Model Predictive Control of a Solar Cooling Plant

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Outline

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• Control objectives and problems
• Solar refrigeration plant model
• HYCON WP2 Benchmark activities
• Hybrid MPC controller
• Conclusions
Some figures

In the United States, commercial buildings account for:

- 36% of total energy use
- 65% of electricity consumption
- 30% of greenhouse gas emissions
- 30% of raw materials use
- 30% of waste output: 136 million tons annually
- 12% of potable water consumption
A success history

- In June 2006, Adobe's West tower became the first building to be certified at the platinum level in the U.S. Green Building Council's permanent LEED-EB program for Green Buildings.
- **spent $1.4 million** on 72 projects, resulting in annual savings of **$1.2 million**. Combining the savings with rebates from local and state agencies, C&W delivered a return on investment of **121%**.
- Green Buildings improve operating efficiency, reduce operating costs, provide a healthier work environment, and, all things considered, they are more sustainable.

Along the way Adobe sas:

- Effectively reduced electricity use 35%
- Effectively reduced natural gas use 41%
- Reduced domestic water use 22%
- Reduced landscape water use 76%
- Diverts up to 85% of its solid waste through composting and recycling
- Reduced total pollution by 26%
- Reduced CO2 emissions by 16%.
Absorption machine

Process variables

- **Controlled variables:**
  - temperatures and flows

- **Manipulated variables:**
  - pump velocity and valves

- **Perturbations:**
  - Solar radiation, ambient temperature, flow through the evaporator of the absorption machine, evaporator input temperature of the absorption machine
Control objectives

1. Fulfill cooling demand.
3. Maximize energy stored at the end of the day.
4. Minimize the number of operating mode changes.

Operating modes

1. Recirculation $l_1 = 1$
2. Loading the tanks with hot water $l_2 = 1$
3. Using the solar collectors $l_3 = 1$
4. Using the solar collectors and gas heater $l_4 = 1$
5. Using the gas heater $l_5 = 1$
6. Using the tanks and gas heater $l_6 = 1$
7. Using tanks $l_7 = 1$
8. Loading the tanks and using the gas heater $l_8 = 1$
9. Recirculation and using the gas heater $l_9 = 1$
10. Using the solar collectors and loading tank $l_{10} = 1$
11. Using the solar collectors and gas heater, and loading tanks $l_{11} = 1$
Finite state machine
HYCON

Hybrid Control: Taming Heterogeneity and Complexity of Networked Embedded Systems

Hybrid systems provide the modeling framework for capturing the richness of behaviors characteristic of embedded systems.

The key feature of hybrid systems is their capability of rigorously describing the dynamics of devices where continuous parts – governed by differential or difference equations and discrete parts – described by finite state machines, if-then-else rules, prepositional and temporal logic interact over time.
The controller is connected with the real plant using OPC library of Matlab/Simulink.

The controller is allocated inside the block called Controller and is connected with the necessary inputs and outputs.
**HYCON activities: Solar plant benchmark**

**Participants**

Proposals from HYCON partners.

- University of Sienna (UNISI).
- University of Dortmund (UNIDO).
- University of Valladolid (UV).
- ETH Zurich (ETHZ).
- University of Seville (US).

Proposals from non HYCON researchers.

- Universidad Tecnológica de Bolívar, Colombia
- University of Almería, Spain
- Federal University of Santa Catarina, Brazil
- Uppsala University, Sweden
- University of Los Andes, Venezuela
- Simón Bolívar University, Venezuela

- Accepted
- Not accepted

**WP2 activities – M25-M36**

- 2nd Controller Validation Campaign.
  - Objective: Apply the controller on the real plant. Two days for each group.
  - February-March (2007)
  - On-site experimentation:
    - Paolo Menchinelli from Sienna University,
    - Darine Zambrano from Los Andes University,
    - Cesar de Prada and Miguel Rodriguez from University of Valladolid

- WP2 Workshop in Sevilla
  - Objective: to present and analyze results and the benchmark exercise itself.
  - March 22-23 (2007)
  - HYCON WP2 benchmark panel analyzes results and takes a decision on award winner.

- Further experimentation by various groups
• Award panel

• Analyzed issues:
  • Results on two days simulation (real environmental data)
  • Results of one day control on the real plant
  • The proposed controller, implementation requirements …

• Award involved 1000 Euros check
Model Predictive Control

- **MPC successful in industry.**
  - Many and very diverse and successful applications:
    - Refining, petrochemical, polymers,
    - Semiconductor production scheduling,
    - Air traffic control
    - ....
  - Many MPC vendors

- **MPC successful in Academia**
  - Many MPC sessions in control conferences and control journals,
    - 4/8 finalist papers for the *CEP best paper award* were MPC papers (2/3 finally awarded were MPC papers)
Why is MPC so successful?

- MPC is Most general way of posing the control problem in the time domain:
  - Optimal control
  - Stochastic control
  - Known references
  - Measurable disturbances
  - Multivariable
  - Dead time
  - Constraints
  - Uncertainties

Real reason of success: Economics

- MPC can be used to optimize operating points (economic objectives). Optimum usually at the intersection of a set of constraints. Obtaining smaller variance and taking constraints into account allow to operate closer to constraints (and optimum).
- Richalet et al, Model Predictive Heuristic Control (MPHC) IDCOM (1976, 1978) (150,000 $/year benefits because of inreased flowrate in the fractionator application)
- Repsol reported 2-6 months payback periods for new MPC applications.
Only the first control move is applied.

Errors minimized over a finite horizon.

Constraints taken into account.

Model of process used for predicting.

Only the first control move is applied again.
Why controlling the solar plant is a challenge?

- The energy source is not a manipulated variable but a perturbation!!!
- Never at a steady state
- Deciding the operating mode is part of the control strategy.

Disturbances prediction: Solar radiation
MPC and hybrid systems

\[ x_{k+1} = A x_k + B u_k + f_k \]

\[ y_{k+1} = C x_{k+1} + g_{k+1} \]

The resulting optimization problem

\[ U = \arg \left( \min_{U,I} J \right) \]

\[ U = \{ u(k), u(k+1), u(k+2), \ldots, u(k+N-1) \} \quad \text{real} \]

\[ I = \{ I(k), I(k+1), I(k+2), \ldots, I(k+N-1) \} \quad \text{Integer} \]

Control operating modes (Darine Zambrano)
Day 2 tests (Darine Zambrano)

(c) Caldera de gas.

(d) Generador.

Figura 4.32: Perfiles de temperatura durante el ensayo del día 2.

(a) Perfil de temperaturas en el evaporador.

(b) Radiación solar.

Day 3 tests (Darine Zambrano)

(a) Perfil de temperaturas en el evaporador.

(b) Radiación solar.
Conclusions

1. Significant gains in energy efficiency obtained by using advanced control.

2. Solar cooling plants have a great potential (solar energy usually available when refrigeration is required)

3. Difficult plant to control (hybrid, high perturbations, environmental conditions and loads, …), hybrid control techniques have proved to be effective.

4. Benchmark was a very positive experience

Model and plant available for experimentation

http://nyquist.us.es/hycon/

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