Data Center Control using LTL

Youhei Okazaki
FL12-3-1
7th, May, 2012

Background

Problem

increasing CO2 emission ⇨ storms, droughts, rising seas
global warming

Green Technology

renewable energy
- wind power
- photovoltaic power ⇨ reduce CO2

save energy
- building control(HVAC)

IEEE Green Technology Conference, April 19-20, 2012

Controlling Green Buildings: Challenges and Opportunities, June 26, 2012

Introduction

HVAC System

data centers(DC)[2] commercial buildings[6]

cooling IT Rack cooling room

cooling: large energy consumption ⇨ efficient control strategy

HVAC System Control Problem
- save energy
- keep temperature in practical range

⇩

physical and comfort constraint {
- Model Predictive Control[4]-[6]
- Temporal Logic for Control[1]

Data Center and Building

Difference

data centers(DC)[2] commercial buildings[6]

cooling IT Rack cooling room

• high energy density(IT Rack)	• low energy density(human)
• no disturbance	• environmental disturbance(sunlight)
• high efficiency layout	• low efficiency layout

data center control has a great influence on save energy

Data Center

Data Center Control Problem[3]

- save energy in each IT Rack
  IT Rack ventilation cooling
  IT Rack fan and air flow control
  maintain IT Rack temperature
- save energy in Chiller
  thermal transfer from DC to outside
  air temperature control

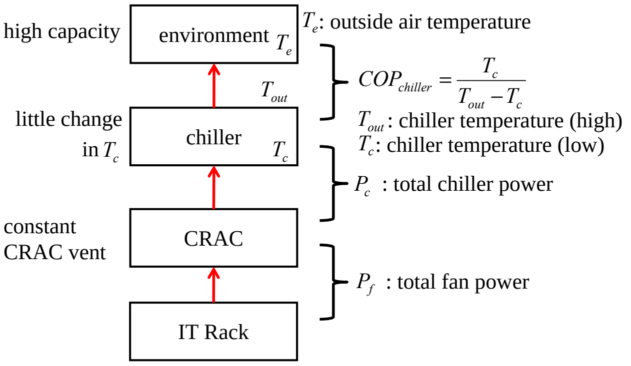
total power: fan power + chiller power

assumption: IT Rack generate same amount of thermal energy
control fan to maintain IT Rack temperature

high air temperature ⇨ chiller power ↓ , fan power ↑
low air temperature ⇨ chiller power ↑ , fan power ↓

minimize total power using air temperature

Data Center Model



high capacity — environment T_e

T_e: outside air temperature

T_{out}

$$COP_{chiller} = \frac{T_c}{T_{out} - T_c}$$

T_{out}: chiller temperature (high)
T_c: chiller temperature (low)

little change in T_c — chiller T_c

P_c : total chiller power

constant CRAC vent — CRAC

IT Rack

P_f : total fan power

Data Center Model

IT Rack Cooling Model

T_{air} : air temperature

T_i : IT Rack i temperature

q_i : thermal energy from IT Rack i

T_r : average air temperature from IT Rack

$\dot{m}_i$: mass flow rate into IT Rack i

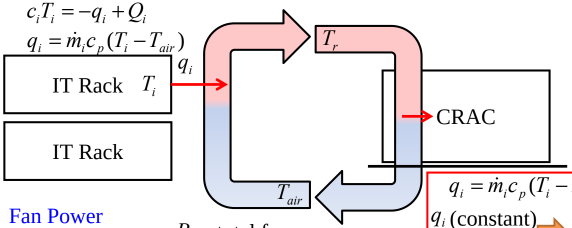
c_p : heat capacity of air

c_i : heat capacity of Rack i

Q_i : heat generation of Rack i

$$c_i \dot{T}_i = -q_i + Q_i$$

$$q_i = \dot{m}_i c_p (T_i - T_{air})$$



$$q_i = \dot{m}_i c_p (T_i - T_{air})$$

q_i (constant) $T_{air} \downarrow$ ⇨ $\dot{m}_i \downarrow$ $P_f \downarrow$

Fan Power

$$P_f = k_f \sum_i (\dot{m}_i)^3$$

P_f : total fan power

k_f : fan power coefficient

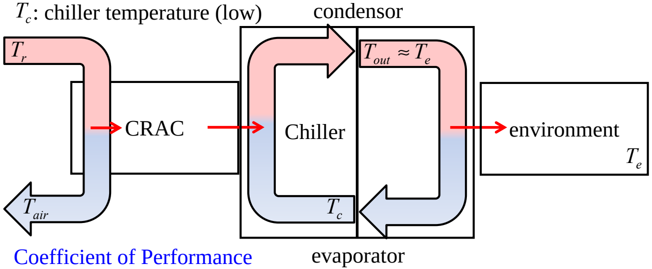
Data Center Model

Chiller Model

T_e: outside air temperature

T_{out}: chiller temperature (high)

T_c: chiller temperature (low)



Coefficient of Performance

$$COP_{chiller} = \frac{T_c}{T_{out} - T_c}$$

$T_c \uparrow$ ⇨ $COP_{chiller} \downarrow$

Data Center Model

IT Rack Cooling Model

$$q_i = \dot{m}_i c_p (T_i - T_{air})$$

$$c_i \dot{T}_i = -q_i + Q_i$$

q_i : thermal energy from IT Rack i

$\dot{m}_i$: mass flow rate into IT Rack i

c_p : heat capacity of air

T_i : IT Rack i temperature

T_{air} : air temperature

c_i : heat capacity of Rack i

Q_i : heat generation of Rack i

Fan Power

$$P_f = k_f \sum_i (\dot{m}_i)^3$$

k_f : Fan Power Coefficient

Coefficient of Performance

$$COP_{chiller} = \frac{T_c}{T_{out} - T_c}$$

T_{out}: chiller temperature (high)

T_c: chiller temperature (low)

Chiller Power

$$P_c = \left(\sum_i q_i \right) \Big/ COP_{chiller}$$

Constraint

$\underline{T}_i \le T_i \le \overline{T}_i$: comfort range $T_{air} \le T_r$: chiller can only decrease temp.

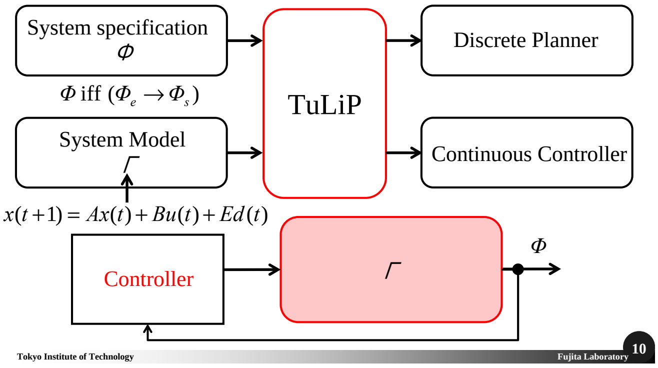
$\underline{m}_i \le m_i \le \overline{m}_i$: fan capacity $\underline{T}_{air} \le T_{air}$: chiller capacity

---

N. Ozay et al. [1]

TuLiP: Receding Horizon Temporal Logic Planning Toolbox

toolbox for synthesize controller



$$x(t+1) = Ax(t) + Bu(t) + Ed(t)$$

TuLiP Synthesis

State Equation(Discrete time)

$$x(t+1) = Ax(t) + Bu(t) + Ed(t)$$

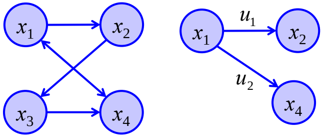
x : various temperatures

u : controllable input

d : IT Rack heat generation

Discretize

make transition system
from state equation

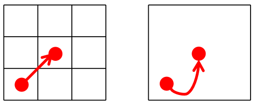


Synthesis

assumption: include initial condition and exception

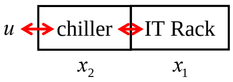
desired behavior: some behavior is necessary,
one sequence of transitions is chosen from this condition

Simulation



calculate input for
moving one point to another
using MPC

Example



System Model(simplified)

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -\frac{1}{c_1} & \frac{1}{c_1} \\ \frac{1}{c_2} & -\frac{1}{c_2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u$$

Constraint

$\underline{x}_1 \le x_1 \le \overline{x}_1$: IT Rack comfort range

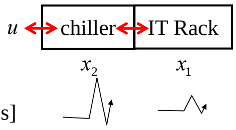
$\underline{x}_2 \le x_2 \le \overline{x}_2$: chiller capacity

$\underline{u} \le u \le \overline{u}$: input capacity

TuLiP(Example)

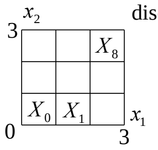
Discretize

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix}=\begin{bmatrix}-0.1 & 0.1\\ 0.5 & -0.5\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix}+\begin{bmatrix}0\\ 1\end{bmatrix}u$$

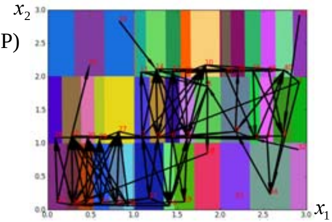


c2d(MATLAB), 0.1[s]

$$\begin{bmatrix}x_1(t+1)\\ x_2(t+1)\end{bmatrix}=\begin{bmatrix}0.9903 & 0.009706\\ 0.04853 & 0.9515\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix}+\begin{bmatrix}0.0004901\\ 0.9755\end{bmatrix}u(t)$$



discretize(TuLiP)
step=30



Finite State Approximations

Finite Transition Systems

$\Gamma := (Q, Q_0, \to)$

Q : finite set of states
Q_0: set of initial states
$\to\subseteq Q\times Q$: set of initial states

given $q, q' \in Q$ if there is a transition from q to q'
we write $q \to q'$

Under Approximation

transition $q \to q'$ is included in Γ only if the continuous flow can strictly implement the transition

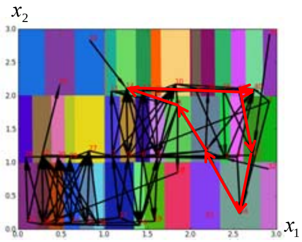
Over Approximation

transition $q \to q'$ is included in Γ as long as there is possibility

TuLiP(Example)

Synthesis

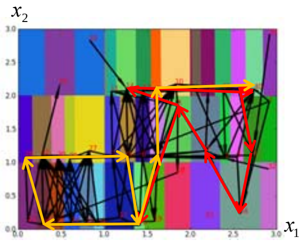
$\square\lozenge X_2 \ \& \ \square\lozenge X_4$



TuLiP(Example)

Synthesis

$\square\lozenge X_0 \ \& \ \square\lozenge X_2 \ \& \ \square\lozenge X_4$



Future Works

Summary

searching data center modeling and other HVAC systems
TuLiP toolbox test and observations

Future Works

test arbitrary TuLiP simulation
servey better problem setting about datacenter
consider more complicated system by TuLiP
analysis of data center problem via TuLiP simulation

Reference

[1] J. Liu, N. Ozay, U. Topcu and R. M. Murray, “Synthesis of Switching Protocols from Temporal Logic Specifications,” Proc. of the 2012 American Control Conference.(submitted)

[2] T. J. Green, E. J. Walsh, J. Punch, “From chip to cooling tower data center modeling: Part I Influence of server inlet temperature and temperature rise across cabinet,” Proc. of the 2010 12th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, pp.1-10, 2010.

[3] M. K. Patterson, “The Effect of Data Center Temperature on Energy Efficiency,” Proc. of the 2008 11th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, pp. 1167 – 1174, 2008.

[4]T. X. Nghiem, M. Behl, R. Mangharam and G. J. Pappas, “Green Scheduling of Control Systems for Peak Demand Reduction,” Proc. of 2011 50th IEEE Conference on Decision and Control and European Control Conference, pp. 5131 – 5136, 2011.

[5] A. Kelman, F. Borrelli, “Bilinear Model Predictive Control of a HVAC System Using Sequential Quadratic Programming,” Proc. of 18th IFAC World Congress, pp. 9869 - 9874, 2011.

[6] F. Oldewurtel, A. Parisio, C. N. Jones, M. Morari, D. Gyalistras, M. Gwerder, V. Stauch, B. Lehmann and K. Wirth, “Energy Efficient Building Climate Control using Stochastic Model Predictive Control and Weather Predictions,” Proc. of the 2010 American Control Conference, pp. 5100–5105, 2010.

[7] Y. Ma, A. Kelman, A. Daly, and F. Borrelli, “Predictive Control for Energy Efficient Buildings with Thermal Storage: Modeling, Stimulation, and Experiments,” Control Systems Magazine, vol. 32, no. 1, pp. 44-64, 2012.