Hierarchical Occupancy-Responsive Model Predictive Control (MPC) at Room, Building and Campus Levels

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Project Summary

**Timeline:**
Start date: 4/1/2016
Planned end date: 3/31/2021

**Key Milestones**
1. MPC software MPCPy v0.1 released (FY17Q4)
2. Completing the building level MPC field test (FY19Q2)
3. Occupant module developed and integrated (FY18Q1)

**Budget:**

**Total Project $ to Date:**
- DOE: $890k
- Cost Share: $3,062k

**Total Project $:**
- DOE: $2,390k
- Cost Share: $4,490k

**Key Partners:**

<table>
<thead>
<tr>
<th>U.S.</th>
<th>China</th>
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<tr>
<td>Johnson Controls</td>
<td>Tsinghua University</td>
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<tr>
<td>Disney</td>
<td>China Academic of Building Research</td>
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<tr>
<td>United Technologies</td>
<td>Ministry of Housing &amp; Urban-Rural Development</td>
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<tr>
<td>Lutron</td>
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<td>Lend Lease</td>
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**Project Outcome:**
- Develop and demonstrate cost-effective occupancy-responsive building and district scale MPC
- Develop and open-source MPC software to spur innovation and promote further exploration through additional research, field testing and industry adoption
- Support BTO Goals for Occupant-Centric Sensors and Controls
## Team

### U.S. Researchers

<table>
<thead>
<tr>
<th>Name, Affiliation</th>
<th>Roles &amp; Responsibilities</th>
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</thead>
<tbody>
<tr>
<td>Mary Ann Piette, LBNL</td>
<td>PI</td>
</tr>
<tr>
<td>Tianzhen Hong, LBNL</td>
<td>Co-PI and Occupant Module Lead</td>
</tr>
<tr>
<td>Michael Wetter, LBNL</td>
<td>MPC Task Lead</td>
</tr>
<tr>
<td>David Blum, LBNL</td>
<td>MPC Researcher</td>
</tr>
<tr>
<td>Baptiste Ravache, LBNL</td>
<td>Occupant Module Researcher</td>
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### U.S. Industry Partners

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<thead>
<tr>
<th>Name, Affiliation</th>
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<tbody>
<tr>
<td>Clay Nesler, JCI</td>
<td>Industry Lead</td>
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<tr>
<td>Robert D. Turney, JCI</td>
<td>Lead Researcher at JCI</td>
</tr>
<tr>
<td>Bruce Rauhe, Disney</td>
<td>Industry Co-Lead and Campus Demonstration</td>
</tr>
<tr>
<td>Jinlei Ding, UTC</td>
<td>Lead Researcher at UTC on Commissioning and MPC demo in China</td>
</tr>
<tr>
<td>Joe Qiao, Lend Lease</td>
<td>Researchers at Lend Lease and Commissioning Task</td>
</tr>
<tr>
<td>David Nieh, Lend Lease</td>
<td></td>
</tr>
<tr>
<td>Robert Nachtrieb, Lutron</td>
<td>Lead Researcher at Lutron</td>
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</table>
### Team

#### China Researchers

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<thead>
<tr>
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<tbody>
<tr>
<td>Wei Xu, Director, CABR</td>
<td>PI</td>
</tr>
<tr>
<td>Da Yan, Tsinghua University</td>
<td>Lead Researcher at Tsinghua and Occupant Module</td>
</tr>
<tr>
<td>Shicong Zhang, CABR</td>
<td>Joint Research on Demonstration Sites, Model Identification to Aid Continuous Commissioning</td>
</tr>
<tr>
<td>Liu Haizhu / Zeng Di, MoHURD</td>
<td>Data Mining for Commissioning</td>
</tr>
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</table>
Problem Statement:
Conventional building control systems unable to meet future building system requirements effectively:
- Energy cost reduction
- Electric grid integration
- Fault detection and diagnosis
- Occupant-responsiveness

Key MPC Advantages
- Consider future disturbances and incentives
- Coordinate multiple systems
- Occupant integration

Key MPC Challenges
- Model development and calibration
- Optimization formulation
- Building installation
- Lack of common framework
Approach

Technical Approach:
- **Develop** - hierarchical, occupancy-responsive model predictive control software (MPC) framework
- **Demonstrate** - multiple buildings sites, showcase robustness and verify performance improvements
- **Distribute** - open-source for industry adoption and research collaboration

Key Issues:
- Data and control requirements
- Model structure and calibration algorithms
- Optimization algorithms
- Occupant integration
- Ease of use and robustness
Distinctive Characteristics

• Developed in this project
  – Data-driven model identification reduces model setup, calibration, and maintenance effort.
  – Hierarchical MPC enables occupant input and feedback at different levels.
  – Occupant integration detects occupant presence and count (Jia and Spanos 2017).

• Leveraging other projects
  – Predict behavior (IEA EBC Annex 66)
  – Open-source software standards facilitate collaboration, scaling, robust API, ecosystem of tools and vendors, and longevity.
Approach

Target Market and Audience:

- Target commercial building HVAC and lighting end uses
- Enable startup and major control companies to enter this new market segment in both the U.S. and China.
- Strong U.S. and China industry consortium with key players of JCI, UTC, Disney, Lutron, and Lend Lease.
Impact

Energy and Other Impacts:

• **Potential Savings**
  – ~20% HVAC from MPC (Zakula et al. 2014)
  – Overall ~1.9 Quad in U.S. and 1.0 Quad in China
  – 30% commercial building energy for occupant-integrated controls (Dong and Lam 2014).
  – $6B per year in US if all commercial buildings
  – Contribute to BTO’s 30% EUI savings by 2030

• **Grid Integration Benefits**
  – Renewable integration through load shifting and shedding
  – Reduce risk of blackouts to avoid estimated costs of $16 - 22 billion, and an anticipated loss of 136,000 jobs just in California (National Energy Policy 2001)

• **Accelerate MPC Technology Adoption**
  – Application of efficient optimization algorithms to reduce computation time
  – Test effectiveness of model learning techniques to reduce setup time
  – Study of how model accuracy affects energy savings and performance
  – Documented software using open-source standards
Impact

Global Impacts:

• Optimize building operations in U.S. and China to reduce energy use and environmental impact
• Provide software platform to test, evaluate, and scale MPC technologies by researchers and industry
• Establish a strong foundation for future international collaborations on MPC and other advanced building technologies
Progress

Software Development

MPCPy v0.1: Open-Source Platform For MPC in Buildings

- Exogenous data collection
- Building system emulation or data collection
- Adaptive model learning
- Control optimization
- Continuous maintenance and development

Occupancy Modeling and Prediction

- Statistical “queueing” approach (Jia and Spanos 2017)
- Predicts occupant count
- Applicable to room and building scales
- Integrated into MPCPy

obModelica: Modelica Library of Occupant Behavior models

- Window opening and closing
- Thermostat interaction
- Blind and light operation
- Integration underway into Modelica Buildings Library

https://github.com/lbl-srg/MPCPy
(Blum and Wetter 2017)

https://jmodelica.org

Occupancy Prediction [#]

Internal Load Prediction [W]
Progress

Field Test of MPC at Room and Building Levels at LBNL Building 59

Building Description
• Computational Research Facility
• 2 Office Floors of ~ 50,000 sf
• UFAD w/ Reheat, 4 Water-Cooled DX RTUs

Timeline
• MPC test started in April 2018 and to complete in March 2019

Data (~420 Points)

HVAC Perimeter Zone
• Temp
• RH valve position
• TU fan speed

Electric and Lighting
• Plug panels for north/south wings
• HVAC panels for RTUs
• Lighting energy for zones

Added Sensing
• Temp for core zones
• Image-based occupancy sensors for south wing
Field Test of MPC at the Room and Building Levels at LBNL B59

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Abatement</th>
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<tbody>
<tr>
<td><strong>System and Modeling</strong></td>
<td>• Careful model formulation (zoning and HVAC)</td>
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<td>• UFAD system design</td>
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<td>• Undersized heating system</td>
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<tr>
<td>• Model size for learning and control</td>
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<tr>
<td>optimization</td>
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<tr>
<td><strong>Data</strong></td>
<td>• Data filtering and cleaning algorithms</td>
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<td>• Useful data points missing</td>
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<tr>
<td>• Data quality and gaps</td>
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<tr>
<td><strong>BMS Integration and IT</strong></td>
<td>• MPC suggests new setpoints for BMS, not directly control HVAC actuators</td>
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<td>• Failure of MPC should not lead to</td>
<td>• MPC on separate server from BMS</td>
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<tr>
<td>failure of BMS</td>
<td>• Ensure separation of control between office and HPC HVAC</td>
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<tr>
<td>• MPC should not affect control of</td>
<td>• Work with LBNL IT on cybersecurity</td>
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<tr>
<td>High Performance Computer</td>
<td></td>
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<tr>
<td>• Cybersecurity</td>
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<tr>
<td><strong>Occupant Comfort</strong></td>
<td>• Report discomfort to facility manager or via a short survey</td>
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<td>• Optimization of room air temperature</td>
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<td>setpoint within an acceptable range</td>
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<td>(ASHRAE Std 55)</td>
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Progress

Field Test of MPC at Room and Building Levels at LBNL Building 59

Modeling

Zone Grouping
(similar on each floor)

Building Level Model
for Control Optimization

Zone Level Model
and Adaptive Learning

Zone Temperature (ºC)

Learn RMSE: 0.20 C
Valid RMSE: 0.22 C

Initial Guess
Measured
After Learning
Validation
Progress

Field Test of MPC at the Room and Building Levels at LBNL B59

Findings

- Modeling and model training approach is promising, needs further testing on all zones
- Continuity of data is a challenge for model training and will be for control
Collaboration and Coordination

• Johnson Controls
  o Opened its LEED, EDGE and Three-Star certified Shanghai HQ building in June, 2017.
  o Building will deploy model-based commissioning and M&V of MPC benefit.

• Disney
  o Engaged in discussions for campus site demonstration

• LBNL
  o Develop commercialization plan through collaboration with industry partners and LBNL IPO office
  o Actively engage LBNL CSO, IT staff, B59 managers and occupants on the field tests and occupant surveys

• Research community / public
  o Conduct public webinars to announce and demonstrate MPCpy software
  o Present at conferences (e.g. ASHRAE, ACEEE and IBPSA) and publish journal articles
Collaboration and Coordination

- Collaboration with China team
  - Jointly developed the research plan
  - Joint activities on model-based commissioning and occupant module
  - Parallel MPC field tests
  - 1 joint technical workshop and three meetings in 2017 and 2018
  - Tsinghua researchers/students exchanged to LBNL
  - Joint research and planned joint IP on building electric load prediction
Remaining Project Work

Task 3 – Field Test Building-Level MPC and Prepare for Campus-Level MPC
- Integration of occupant module into MPC at building level
- Finish modeling and develop control optimization
- Field test the building-level MPC
- Development of campus-level MPC
- Occupant module development at the campus level
- Campus-level MPC field test preparation

Task 4 - Demonstration of the MPC at the campus level
- Integrate occupant module and MPC at campus level
- Test through simulation
- Verify through full-scale field test at a Disney campus
Remaining Project Work

Task 5 - Commissioning of MPC technology and the CERC demonstration buildings

- Develop MPC commissioning guide to detail data, procedures, and tools used to commission MPC at room, building, and campus levels.

Task 6 - Commercialization and dissemination

- Develop commercialization plan through collaboration with industry partners and LBNL IPO office
- (2) workshops to market the occupancy responsive MPC technology to industry leaders for technology transfer and adoption,
- (5) presentations in national conferences, e.g. ASHRAE, ACEEE and IBPSA and (5) publication of peer-review journal articles
- Dedicated project web site to detail MPC technology, potential energy savings and other benefits, and
- 1 or several open-source software repositories on github.com to host open-source code.
Thank You

LBNL
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REFERENCE SLIDES
Project Budget

Project Budget: $430k (Year 1), $460k (Year 2)
Variance: Site for building-level field test changed to LBNL Building 59
Cost to Date: $460k (Year 2)
Additional Funding: NA

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<tr>
<td>DOE</td>
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<tr>
<td>Cost-share</td>
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<td>Cost-share $1,531k</td>
<td>Cost-share $660k</td>
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</table>
References

- **IEA, 2012, EBC Annex 60, iea-annex60.org**
- **LBNL, behavior.lbl.gov.**