Cyber Physical Systems PI Meeting, Spring 2025

CPS Medium: Physics-informed Learning and Control of Passive and Hybrid Conditioning Systems in Buildings

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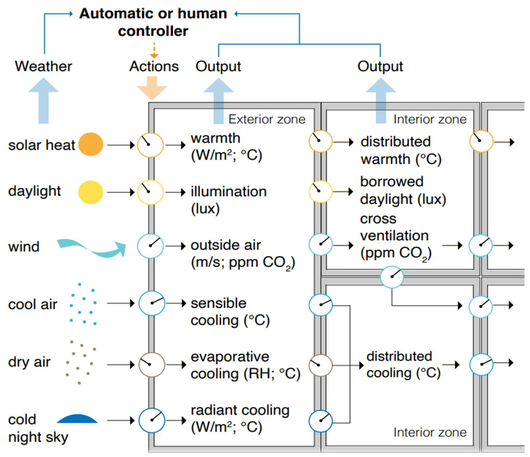
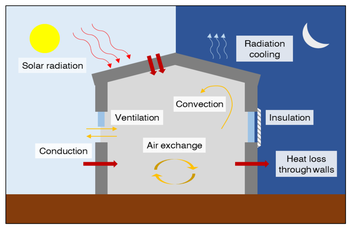
Goal: Design model-based and data-driven strategies for controlling passive and active building conditioning systems





Motivation: Harnessing passive climatic resources for heating and cooling in buildings will provide significant energy savings.

Challenges:

- Passive climatic resources such as available solar radiation, outside air (temperature and quality), etc. are time-varying and unpredictable: system must respond and adapt quickly.
- Control strategies must be climate-specific, portable across building types and layouts, and easily deployable for wide adoption.

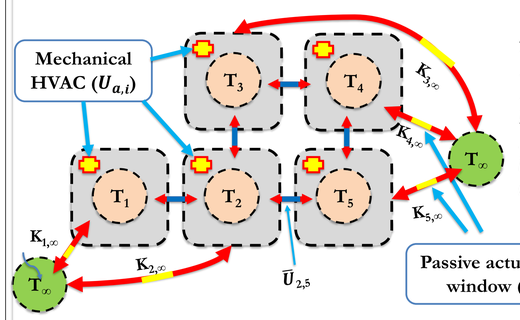
Scientific Impact:

- New modeling paradigm for a broad class of CPS systems with coupled mass and heat transfer using graph-based locally interactive bilinear structure.
- Novel approaches for analysis and design of controllers that exploit this structure.

Broader Impacts:

- Adoption of passive mechanisms for heating, cooling and ventilation: increased energy savings
- Public perceptions about passive strategies influenced through outreach, awareness and education; and dissemination of research findings

Locally-interactive Bilinear Flow(LiBF) Models for Hybrid Conditioning Systems



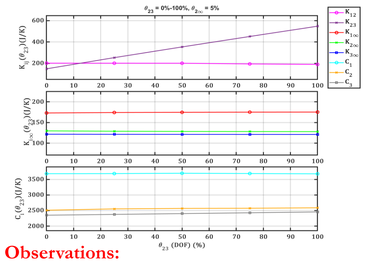
T_∞= Ambient Temperature
T_i =Temp. of i^{th} Zone
N= total number of zones
B_i= Average Transmittance of wall
N_i = neighboring zones for i^{th} zone
$S_{\infty,i}$ = Solar irradiation in Zone i
$\bar{U}_{ij}(\theta_{ij})$ = Thermal interaction.
θ_i = Window Opening fraction

Physics-informed Graph-based Dynamical Model

$$C_i\dot{T}_i = K_i(\theta_i)(T_\infty - T_i) + B_{i\infty}(\theta_i)S_{\infty,i} + U_{a,i} + \sum_{j\in N_i} K_{ij}(\theta_{ij})(T_j - T_i)$$

Validation of LiBF Model

- Validation study on LiBF model structure
- Door and window opening related to thermal conductance between zones (and the ambient)



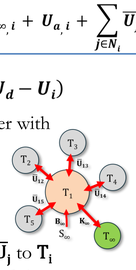
Key Observations:

- LiBF model captures the effect of passive elements.
- Window/door openings only affect local behavior.
- Other thermal parameters mostly unchanged

Decentralized Design for Control of Hybrid Conditioning Systems

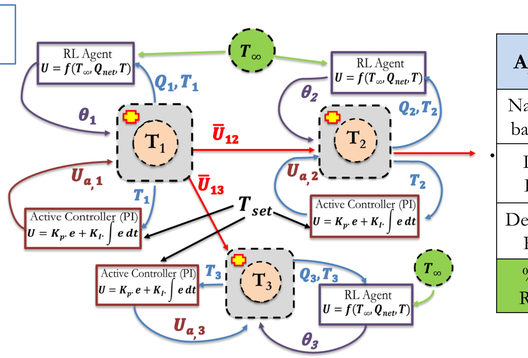
i^{th} zone dynamics: $C_i\dot{T}_i = K_i(T_\infty - T_i) + B_i S_{\infty,i} + U_{a,i} + \sum_{j\in N_i} \bar{U}_j$

- Lyapunov (storage) function for the i^{th} zone
  $V_i = \frac{1}{2}(T_i - T_d)^T C_i (T_i - T_d) + \frac{1}{2}(U_d - U_i)^T . K^{-1}(U_d - U_i)$
- Can be leveraged to design decentralized controller with $V = \sum_{i=1}^{N} V_i$.
- Each zone has:
  - Active HVAC controller (e.g.: PI control)
  - Passive HVAC: Model-free RL agent
- With this setup, the model is passive from $\sum_{j\in Ni} \bar{U}_j$ to T_i

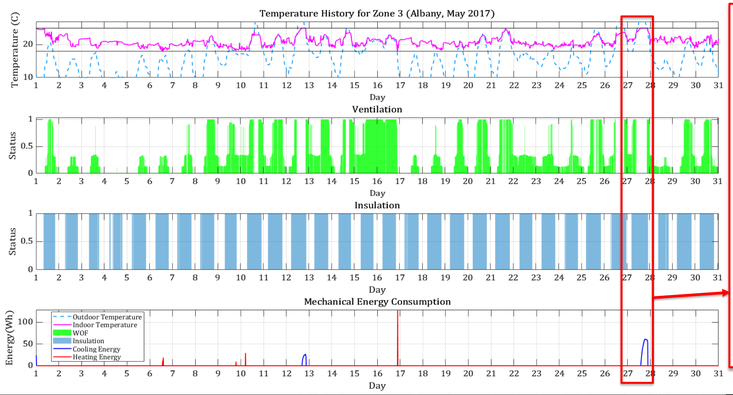


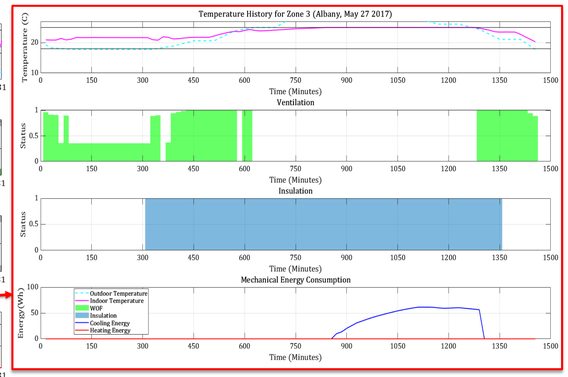
Overall zone dynamics with the graph-model:

$$C_i\dot{T}_i = K_i(\theta_i)(T_\infty - T_i) + B_i S_{\infty,i} + U_{a,i} + \sum_{i=1}^{N}\sum_{j\in N_i} \bar{U}_{ij}(\theta_{ij})$$



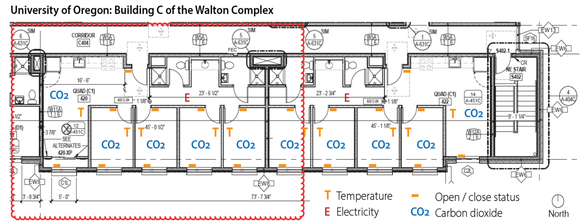
Approach	Energy
Naïve Temp-based action	1061 MJ
Imitation Learning	110.95 MJ
Decentralized RL agent	53.90 MJ
%Energy Reduction	94.9%



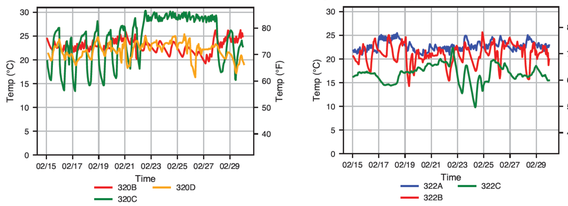


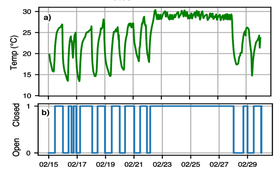
Validation Testbed (at Univ. of Oregon)

Fully instrumented building with a digital twin (calibrated Energy Plus model) for modeling/control design, energy savings, and occupant response: data collection started



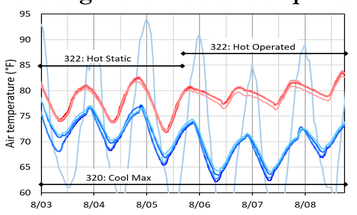
Heating Performance (W24): Suite 320 occupants preferred warmer temperatures. Bedroom air temperatures maintained in (a) Suite 320 showed higher maximum temperatures than in (b) Suite 322, indicating higher thermostat set-points in the former; additionally, the sizable temperature swings in 320C, 322B, and 322C indicated the use of cooler outdoor air to adjust room temperatures (graphs below).





Observation: Occupants frequently opened windows to avoid over-heating. (See Fig left). open positions corresponded to temperature lows.

Passive Cooling Performance Comparison (S24):



. **(a) Cool Max**:, Windows, and interior doors closed during the day and opened at night; box fans assisted ventilation at night. **(b) Hot Static** with windows always open; blinds always half closed; interior doors always closed; and fans on during the warmest hours **(c) Hot Operated:** counterproductive occupant behavior, with blinds open during the day & closed at night; windows open during the day for breeze and closed at night for security; interior doors always closed; and fans on during the warmest hours .

Award ID#: 2241795, 2241796