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# Co-design of Control Algorithm and Embedded Platform for HVAC Systems

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## Motivation

Smart buildings today have sophisticated and distributed control systems, as part of the **Building Automation Systems (BAS)**. The task of the control system is to maintain the building climate within a specified range, control the lighting based on the occupancy schedule, and monitor the system performance and failures. To accomplish this, the BAS has to deal with computational and communication issues in the large networks in buildings. Hence, having newly introduced computational and communication sides on top of their physical elements, new smart buildings are great examples of *cyber-physical systems.*

***Hence, smart buildings need to be designed as a network of interacting elements with physical inputs and outputs instead of as standalone devices.***

## 2012 Main Objectives

The design of HVAC systems involves three main aspects:

- Physical components and environment,
- Control algorithm that determines the system operations based on sensing inputs,
- Embedded platform that implements the control algorithm.

In the **traditional** *top-down approach*, the design of the HVAC control algorithm is done without explicit consideration of the embedded platform.

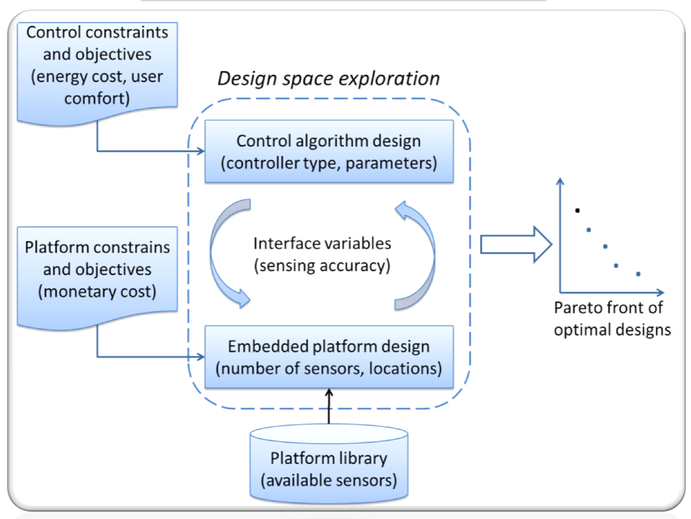
*With the…*

- *employment of more complex HAVC control algorithms for energy efficiency,*
- *use of distributed networked platforms, and*
- *imposing of tighter requirements for user comfort,*

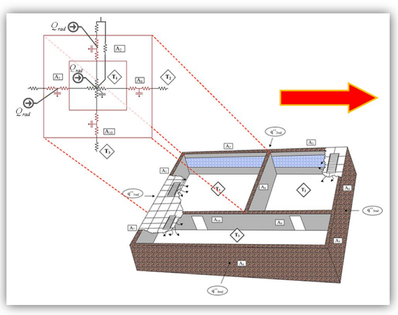
*the assumption that the embedded platform will always be sufficient for any control mechanism is **no longer** true.*

## The Problem

Co-design framework for HVAC systems




## Sensing and Prediction Accuracy Modeling



Sensing uncertainty | Prediction uncertainty

$$x_{k+1} = Ax_k + Bu + E(\tilde{d}_k + w_k)$$
$$z_k = Cx_k + Fv_k$$

The unmodeled dynamics is estimated using the measurable quantities below:

$$\hat{d}_t = aq''_{rad_i}(t) + b\dot{q}_{int}(t) + cT_{out}(t) + e$$
$$= \bar{a}\hat{T}_{out}(t) + \bar{b}\hat{\Psi}(t) + \bar{e}$$

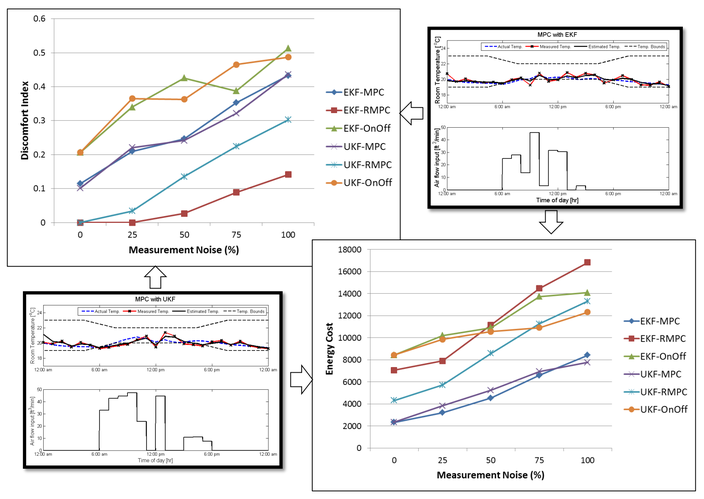
$T_{out}$ : Ambient Temp.
$\Psi$ : $CO_2$ level

Accuracy of forecast of $T_{out}$ and $\Psi$ influences the accuracy of the estimated disturbance

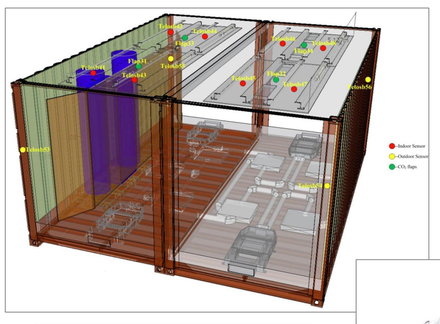
## Control Design with Accuracy Consideration

- **On-Off control** which serves as a baseline to compare the other controllers against.
- **Model Predictive Control** to account for system constraints and optimization of energy consumption.
- **Robust Model Predictive Control** to account for additive (sensing and prediction) uncertainties on top of MPC..
- **Extended Kalman Filter** and **Unscented Kalman Filter** for estimating the unmeasured states and for filtering the measured states.

## Simulation Results




## Sensing System Setup



BubbleZERO Research Setup

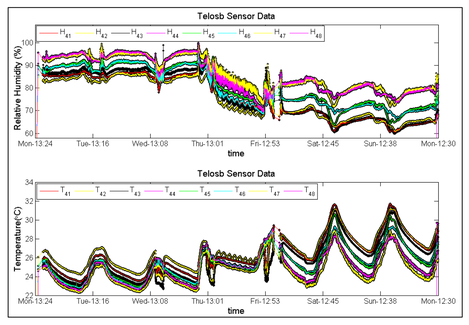
Which is conceived as part of the Low Exergy Module development for Future Cities Laboratory (FCL)

The environment sense system includes:

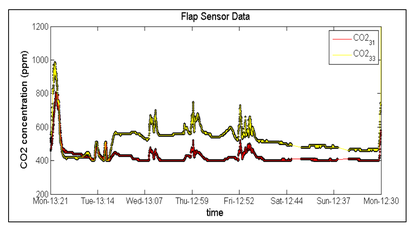
- 8 indoor sensors (Telosb41-48)
- 4 CO2 concentration sensors (flap31-34)
- 4 outdoor sensors (Telosb53-56)

## Sensor Readings from the Setup

Temperature measurements from 8 sensors located spatially at different places in the room for July 16-23 of 2012. The statistics of the sensor measurement error is extracted from this set of data.




CO2 measurements from 2 sensors located spatially at different places in the room for July 16-23 of 2012.

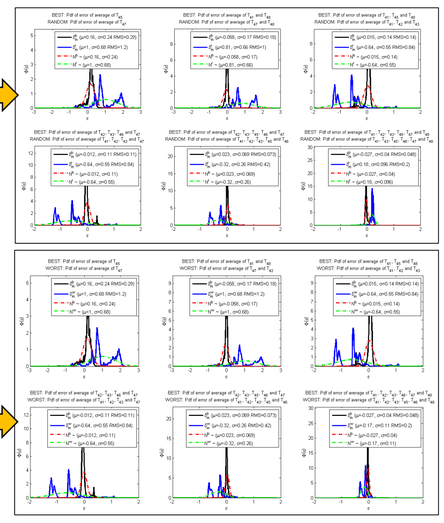



## Inaccuracy Characterizations for sensors

Average error of k sensors for the Minimal error set of sensors and a **random** choose of sensors.

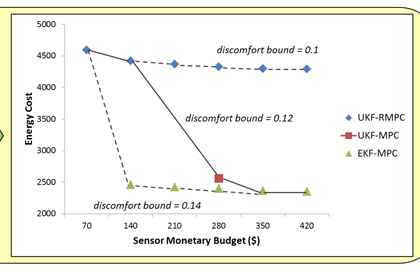
Each figure plots the *pdf* of the difference of the average of k sensor readings with the average of all $n_{ts}$=7 sensor readings. The best, worst and random set of sensors are selected based on their resulting $\Delta_{rms}$ error.

Average error of k sensors for the Minimal error set of sensors and the **worst** choose of sensors.

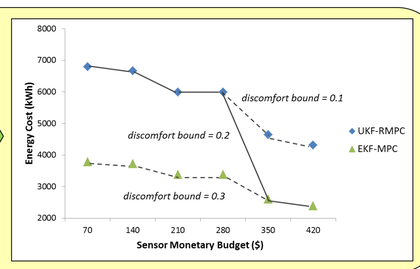


## Pareto Front Under Discomfort Index Contraints

Pareto front under comfort constraints with **random** sensor locations




Pareto front under comfort constraints with **best** sensor locations




## Conclusion and References

- Proposed a co-design framework for HVAC systems that explores the control algorithm design and the sensing platform design together, by analyzing their inter-dependencies through the sensing accuracy.
- Analyzed the relation between sensing accuracy and the number and locations of sensors, based on collected data from a well-instrumented test-bed, BubbleZERO.
- Explore the design space of both control algorithm and sensing platform, and generate Pareto fronts with optimal energy and monetary cost.

**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

- Further study the interdependencies between the HVAC control algorithm and the embedded platform.
- Co-design of *Controller* and *embedded platform* for HVAC systems considering also:
  - ➢the communication channel reliability, and
  - ➢the computing power of embedded processors,
  - ➢And study their impact on the quality and cost of the control algorithms.