BEARS | SinBerBEST

Development of Building Automation and Control (BAC) Systems - Modelling and Controller Design

Mehdi Maasoumy and Alberto Sangiovanni-Vincentelli
University of California at Berkeley

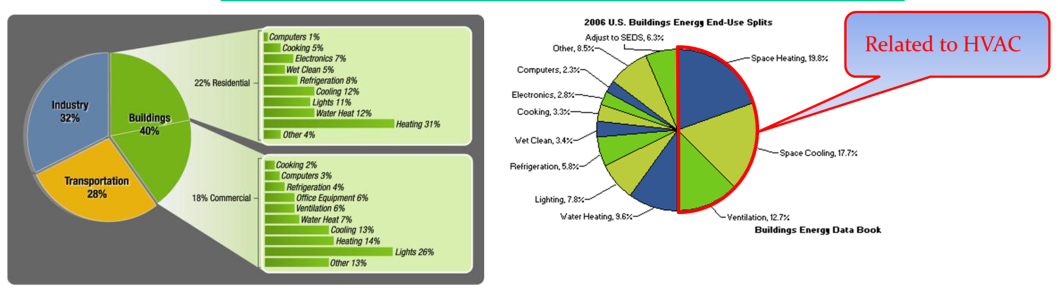
Supported by:

Funded by:
National Research Foundation

Motivation

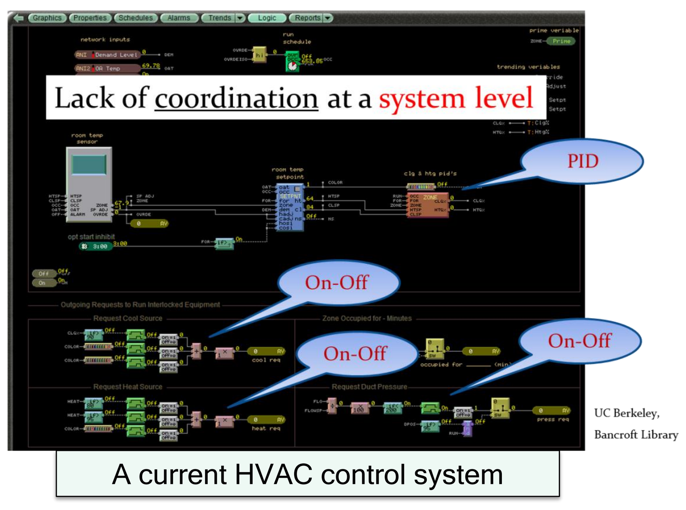
Buildings are the dominant consumers of energy with 40% of total energy consumption. About 50% of the energy consumed in buildings is directly related *to space heating, cooling and ventilation*. Therefore, reducing the energy consumption of buildings by designing smart control systems to operate the Heating, Ventilation and Air Conditioning (HVAC) system in a more efficient way is critically important to address energy security and environmental concerns in the United States and worldwide.
However the control logic governing today's buildings uses simple control schemes dealing with one subsystem at a time. This can lead to scenarios such as simultaneous heating and cooling which deteriorates the overall efficiency of the system.

Total US energy consumption for buildings: 40%
Total US electricity consumption for buildings: 72%
Total US natural gas consumption for buildings: 55%



2012 Main Objectives

Statistically, 1/3 of buildings are constantly unoccupied, but fresh air supplies are provided almost permanently in buildings, and air conditioning systems do not take this into account… Control logic governing today's buildings uses simple control schemes dealing with one subsystem at a time…



A current HVAC control system

The Problem

- Modeling *thermal dynamics* of buildings
- Calibrating the model with *historical data*
- Validating the model with a *different set of data*
- Design the *control architecture* for the whole system
- Design *optimal control* which maintains the temperature within the *desired bounds* using *minimum* amount of energy

The objective is to:

Design a controller that takes into account:

- Outdoor weather conditions
- Internal heat gains
- Indoor air quality
- Cooling demands
- HVAC process components

Thermal characteristics of building components

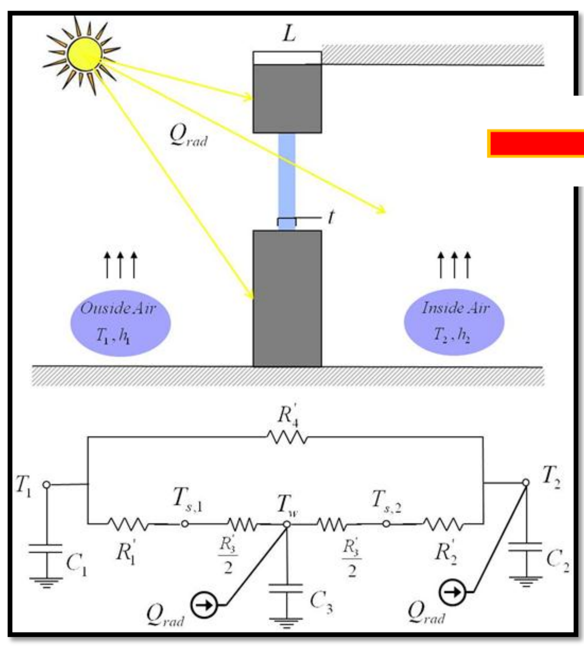
- Thermal properties of building elements:
- Heat storage in capacitors (nodes):

$$C = mc_p$$

- Heat transmission through resistors (links):

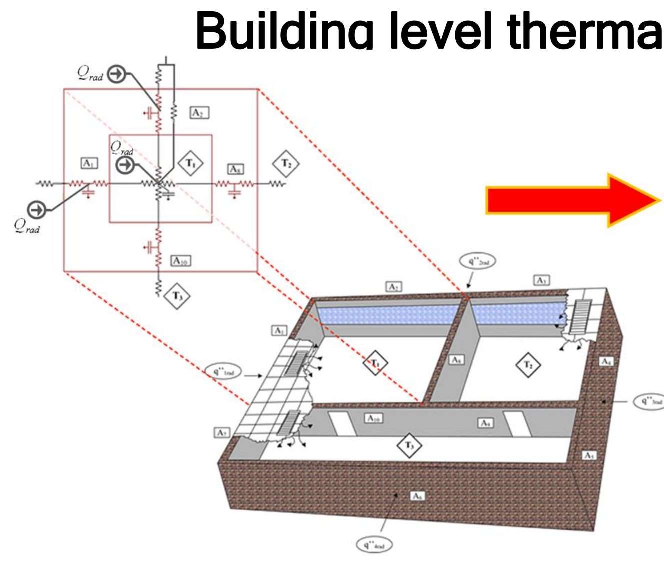
$$R'_{cond} = \frac{T_{s,1}-T_{s,2}}{Q} = \frac{L}{kA}$$

$$R'_{conv} = \frac{T_s-T_\infty}{Q} = \frac{1}{hA}$$



More details can be found in [4,5]

Building level thermal circuit



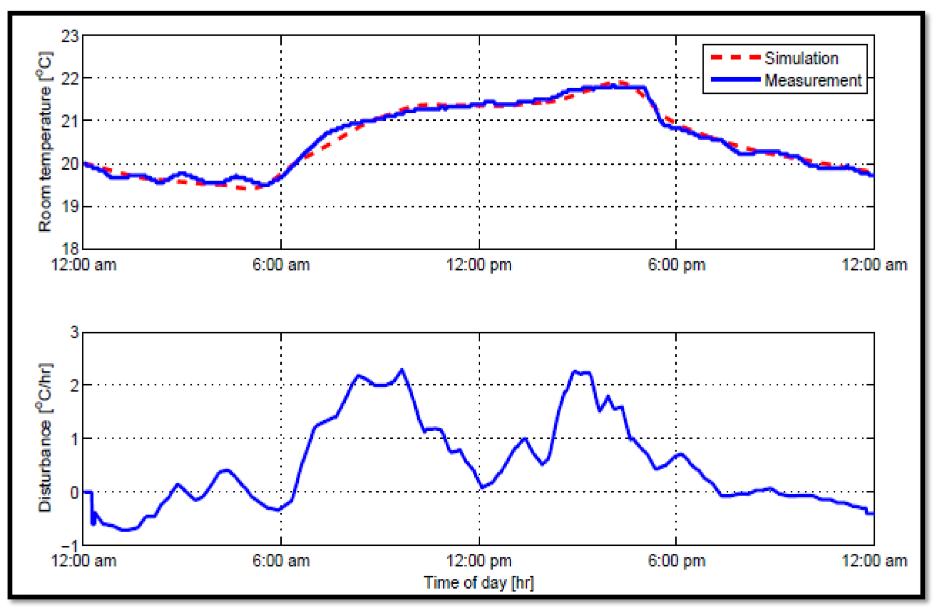
$$\dot{x}(t) = Ax(t) + Bu(t) + d(t)$$
$$y(t) = Cx(t)$$

State vector: $x(k) = [T_{w_1}(k)\ \cdots\ T_{w_p}(k)\ T_{r_1}(k)\ \cdots\ T_{r_m}(k)]$ — Temperature of rooms

Input vector: $u(k) = [\dot{m}_1(k)\ \cdots\ \dot{m}_m(k)]$ — Airflow input to rooms

Disturbance vector: $d(k)$ — Unmodeled dynamics to be estimated

Model Calibration Process



More details can be found in [2]

Min-Max Strategy for Robust MPC

$$J_0(x(t),U_t) \triangleq \max_{w_{[\cdot]}} \{\sum_{k=0}^{N-1} |u_{t+k|t}| + \kappa \max(|u_{t|t}|,\cdots,|u_{t+N-1|t}|) + \rho\sum_{k=1}^{N}(|\overline{\varepsilon}_{t+k|t}| + |\underline{\varepsilon}_{t+k|t}|)\}$$

$$\text{s.t.}\quad x_{t+k+1|t} = Ax_{t+k|t} + Bu_{t+k|t} + Ed_{t+k|t} + Fw_{t+k|t},\quad w_{t+k|t} \in \mathbb{W},\quad k = 0,\cdots,N-1$$

worst-case objective is calculated.

Robust counterpart of an uncertain optimization problem

$$J_0^*(x(t)) \triangleq \min_{U_t} \quad J_0(x(t),U_t)$$

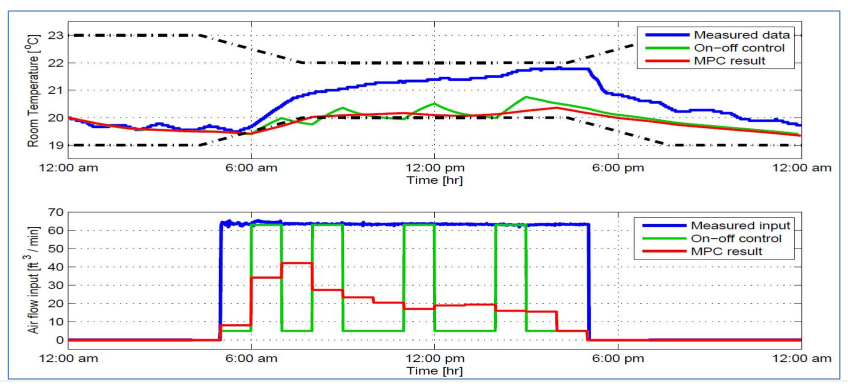
subject to

$$x_{t+k+1|t} = Ax_{t+k|t} + Bu_{t+k|t} + Ed_{t+k|t} + Fw_{t+k|t}$$
$$y_{t+k|t} = Cx_{t+k|t}$$
$$\underline{T}_{t+k|t} - \underline{\varepsilon}_{t+k|t} \le y_{t+k|t} \le \overline{T}_{t+k|t} + \overline{\varepsilon}_{t+k|t}$$
$$\underline{\varepsilon}_{t+k|t}, \overline{\varepsilon}_{t+k|t} \ge 0$$
$$\forall \quad w_{t+k|t} \in \mathbb{W} \qquad \forall \quad k = 0,\cdots,N-1$$

optimize the **worst-case** scenario cost function with respect to uncertainties

More details can be found in [3]

MPC Simulation Results

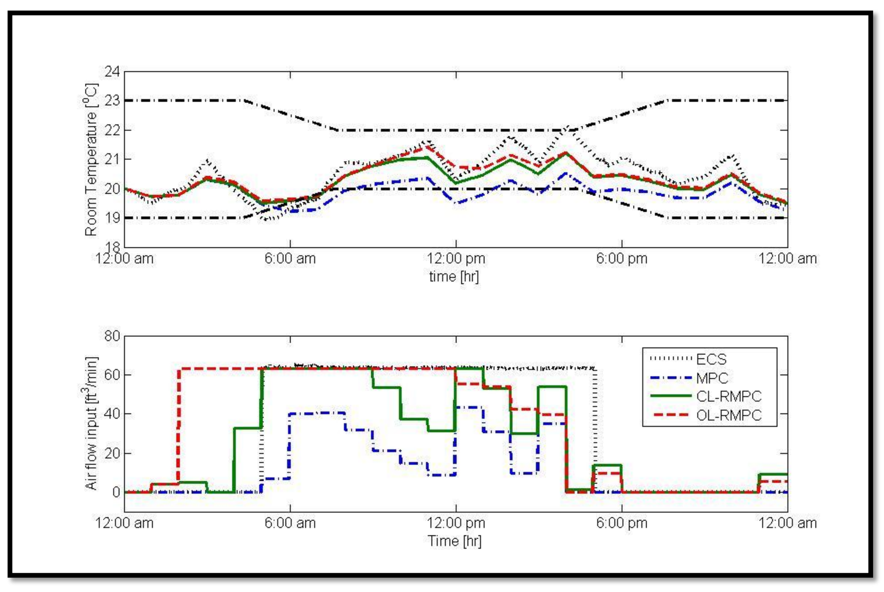


Controller	Total input $[ft^3]$	Peak input $[ft^3/min]$	Total energy $[kWh]$	Running time $[s]$
Original control	45360	63	12.46	-
On-off control	17520	63	4.62	1.8
MPC	14870	42	3.33	102.4

Reductions: Total input 68% (original → MPC), 66% (original → on-off); Peak input 35%; Total energy 73%.

Comparison of on-off control with MPC

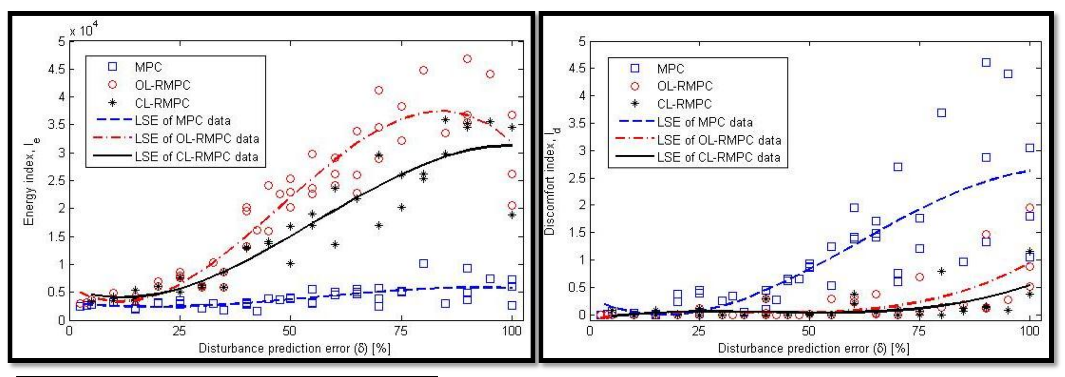
MPC vs. Robust MPC



Comparison of Existing Control System (ECS), Model Predictive Control (MPC), Open Loop Robust MPC (OL-RMPC) and Closed Loop Robust MPC (CL-RMPC)

More details can be found in [3]

RMPC: Energy vs. Comfort



$$P_c(t) = \dot{m}_c(t)c_p[T_{out}(t) - T_c(t)]$$
$$P_h(t) = \dot{m}_h(t)c_p[T_h(t) - T_{out}(t)]$$
$$P_f(t) = \alpha\dot{m}^3(t)$$

$$I_D = \int_{t=0}^{24} \left[\min\left\{\left|T(t)-\overline{T}(t)\right|, \left|T(t)-\underline{T}(t)\right|\right\} . \mathbf{1}_{\mathcal{B}(t)^c}(T(t))\right] dt$$

$$I_E = \int_{t=0}^{24} [P_c(t) + P_h(t) + P_f(t)]\, dt$$

Energy index and Discomfort index vs. uncertainty bound

Conclusion

- **Presented** thermal modeling of the building and **Calibrated** the model using historical data
- **Proposed** a methodology to estimate the unmodeled dynamics of the system
- **Designed MPC** strategy without consideration of uncertainty
- **Showed** 73% less energy consumption compared to the original controller on the building, by reducing total and peak airflow into the room.
- **Designed MPC** strategy that is **robust** against additive uncertainty.
- **Evaluated** the performance of two robust optimal control strategies,
- i.e. OL-RMPC & CL-RMPC.
- **Proposed** a new uncertainty feedback parameterization for the CL-RMPC which results in Same energy and discomfort indices as previous parameterizations with fewer decision variables, linear in N, as opposed to quadratic, With average simulation time of 30% less.

References:

1) Mehdi Maasoumy, Alberto Sangiovanni-Vincentelli, "Total and peak energy consumption minimization of HVAC systems using model predictive control." IEEE design and test, special issue on green buildings. June 2012.

2) Yang Yang, Qi Zhu, Mehdi Maasoumy, Alberto Sangiovanni-Vincentelli, "Development of Building automation and control systems." IEEE design and test, special issue on green buildings. June 2012.

3) Mehdi Maasoumy, Alberto Sangiovanni-Vincentelli, "Optimal control of HVAC system in the presence of imperfect predictions." ", Dynamic System Control Conference, Fort Lauderdale, FL, Oct. 2012.

4) Mehdi Maasoumy, Alessandro Pinto, Alberto Sangiovanni-Vincentelli, "Model-based Hierarchical Optimal Control Design for HVAC Systems", Dynamic System Control Conference, Oct31-Nov2, 2011, Arlington, VA, USA

5) Mehdi Maasoumy, Alberto Sangiovanni-Vincentelli, "Building Operating Platform Design for High Performance Zero-Energy Buildings", Master's Thesis, University of California, Berkeley. May 2010.

Future Goals

- Co-design of *Controller* and *embedded platform* for HVAC systems
  - *Sensing error modeling*
    Relation between the sensing errors and the number and locations of temperature and CO2 sensors using:
    1) computational fluid dynamics (CFD)
    2) real sensor readings from test-beds.
  - *Co-design Formulation*
    Optimal design of controller having in mind the computation and communication limitations of the embedded platform.