Multi-Scale Thermal Control and Optimization Problems in Data Centers

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Sustainable IT Ecosystem

Data Centers at the Core
for management of resources at community scale
Outline

• Cooling infrastructure in data centers
  – Cooling generation/delivery/distribution/consumption

• Cooling delivery and distribution
  – Zonal cooling control in data center level
  – Local cooling control through Adaptive Vent Tile
  – Integrated local and zonal cooling control

• Cooling demand management

• End-to-end optimization

• Challenges and opportunities
Data Center Infrastructures
Resource supply and demand

Operational Envelopes
These zones show acceptable temperature and humidity combinations for IT inlet air.

ASHRAE Recommended
ASHRAE Allowable
ASHRAE 3B-35/10

Credit: ASHARE
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Data Center Cooling Delivery and Distribution

Cold and Hot

Ref: Chandrakant D. Patel, Cullen E. Bash, Ratnesh Sharma, Smart Cooling of Data Centers, in ASME 2003 International Electronic Packaging Technical Conference and Exhibition (InterPACK2003), July 6–11, 2003, Maui, Hawaii, USA
Data Center Cooling Delivery and Distribution

Conventional Room Control

- Conventional control
  - a carry over from room level comfort cooling,
  - regulates the return air temperature to a given setpoint
  - Fans are typically fixed speed running continuously at 100%
  - Individual Air Handlers are self controlled and not coordinated
  - results in very cold air being supplied to the room ~ 12°C / 55°F on average due to mixing in the room.
Data Center Cooling Delivery and Distribution

Dynamic Zonal Cooling Control

- Dynamic Zonal Cooling
  - regulates cooling on the supply side of the air handlers.
  - supply air cooling is regulated by sensing temperature at the intake of equipment racks
  - Fans use variable speed control
  - results in a much higher supply air temperature ~ 68-72°F, a much higher return air temperature ~ 85-95°F.


Data Center Cooling Delivery and Distribution

Challenges

- IT workload distribution
- Time-varying cooling demand
  - Heterogeneity of the servers/Workloads
  - Time varying workload
- Location dependent cooling efficiency
- Re-circulation and reversed flows exist.
- Sharing the cooling capacity through the floor plenum and the open space above the floor
Data Center Cooling Delivery and Distribution

Zonal Effects of the CRAC units

Regions of Influence

Data Center Room

Thermal Correlation Index:

\[ TCI(CRAC_i, \text{Temp}_j) = \frac{\Delta\text{Temp}_j}{\Delta\text{CRAC}_i} \]

Data Center Cooling Delivery and Distribution

Coordinated CRAC Control

HP Labs Data Centre, Palo Alto, CA

Conventional Mode

Dynamic Smart Cooling Mode

35% Energy Savings
Improved reliability


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Data Center Cooling Delivery and Distribution

Localized cooling distribution through Adaptive Vent Tile

Adaptive MPC AVT control driven by Inlet temperatures

\[ \min J(V) = \sum_{i=1}^{N} \left( (h_{i} + V) - T_{i} \right)^{2} + \sum_{i=1}^{M} \left( (h_{i} + V) - T_{i} \right)^{2} \]

\[ T(k+i) = A T(k+i-1) + B V(k+i) \]

\[ T(k+i) \leq T_{\text{ref}}, i = 1, 2, \ldots, \text{hp} \]

\[ V(k+i) \leq V_{i}, i = 0, 1, \ldots, h_{u} - 1 \]

\[ V(k+i) \geq V_{i}, i = 0, 1, \ldots, h_{u} - 1 \]

Ref: Zhikui Wang etc., KRATOS: automated management of cooling capacity in data centers with adaptive vent tiles, IMECE2009, November 13-19, Lake Buena Vista, Florida, USA
Data Center Cooling Delivery and Distribution

Demo: Adaptive MPC AVT control driven by Inlet temperatures

Before Control

After Control

Temperatures (°C)

Tile Openings (%)

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By maintaining a constant pressure drop across the tiles, the flow rate becomes proportional to its opening

\[ \Delta P = 1.35 \rho \frac{V^2}{A^2} \]

Experiments show temperate behavior can be approximated using first order models, and a model with diagonal matrix \( A \) is sufficient for prediction.

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- 17 equipment racks (Fx, Gx)
- 20 adaptive vent tiles (VFx, VGx)
- 2 CRAC/CRAHs
- Differential pressure sensing at above (A) and below (B) the floor
- Supply air temperature from CRAC/CRAH fixed

\[ fit = 100 \left(1 - \frac{\text{norm}(T_1 - T_2)}{\text{norm}(T_1 - \text{mean}(T_1))}\right) \]
Data Center Cooling Delivery and Distribution

Integrated air flow control

(a) Intake temperature
(b) Mean of Tile Openings
(c) VFD Setting
(d) Power by blowers

Data Center Cooling Delivery and Distribution

Model based Predictive Control

\[ \text{Min} \, J(U) = \sum_{i=0}^{nu} \left( \frac{\|VFD(i+k)\|^2}{U_{\text{VFD}}} + (C - SAT(k+i))k_{S\text{AT}} + \frac{\|VFD(i+k) - VFD(i+k-1)\|^2}{U_{\text{VFD}}} \right) \]

subject to:

\[ T(k+1) = AT(k) + d \cdot VFD \cdot (SAT - T) \sum_{N\text{tile}} b_{\text{tile}} U_{\text{tile}} + C_k \]

holistic model

\[ T(k+i) \leq T_{\text{ref}}, \, i = 1, 2, ..., hu \]

\[ U_{\text{tile}} \leq U_{\text{tile}}(k+i) \leq \overline{U}_{\text{tile}}, \, i = 0, 1, ..., hu - 1 \]

50% < VFD(k+i) ≤ 90%, i = 0, 1, ..., hu - 1

constraints

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  – Thermal-aware workload/power management

• End-to-end optimization

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Cooling Demand Management

Cooling aware workload and power management

Local Workload Placement Index:

\[ (T_{ref} - T_{inlet}) + \sum_j (SAT_j - SAT_{min}) YCL_j - (T_{inlet} - T_{vent}) \]

Thermal Management Margin
Air Condition Margin
Hot Air Recirculation


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Cooling Demand Management

Cooling aware workload and power management

Anticipated savings per year (2MW data center)

<table>
<thead>
<tr>
<th>Energy</th>
<th>Costs</th>
<th>CO2</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.9GWh</td>
<td>$492,000</td>
<td>2915 tons</td>
<td>4,700,000 Gallons</td>
</tr>
</tbody>
</table>

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• **End-to-end optimization**
• Challenges and opportunities

**End-to-End Optimization**

**supply and demand management**
End-to-end Optimization

New metric: COPg

Typical Efficiency Metric: Power Usage Effectiveness, PUE:

Total Data Center Power
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IT Equipment Power

Metric of Evaluation: 'Grand' Coefficient of Performance, COPg:

(IT Workload Power – IT Overhead)

(IT Overhead + Facility Overhead Power)

IT Overhead= IT Idle Power + IT Fans + Leakage

End-to-end Optimization

Multi-scale energy modeling

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Ref: Thomas J. Breen etc., From chip to cooling tower data center modeling: Part I
Influence of server inlet temperature and temperature rise across cabinet, InterPack 2010
End-to-end Optimization
Multi-scale energy modeling

Monotonically increasing data center temperature may not necessarily be better!

High-temperature Component Design
Ref: Thomas J. Breen etc., From chip to cooling tower data center modeling: Part I Influence of server inlet temperature and temperature rise across cabinet, InterPack 2010

End-to-end Optimization
Multi-scale energy modeling

Optimal point for $T_{HS} \sim 60 \, ^\circ C$, $L_x \sim 0.2 \, W/\circ C$

Optimal point for $T_{HS} \sim 70 \, ^\circ C$, $L_x \sim 0.4 \, W/\circ C$

Ref: Thomas J. Breen etc., FROM CHIP TO COOLING TOWER DATA CENTER MODELING: CHIP LEAKAGE POWER AND IT’S IMPACT ON COOLING INFRASTRUCTURE ENERGY EFFICIENCY, InterPACK2011, July 6-8, 2011, Portland, Oregon, USA
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Data Center Cooling Control and Optimization

Challenges

• Scalability
• Adaptive
• Model reduction
• Sensors
• Integration
• Optimization
• ...
Thank You

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