</td>
<td>Outputs from each sample</td>
</tr>
<tr>
<td>EnergyPlus model with zero sensor error</td>
<td>Sensor readings</td>
<td>Perturb sensor readings, (Monte Carlo)</td>
<td>Samples (with new sensor values )</td>
</tr>
<tr>
<td>EnergyPlus EMS control sequence</td>
<td>EnergyPlus EMS control sequence</td>
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</tbody>
</table>

- Output Energy, Comfort, Ventilation, etc. Distribution
- Sensitivity Index (e.g., Sobol index) $S_i = \frac{D_i}{D}$

- 16 climate zones
- Nationwide energy savings
Sensor Error Analysis - Testing Methodology

- ASHRAE GPC 36 (RP-1747) CO₂ based demand control ventilation
- Comply with ASHRAE 62.1
- Dynamic reset zone level ventilation rate
- Coordinate the zone level and the AHU economizer controls
- Implementable on the DDC system
  - Trim & Response
  - No iterations
- Field demonstrations

\[ V_{bz} = \text{MIN}\left( P_z R_p + A_z R_a \left[ \max\left[0, \left( \frac{C_{bz} - C_{sz}}{km} \right) \right] E \left( V_{pz} R_p + A_z R_a \right) \right] \right) \]

\[ Zone_{co2} = Zone_{co2\_accurate} + CO2\_bias \]

\[ Zone_{airflow} = Zone_{airflow\_accurate} \times [1 + bias\%] \]

- Zone air CO₂ concentration bias with (μ, σ)=(0, 100) ppm
- Air flow rate bias with (μ, σ)=(0, 0.333)
Sensor Error Analysis - Preliminary Results (1)

- Energy Resource Station at Iowa Energy Center
- 8 Test rooms
- 2 VAV AHUs
- 8 VAV terminal VAV box
- Dynamic occupancy schedule
- 2,000 samples (i.e., 2,000 E+ simulations)
- Errors from 10 sensors (perturbed at the same time)

- Red dot is the case without sensor errors
- Distributions have 2 modes
  - Nonlinearities in EnergyPlus
  - Proposed DCV sequences include limits to protect against impacts of sensor error (e.g. Vot<=design Vot)
Sensor Error Analysis - Preliminary Results (2)

Sensor Error Impacts on HVAC Energy Consumption

- 10 sensors
  - 3 zone CO₂ sensors
  - 2 AHU supply air CO₂ sensors
  - 2 AHU outside air flow sensors
  - 3 zone supply air flow sensors

- AHU1 OA flow sensor has the largest impact on HVAC energy consumption
- AHU2 OA flow sensor has the second largest impact
- Zone CO₂ sensors and AHU supply air CO₂ sensors have smaller impacts
Sensor Error Impacts on Ventilation Performance

- CO₂ sensor accuracy has more influence on the ventilation performance compared with air flow sensor accuracy
- Ongoing study with more building types and more climate zones

- AHU supply air CO₂ sensors have the largest influence on ventilation performance, while other CO₂ sensors at the zone level have relatively large impacts as well
- The impact from flow sensors is relatively small
c. System Level Controlled Lab Testing (1)

- PNNL will host system level controlled lab testing for residential building setting
  - PNNL’s Lab home
  - Two identical 1,500 ft\(^2\) all-electric 3 BR/2BA homes
  - Both homes contain full end-use metering, a suite of environmental sensors, and remote data collection
c. System Level Controlled Lab Testing (2)

- Well Living Lab (WLL) - the first scientific research center exclusively committed for **human-centered** research to understand human-building interactions.
  - State-of-the-art IoT and BMS system and sensor network
  - Comprehensive monitoring for real-time operational and environmental information
  - Enhanced environment and system control capabilities
  - Exceptional reconfigurability, flexibility and adaptability

- WLL will host a system-level controlled lab testing with commercial building settings
  - Configure three modules with office settings to host the dynamic testing for the proposed occupancy-driven HVAC control
### d. System Level Field Trial Testing

- Control logics will follow ASHRAE GPC 36 in at least one commercial building
- Measurement & verification will follow ASHRAE Standards & Guideline (e.g., Guideline 14)

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<tr>
<th>Building</th>
<th>Building Characteristics</th>
<th>Scope of Test Plan</th>
</tr>
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<tbody>
<tr>
<td>Tuscaloosa City Hall Complex, Tuscaloosa, AL</td>
<td>Office building in climate zone 3A; Floor plan: open office with conference room, close offices with conference room; Control: WebCTRL</td>
<td>2nd floor with 27 VAV boxes served by one AHU</td>
</tr>
<tr>
<td>South Engineering Research Center Building, Tuscaloosa, AL</td>
<td>Academic building in climate zone 3A; Floor plan: classroom with office rooms; Control: Schneider Electric</td>
<td>Classrooms and offices served by two AHUs on the 2nd floor</td>
</tr>
<tr>
<td>Marriott Residence Inn on Riverwalk, San Antonio, TX</td>
<td>A hotel building in climate zone 2A; Floor plan: hotel rooms with public space; Control: WebCTRL</td>
<td>Public space with six rooftop units</td>
</tr>
<tr>
<td>Applied Engineering and Technology Building, San Antonio, TX</td>
<td>Academic building in climate zone 2A; Floor plan: classroom with office; Control: Siemens</td>
<td>Ground floor with 20+ mixed class rooms and offices</td>
</tr>
<tr>
<td>2 residential houses in Tuscaloosa, AL</td>
<td>Residential home built in 1970 and 2010 (modern open floor plan)</td>
<td>4 bedroom single family house</td>
</tr>
<tr>
<td>2 residential houses in San Antonio, TX</td>
<td>Residential home built in 1940 and 2000 (modern open floor plan)</td>
<td>3 and 2 bedroom single family house</td>
</tr>
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Ongoing and Future Work: Community Engagement

• Alignment of protocols with market needs
  ➢ Engage with other ARPA-E SENSOR teams and other research teams
  ➢ Identify applicable associations
  ➢ Engage with key stakeholders with competitive landscape & strengths
  ➢ Adapt energy models to include financial considerations

• Codes and standards development plan
  ➢ Sensor and system requirements related to advanced occupancy-based controls
  ➢ ASHRAE standards 90.1, 62.1
  ➢ Start to initiate the new ASHRAE standard/guideline*
  ➢ Organize annual workshop
    ▪ Concurrent with ASHRAE annual meeting in Kansas City (June 2018)*

• Project industry advisory board
  ➢ Siemens, UTC/ALC, JCI...
  ➢ PNNL, ORNL...
  ➢ Recruit more members

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