International Research Cooperation
PROBRAL 2007-2008 CAPES/DAAD
University of Brasília/Brazil – University of Kaiserslautern/Germany

"Networked Control with Distributed Processing for Building Automation in an Ambient Intelligence Framework"

Adolfo Bauchspiess

Kaiserslautern, 23.7.2006

Contents

- Brazil - Brasília – UnB
- PROBRAL
- Some on going UnB-Projects
- Energy Saving with Fuzzy Distributed Control
- Wire Less Building Automation
- Conclusions & Perspectives

BRAZIL

- Pelé - Soccer
- Carnaval – Samba
- Rio de Janeiro

Brazil

Equator

~ 8.5 Mio Km^2
~ 190 Mio Inh.
~ 8.000Km Coast

BRInC

Brasília
15°45´S
47°52´W

Brasília – Capital City of Brazil

- 1960 – President J. Kubitschek, Architekt O. Niemeyer
- 1.000m over the see level
- ~ 2 Million Inhabitants (Federal District)
- Highest income rate in south america
- Paranoá Lake

Universidade de Brasília

(Oscar Niemeyer, 1961)

Technological Faculty

4 Departments
- Electrical Eng. - ~200 Beginners/Year
- Mechanical Eng.
- Civil Eng.
- Forest Eng.

6 Degrees
- Electrical Eng.
- Mechatronic Eng.
- Communication Network Eng.
- Mechanical Eng.
- Civil Eng.
- Forest Eng.

Electrical Engineering Department

43+ lecturers in 5 areas:
Control and Automation, Telecom, Electronics,
Power Systems & Communication Networks.

Areas organized in research groups,
GRAV – Grupo de Robótica, Automação e Visão Computacional
LAVSI – Laboratório de Automação, Visão e Sistemas Inteligentes
LARA – Laboratório de Robótica e Automação

GRAV

Associate Prof. Dr. Adolfo Bauchspiess
Adjoint Prof. Dr. Geovany de Araújo Borges
Adjoint Prof. Dr. João Yoshiyuki Ishihara
Adjoint Prof. Dr. Marco A. F. Egito Coelho

PROBRAL
PROgrama de Cooperação Internacional BRasil-ALemanha

"Networked Control with Distributed Processing
for Building Automation
in an Ambient Intelligence Framework"

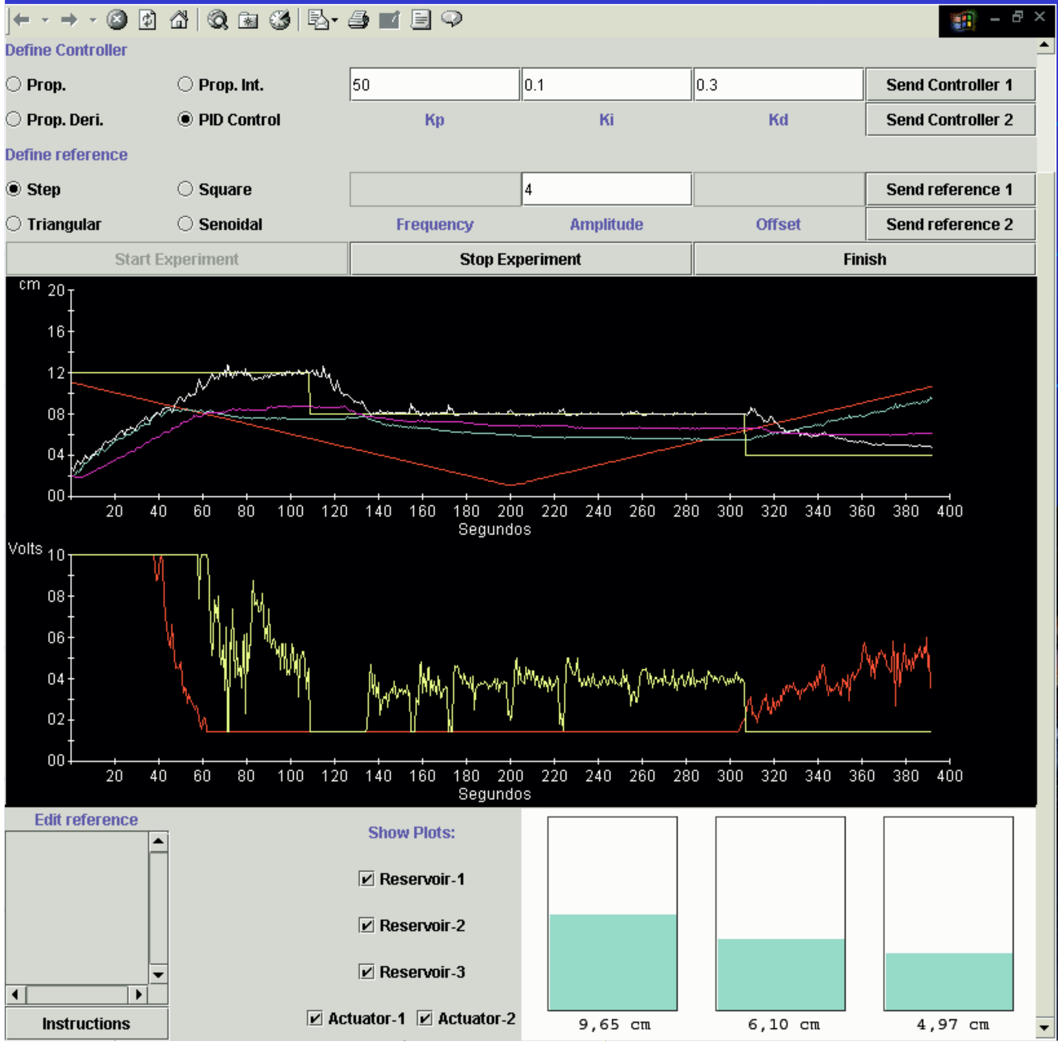
- Only supports Interchange of Researchers
- Each side must have local research ($) support
- ~ 2 Profs. + 2 Ph.D candidates / Year
- 2 (+ 1) Years

Some on-going UnB-Projects

- LEARn
- Expansion-CARCARAH
- ...
- Related with PROBRAL:
  - SAPIEn
  - CT-Energ
  - FINEP-INOVA

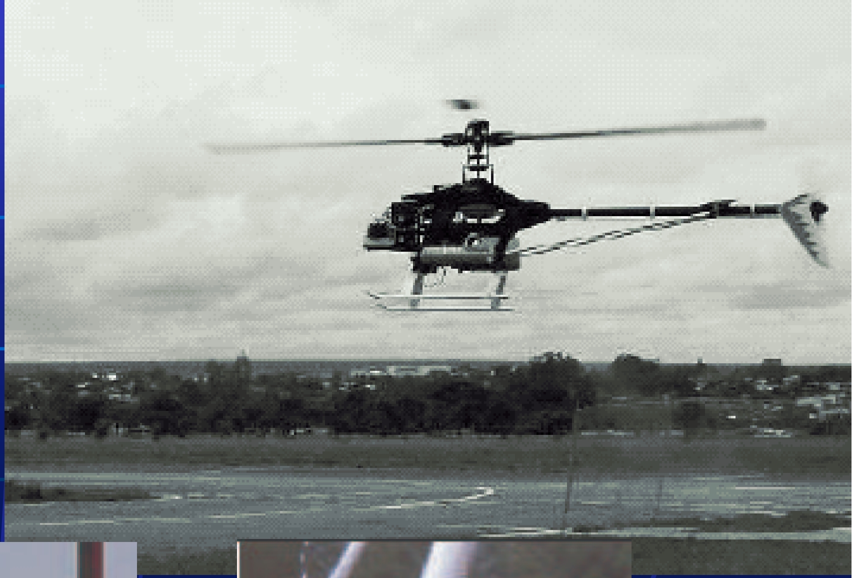
LEARn

Laboratório de Ensino de Automação Remota.



UAV Inspection of Power Transmission Lines

Project Carcarah
-Expansion Ltda
-ANEEL



Projects: SAPIEn, CT-Energ and FINEP-INOVA

Energy-Saving Approach:

Model-Based HVAC Control

$$J = \underbrace{\sum_{i=1}^{h_p} \left(y(k+i) - y_R\right)^2}_{comfort\ related} + \sum_{i=0}^{h_c-1} \Delta\mathbf{u}^T(k+i)\mathbf{Q}_{\Delta u}\Delta\mathbf{u}(k+i) + \underbrace{\mathbf{u}^T(k+i)\mathbf{Q}_u\mathbf{u}(k+i)}_{energy\ related}$$

Where:

h_p – *prediction horizon*

h_c – *control horizon*

y – *controlled variable*

y_R – *reference*

u – *manipulated variable*

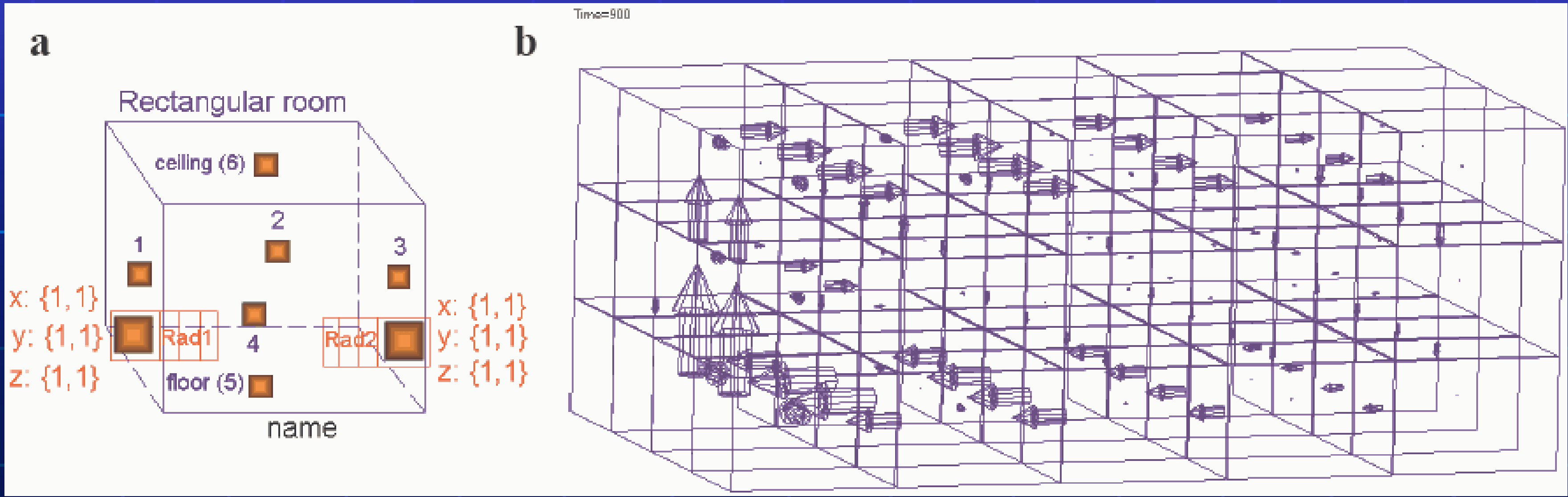
$\mathbf{Q}_{\Delta u}, \mathbf{Q}_u$ – *weighting matrices*

Predictive Cost Function:

Considers comfort and energy saving. Needs model!

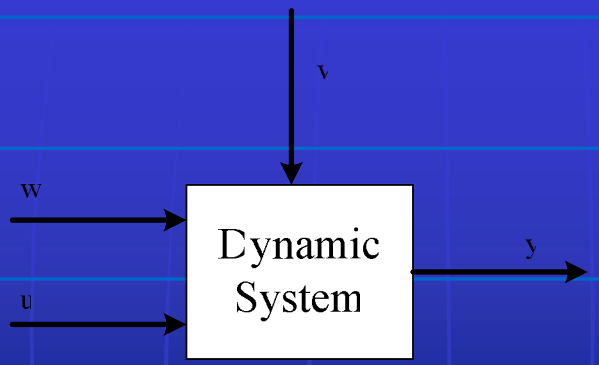
Distributed Parameter Modelling

- Transport Phenomena
- Ex. Heat Flow



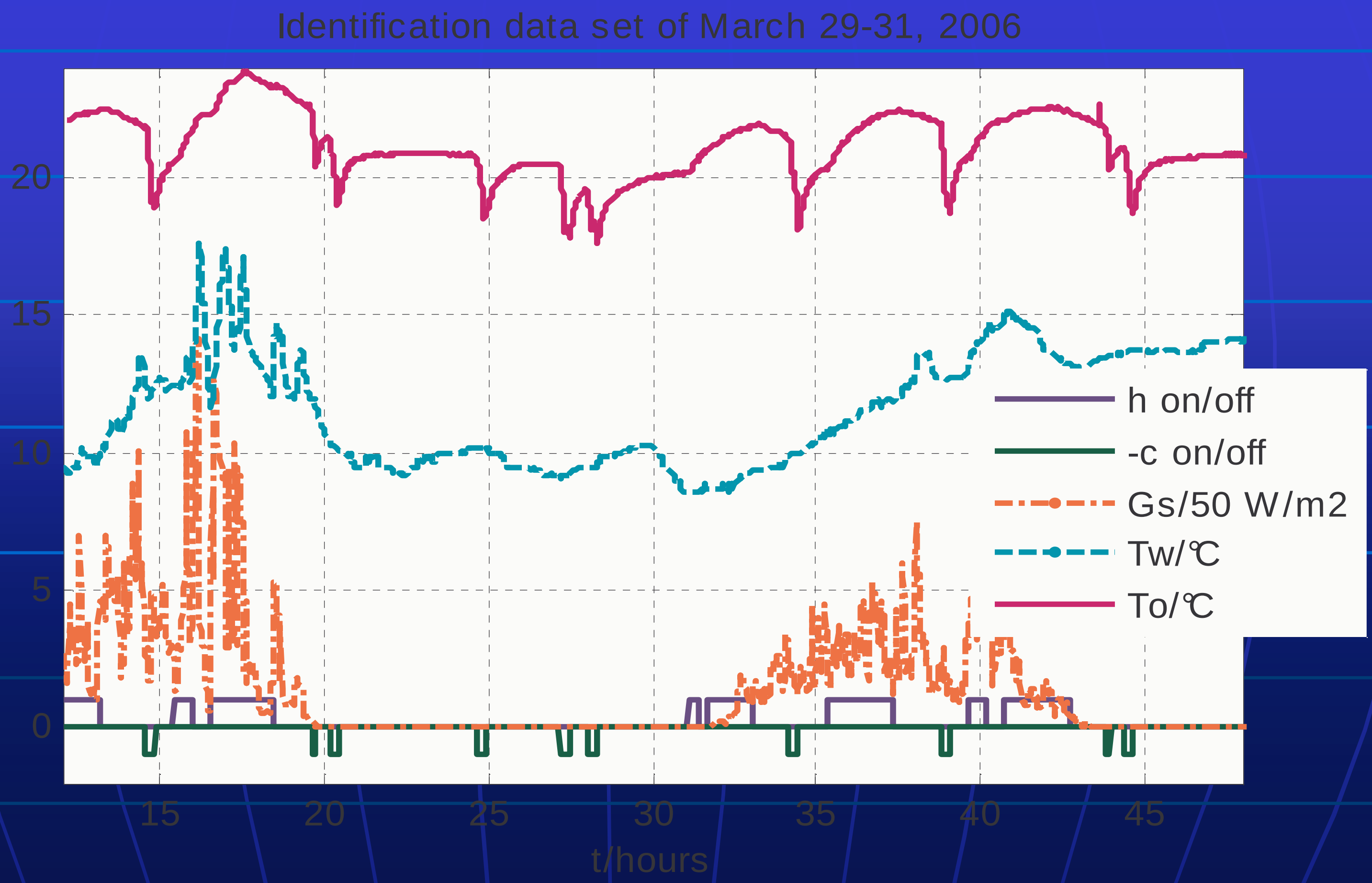
Wind velocity simulation in Modelica, by Felgner, ASIM2002

Dynamic System Identification



u - input (manipulated variable)
y – output (controlled variable)
w – measurable disturbance
v – non-measurable disturbance

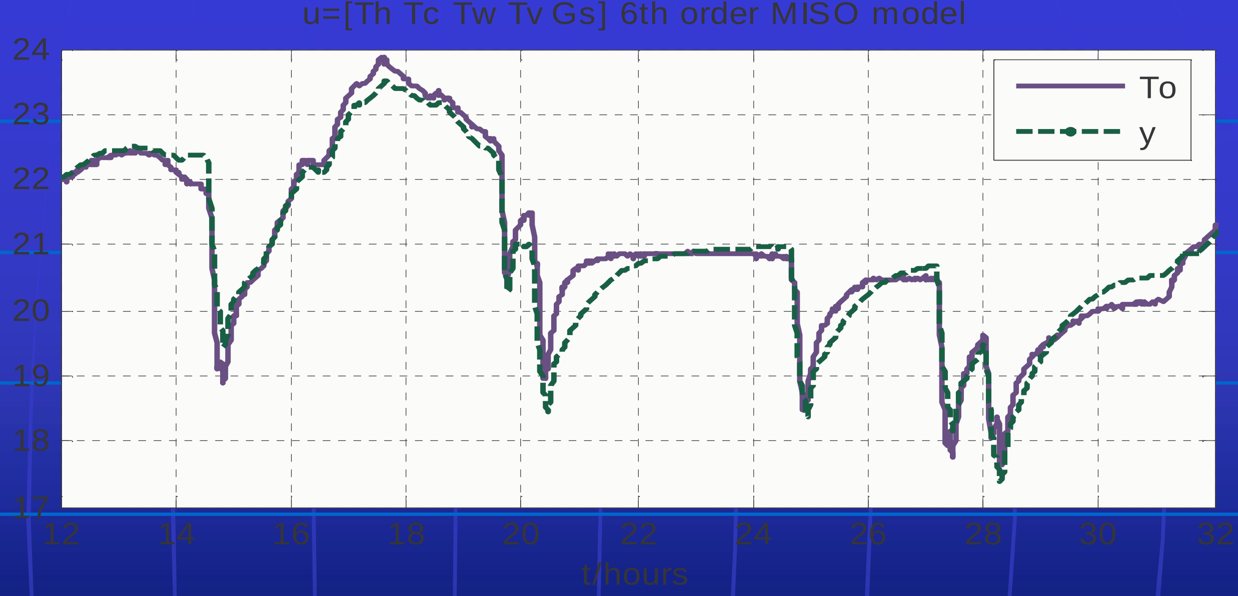
First-Principles Identification (KL-2006)

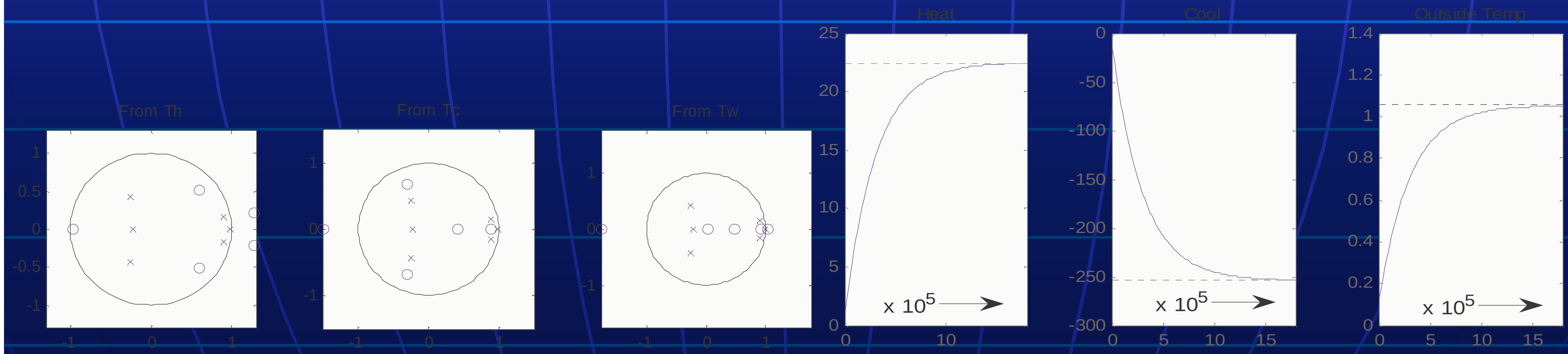


Typical identification data set

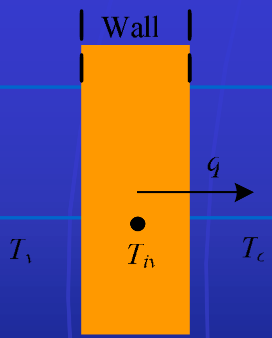
a) Linear MISO approach

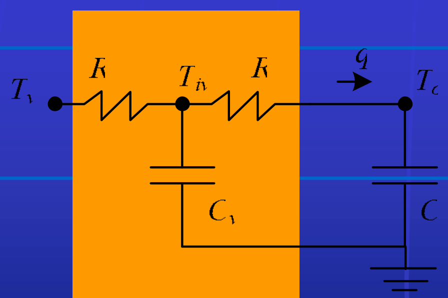
$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{E}\mathbf{e}$$
$$y = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}$$

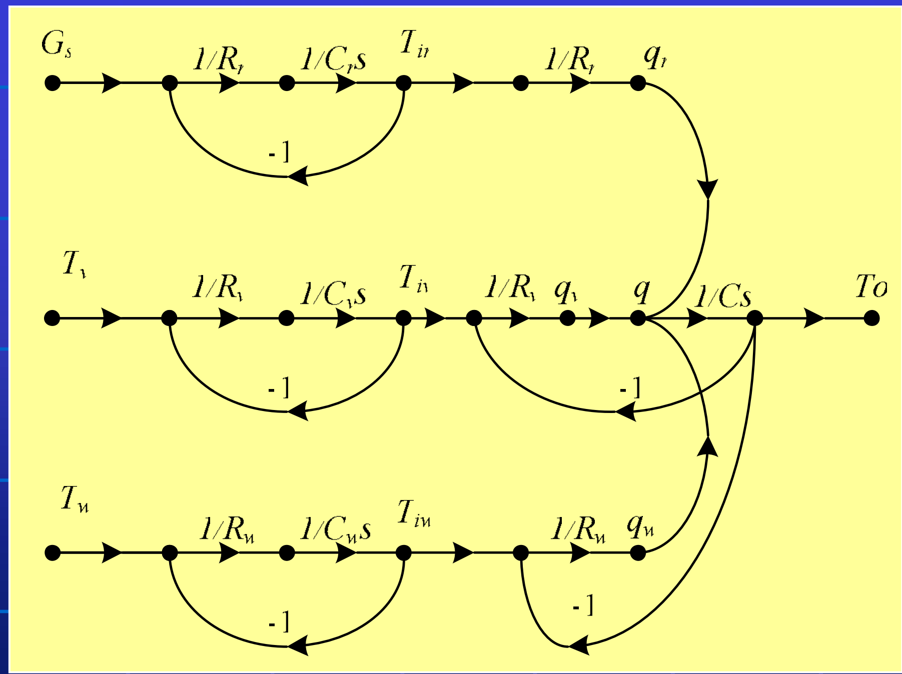




b) First-Principles Structured Identification







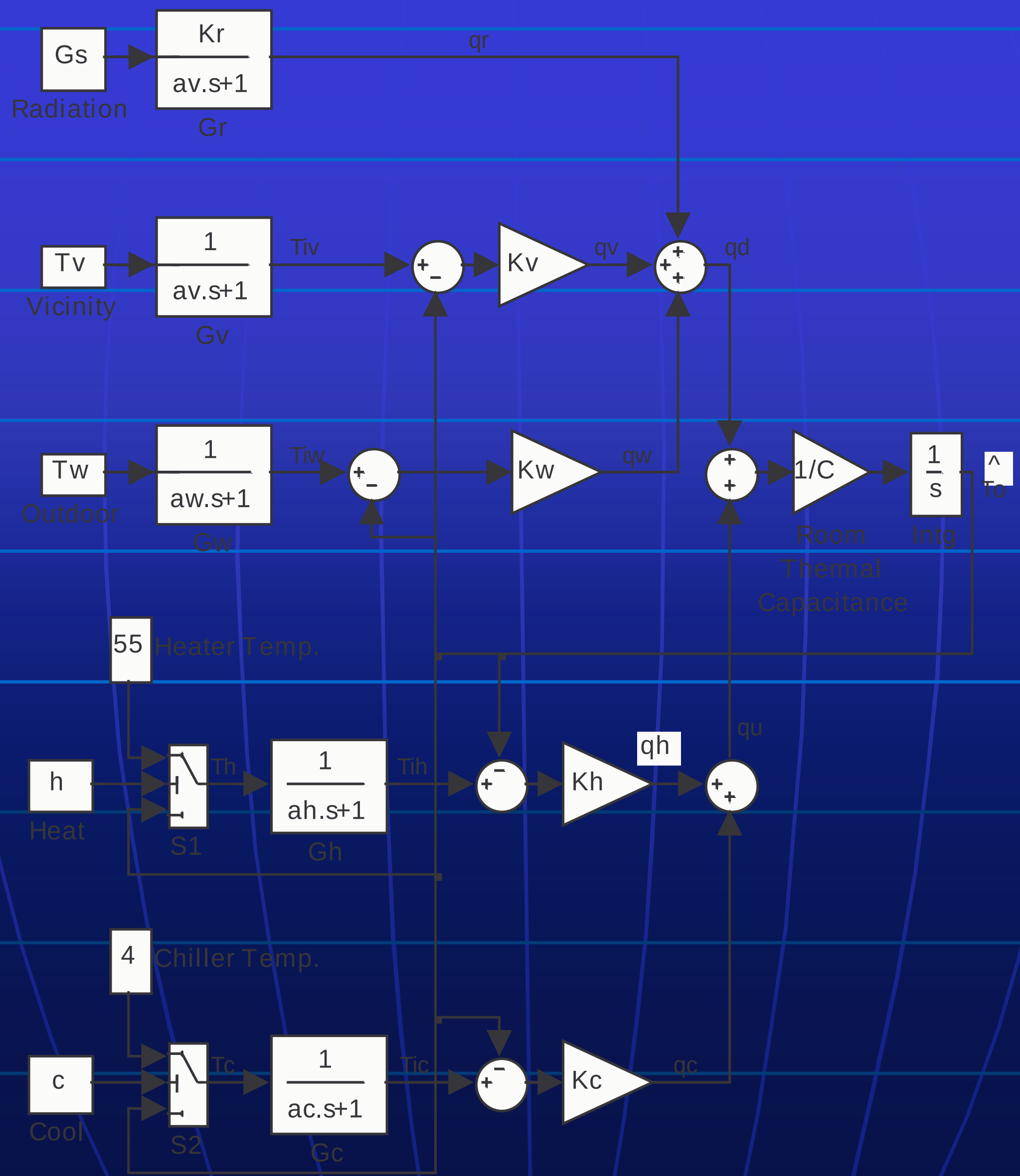
2R1C analogy of the vicinity heat transfer

2R1C-based disturbance model

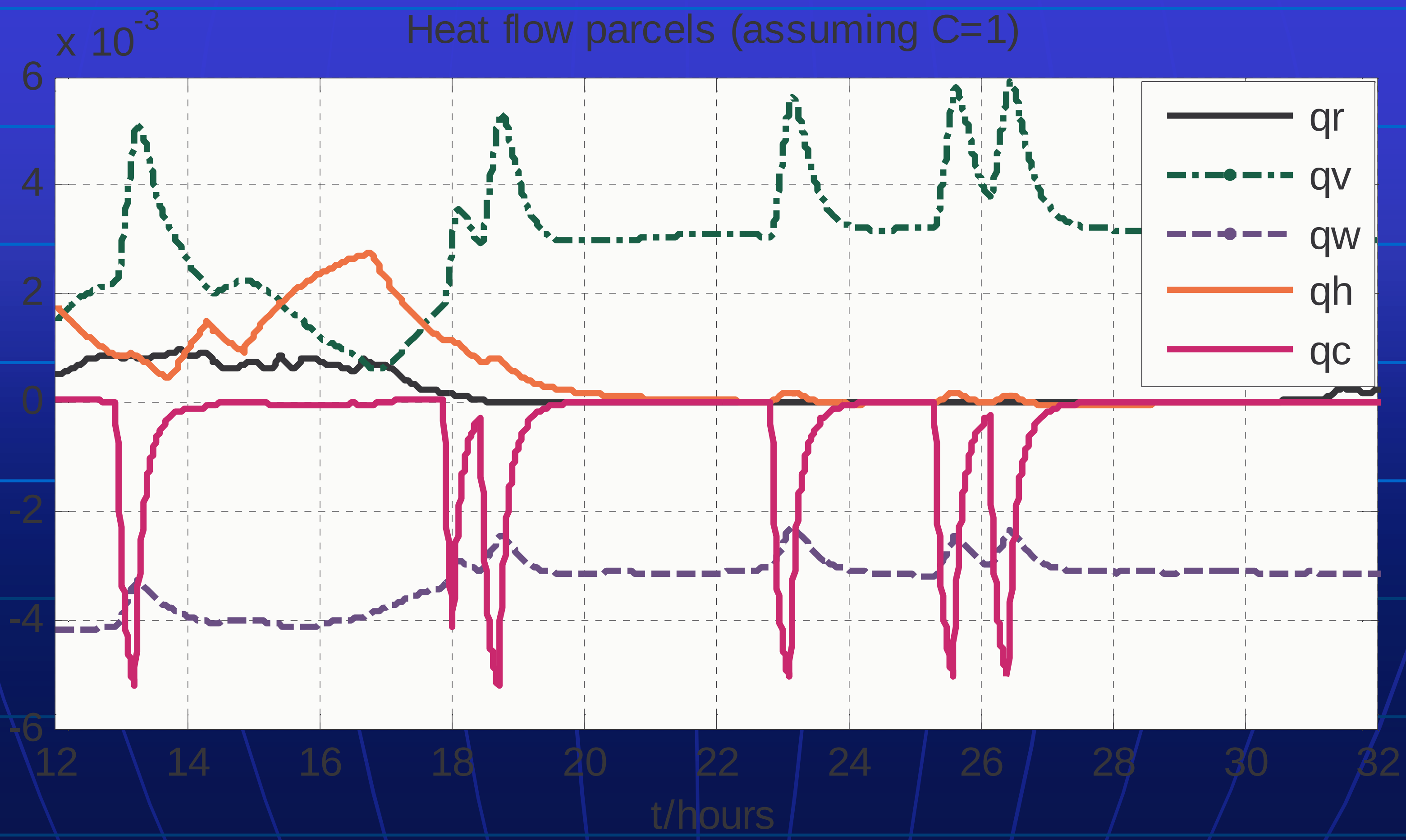
Heat flow due to disturbances:

$$q_d = \frac{aK_r s.G_s(s)}{(as+1)(a_r s+1)} + \frac{aK_v s.T_v(s)}{(as+1)(a_v s+1)} + \frac{aK_w s.T_w(s)}{(as+1)(a_w s+1)}$$

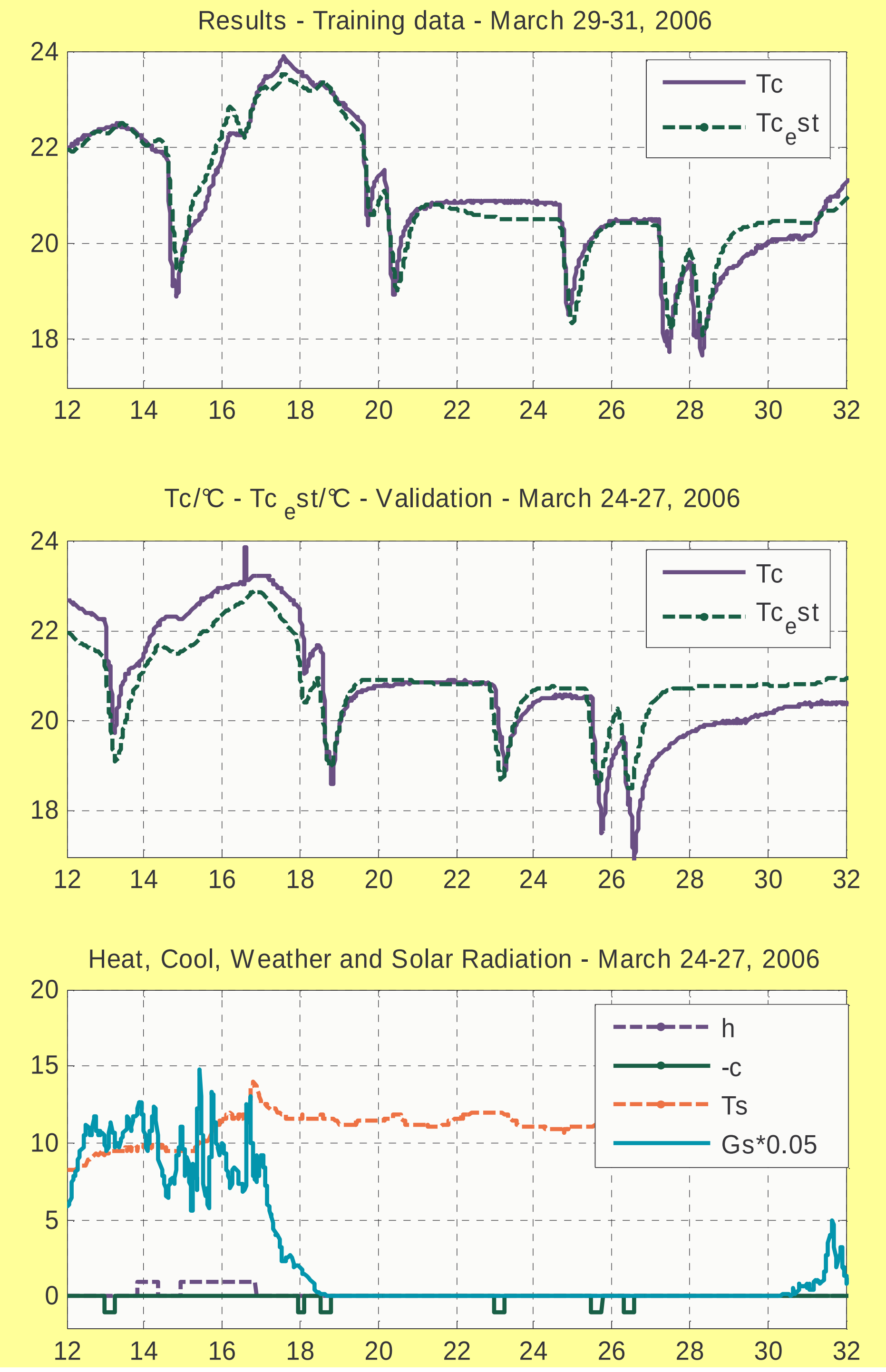
First-principles structured thermal model



Heat flow obtained with the first-principles structured identification



Results of the first-principles structured identification



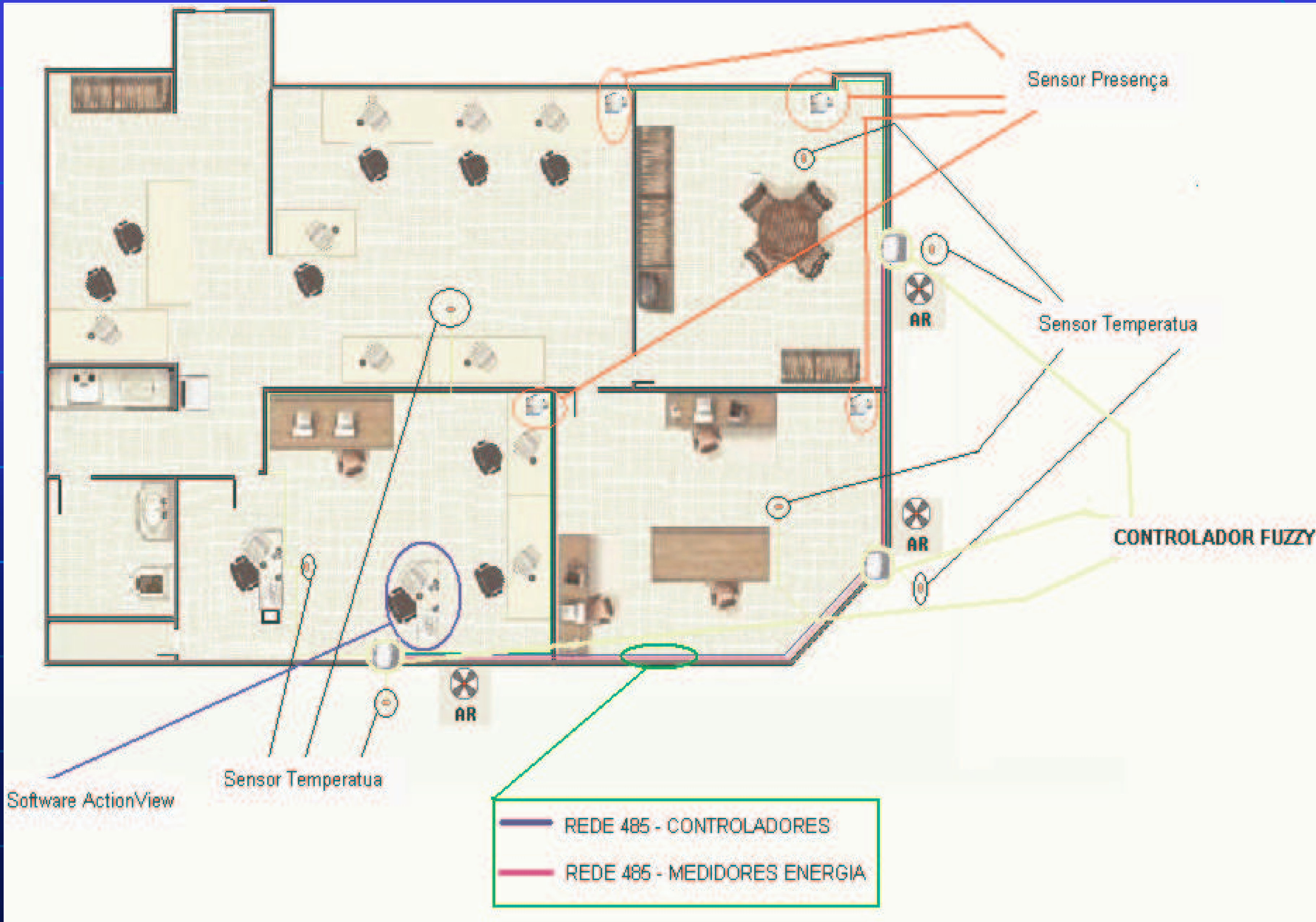
PROBRAL-Related

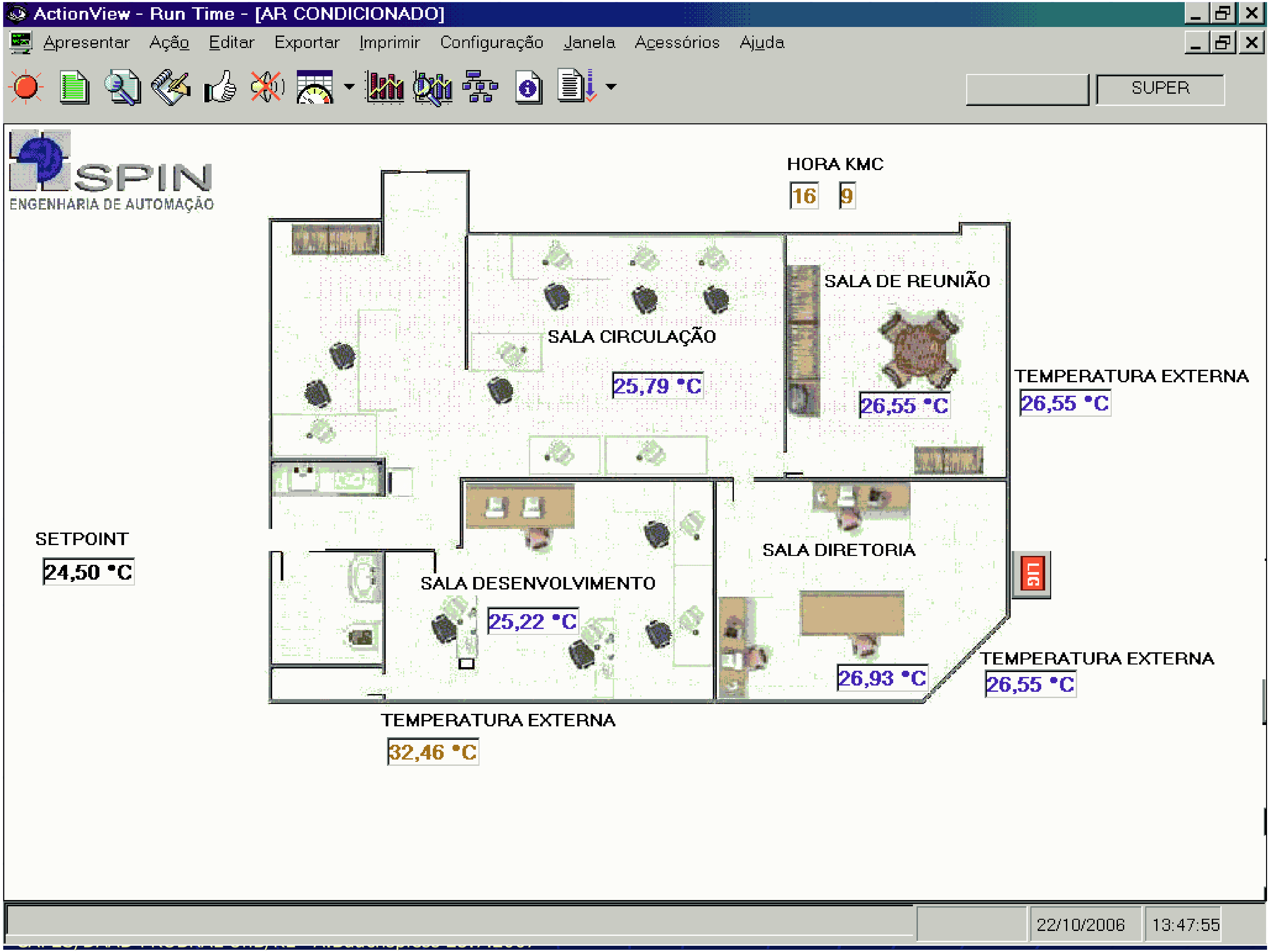
SAPIEn – Energy Saving by Fuzzy Distributed Control

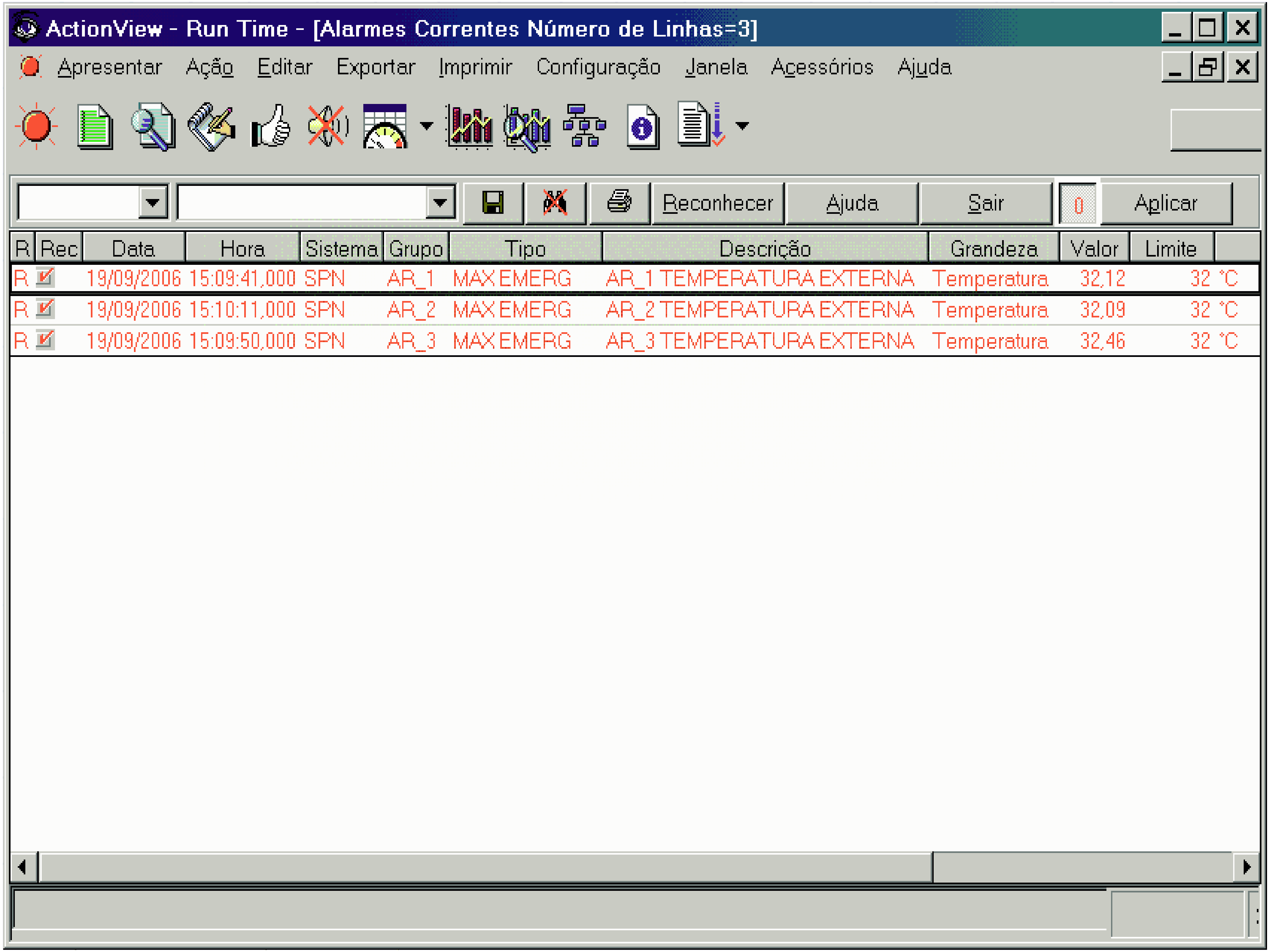
- Energy Saving
- Thermal Comfort
- Building Automation
- FAP-DF suport

Campus UnB (2007) 995 window air conditioners
>R$1.000.000,00/Year (1€ ≈ 2,56 R$)

Experimental Environment




ActionView - Run Time - [AR CONDICIONADO]
Apresentar Ação Editar Exportar Imprimir Configuração Janela Acessórios Ajuda
SUPER
SPIN
ENGENHARIA DE AUTOMAÇÃO
HORA KMC
16
9
SALA DE REUNIÃO
SALA CIRCULAÇÃO
25,79 °C
26,55 °C
TEMPERATURA EXTERNA
26,55 °C
SETPOINT
24,50 °C
SALA DIRETORIA
LIG
SALA DESENVOLVIMENTO
25,22 °C
26,93 °C
TEMPERATURA EXTERNA
26,55 °C
TEMPERATURA EXTERNA
32,46 °C
22/10/2006
13:47:55

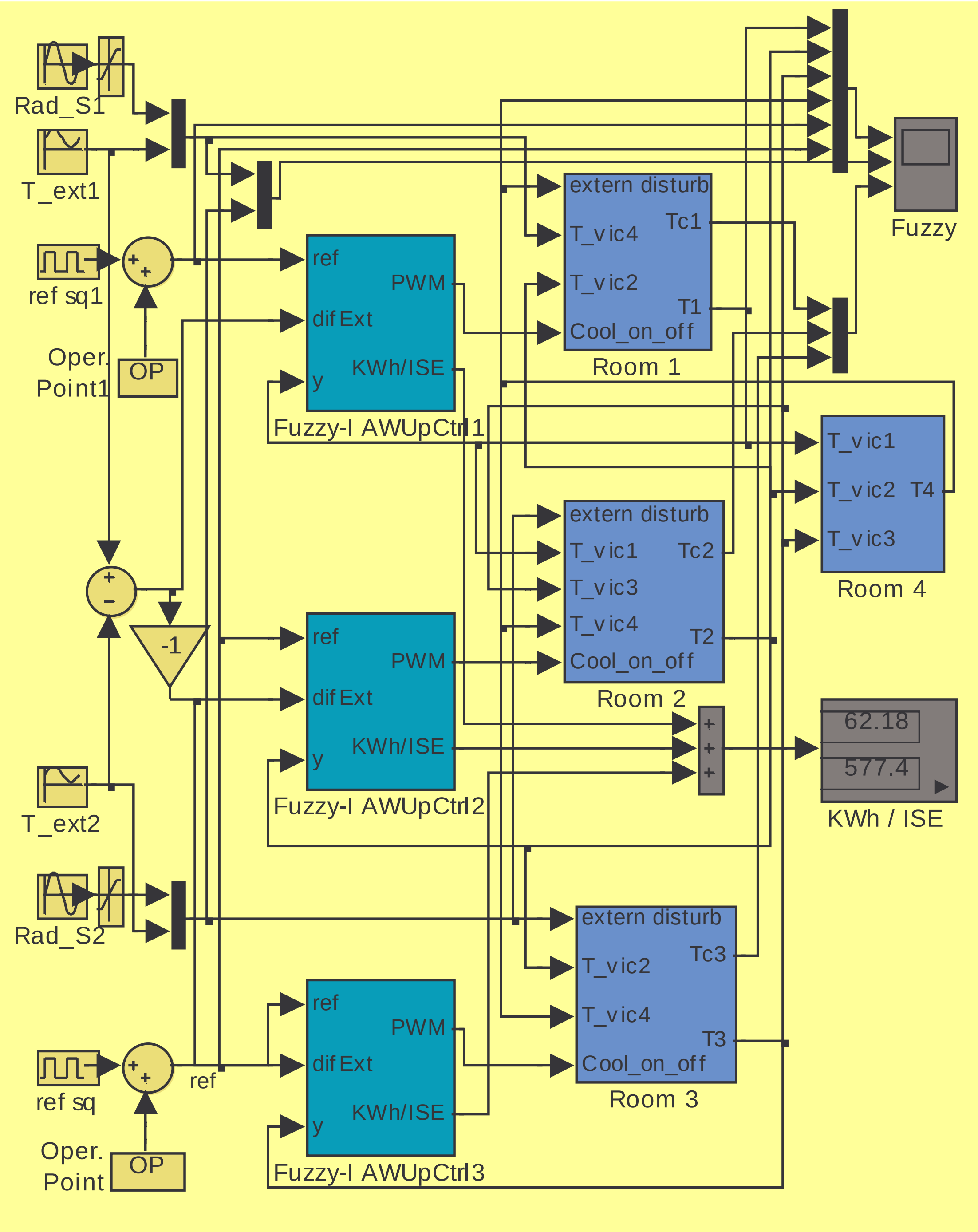

ActionView - Run Time - [Alarmes Correntes Número de Linhas=3]
Apresentar Ação Editar Exportar Imprimir Configuração Janela Acessórios Ajuda
Reconhecer
Ajuda
Sair
0
Aplicar
R Rec Data Hora Sistema Grupo Tipo Descrição Grandeza Valor Limite
R 19/09/2006 15:09:41,000 SPN AR_1 MAX EMERG AR_1 TEMPERATURA EXTERNA Temperatura 32,12 32 °C
R 19/09/2006 15:10:11,000 SPN AR_2 MAX EMERG AR_2 TEMPERATURA EXTERNA Temperatura 32,09 32 °C
R 19/09/2006 15:09:50,000 SPN AR_3 MAX EMERG AR_3 TEMPERATURA EXTERNA Temperatura 32,46 32 °C

SIMULATION

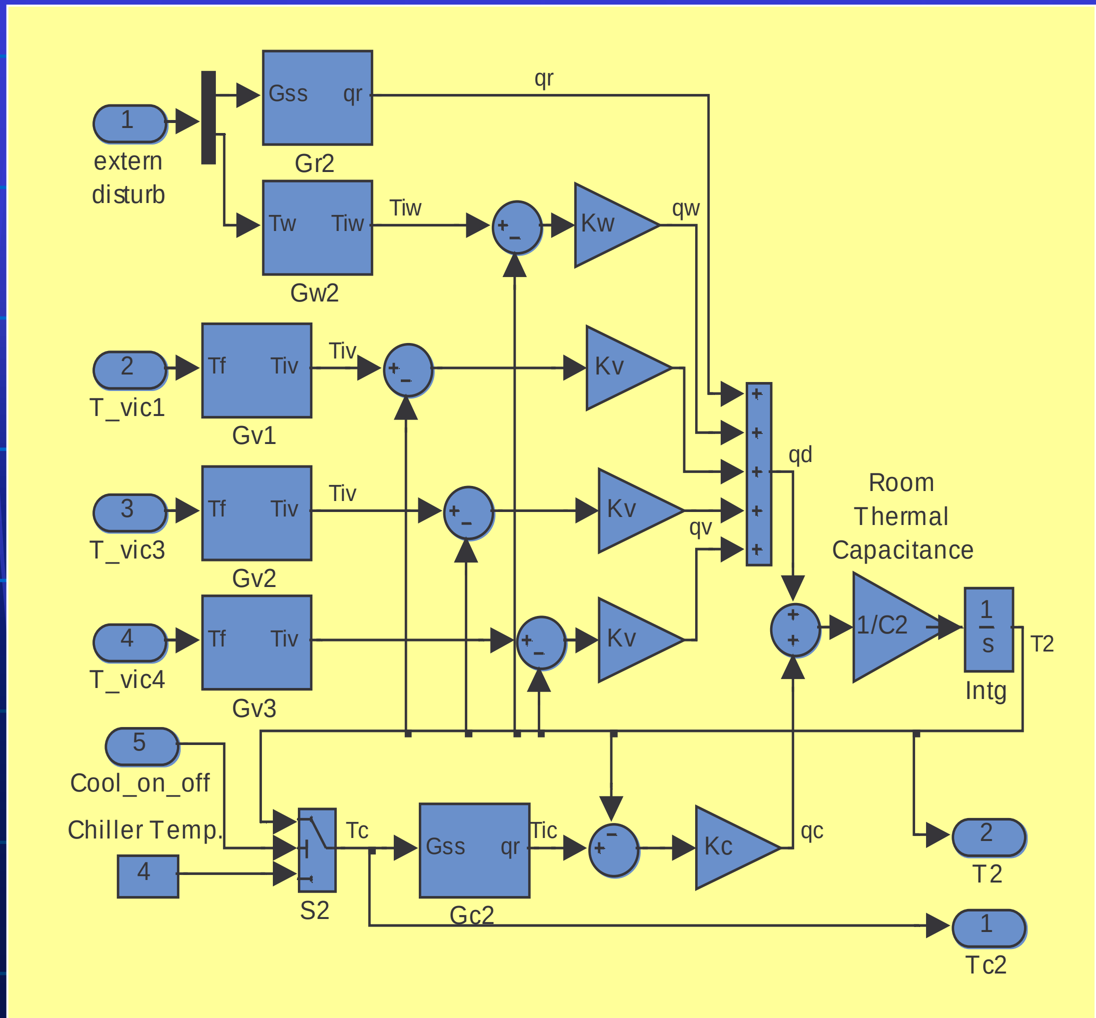
Simulink®

MIMO process:

- 4 rooms
- 3 air conditioners

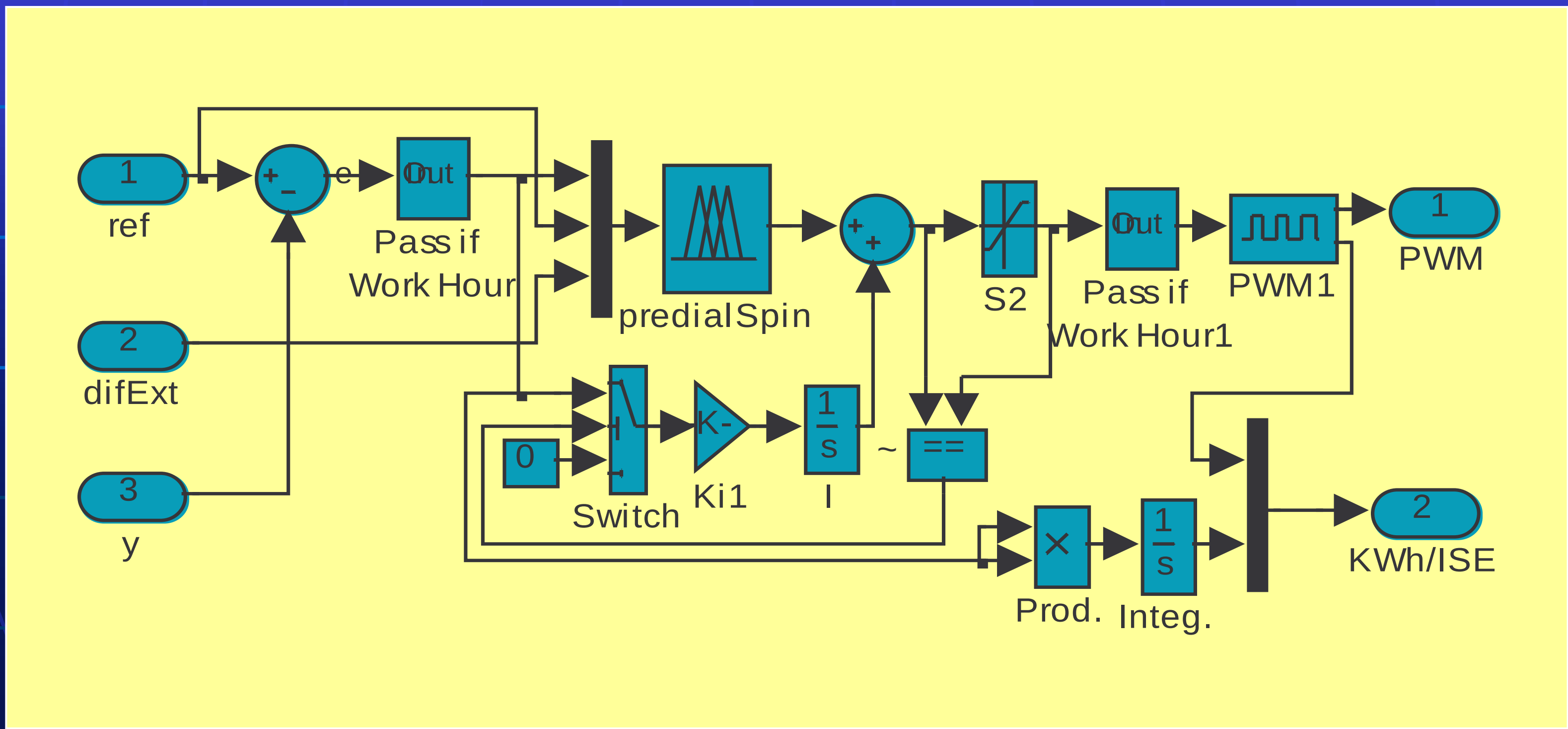


Room Model



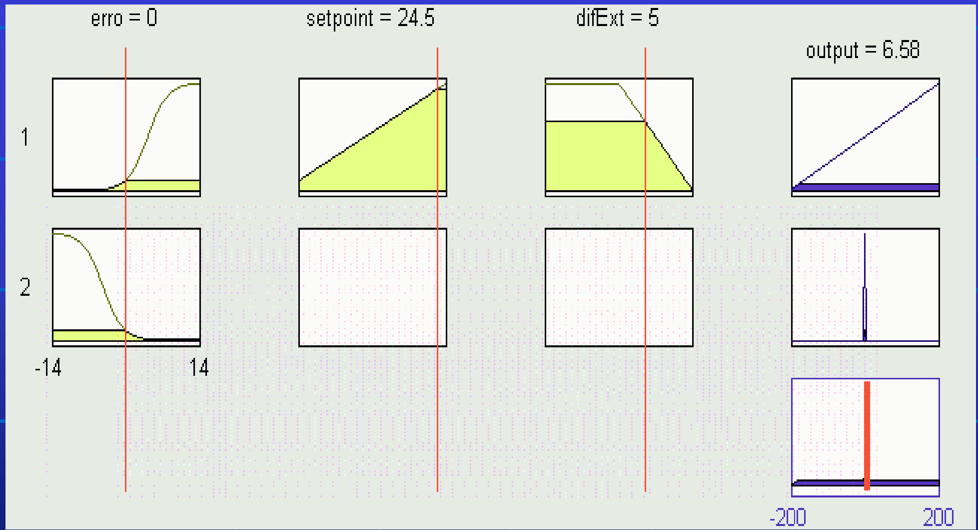
1
extern
disturb
Gss qr
Gr2
qr
Tw Tiw
Gw2
Tiw
Kw
qw
2
T_vic1
Tf Tiv
Gv1
Tiv
Kv
3
T_vic3
Tf Tiv
Gv2
Tiv
Kv
qv
4
T_vic4
Tf Tiv
Gv3
Kv
qd
Room
Thermal
Capacitance
1/C2
1
s
Intg
T2
5
Cool_on_off
Chiller Temp.
4
S2
Tc
Gss qr
Gc2
Tic
Kc
qc
2
T2
1
Tc2

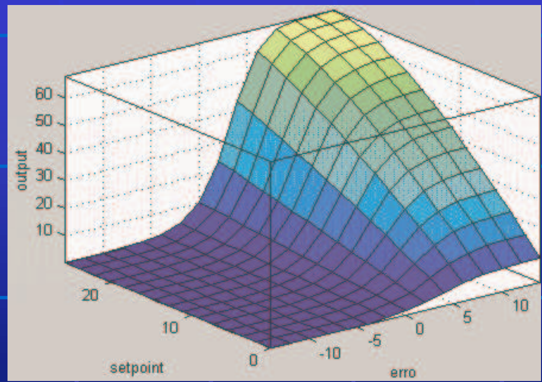
Controller

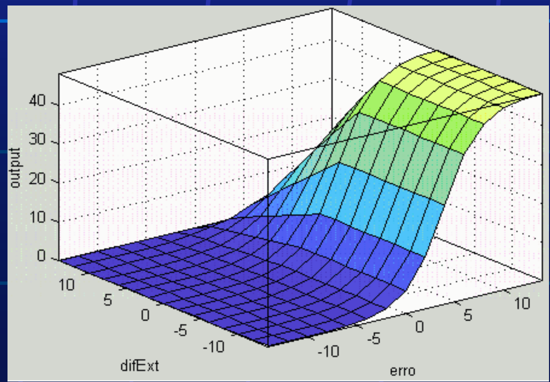


1
ref
e
Out
Pass if
Work Hour
2
difExt
3
y
predialSpin
Switch
0
K-
Ki1
1
s
I
~
==
S2
Out
Pass if
Work Hour1
PWM1
1
PWM
Prod.
1
s
Integ.
2
KWh/ISE

Fuzzy Rule Basis



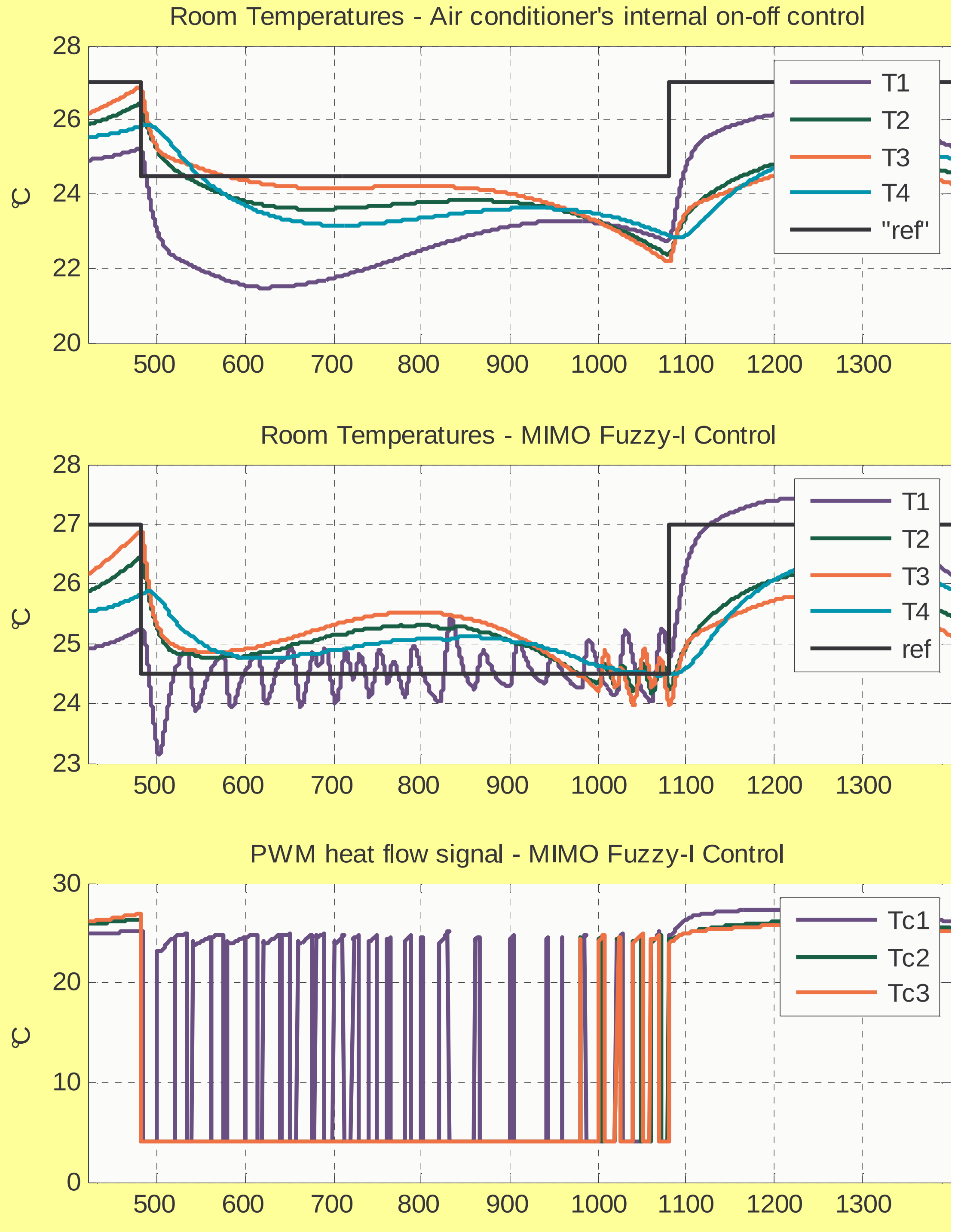




1) *IF (erro = p) AND (setpoint = set) AND (Difext = d) THEN (output = p)*

2) *IF (erro = n) THEN (output = zero)*

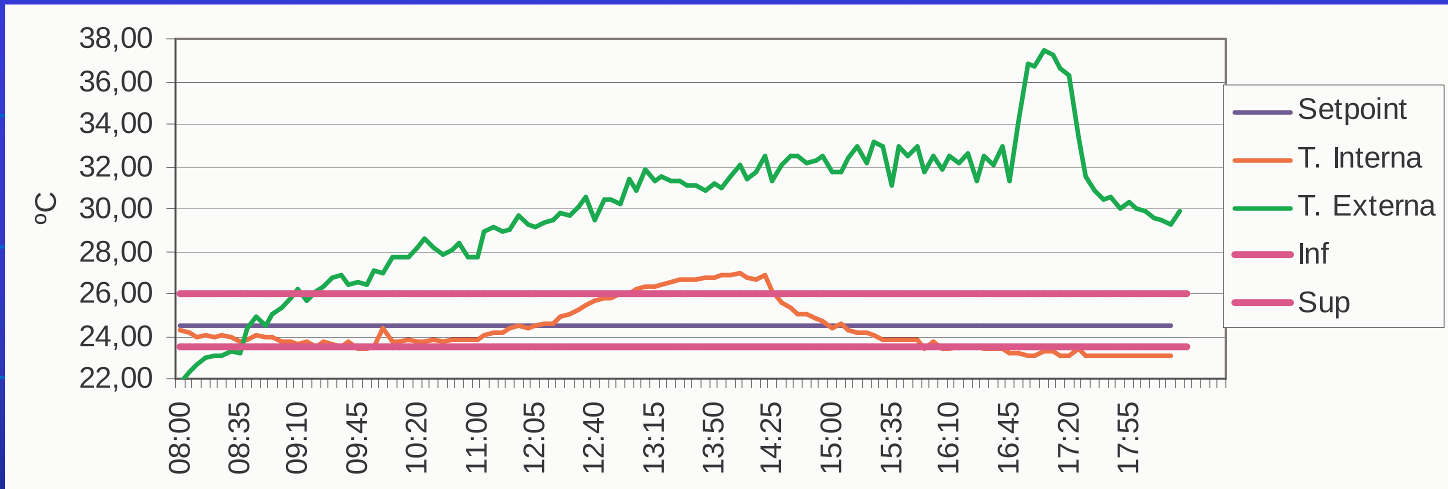
Simulation Results



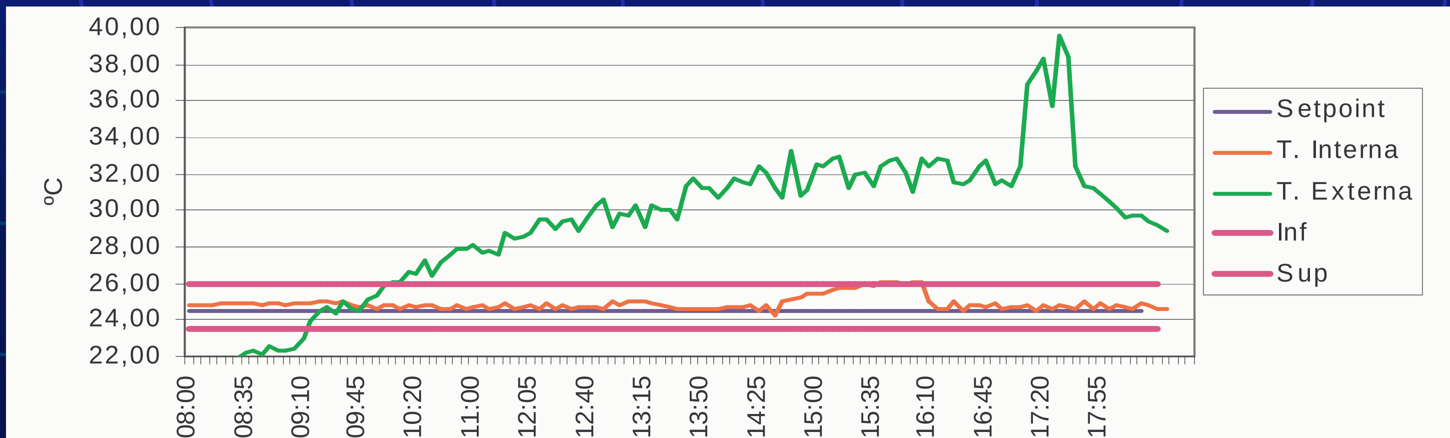
Distributed building controller Prototype

Developing Room

On-Off 16-09-2006

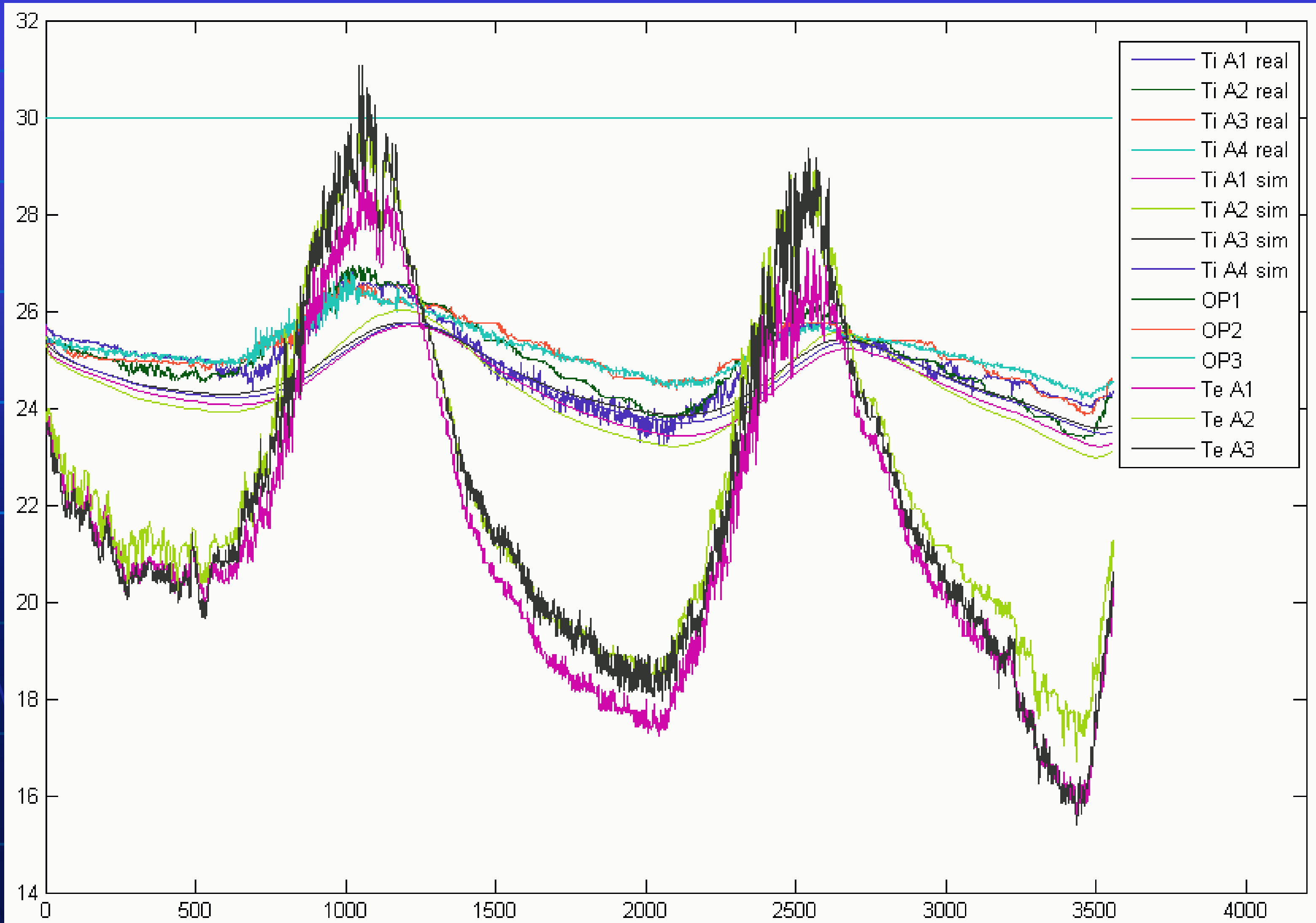


Fuzzy Control 14-09-2006



~30% saving!

Measured and Reconstructed Signals - Multi-Room Experiment (June 2007)



Intelligent Building Automation
Wire Less Prototype – LAVSI-LARA/ENE-UnB

Singular Systems (Descriptor Systems)

João Yoshiyuki Ishihara

Outline

- Introduction
- What is a singular system (descriptor system)?
- Examples of descriptor modeling
- Some results: stability, filtering
- Future work related to PROBRAL

What is a singular system (descriptor)?

$$f\left(x(t),\dot{x}(t),u(t)\right)=0$$

Implicit equations

Linear case

$$E\dot{x}(t)=Ax(t)+Bu(t)$$

Singular equations

In particular:

$$\dot{x}(t)=Ax(t)+Bu(t)$$

Usual state-space equations

What is a singular system (descriptor)?

Another characterization

$$E\dot{x}(t) = Ax(t) + Bu(t)$$

Can be re-written as:

$$\begin{aligned} \dot{x}(t) &= Fx(t) + Gu(t) \\ 0 &= Hx(t) + Ju(t) \end{aligned}$$

Differential-algebraic equations

Descriptor model

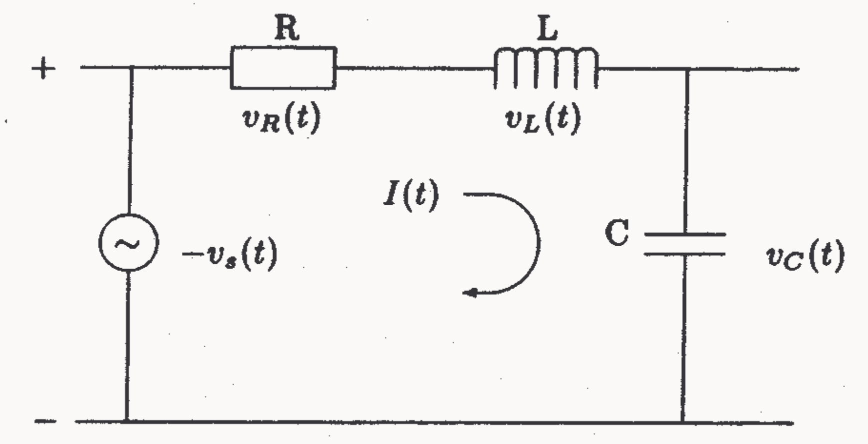


Fig. 2. A simple RLC circuit.

RLC circuit equations

$$L\frac{dI(t)}{dt} = v_L(t)$$

$$\frac{dv_C(t)}{dt} = \frac{1}{C}I(t)$$

$$0 = -RI(t) + v_R(t)$$

$$0 = v_L(t) + v_C(t) + v_R(t) + v_S(t)$$

$$E\dot{x}(t) = Ax(t) + Bu(t)$$

$$\begin{bmatrix} L & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{I}(t) \\ \dot{v}_L(t) \\ \dot{v}_C(t) \\ \dot{v}_R(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1/C & 0 & 0 & 0 \\ -R & 0 & 0 & 1 \\ 0 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} I(t) \\ v_L(t) \\ v_C(t) \\ v_R(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} v_S(t)$$

$$y(t) = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix} x(t)$$

descriptor equations

Example: Robot with Restricted Motion

Minimização de energia para robôs com restrição
Trabalho de mestrado no LAC - Aluno: Cauê Peres
Orientador: Paulo Sérgio P. da Silva
Ano - 2002

Robot with Restricted Motion

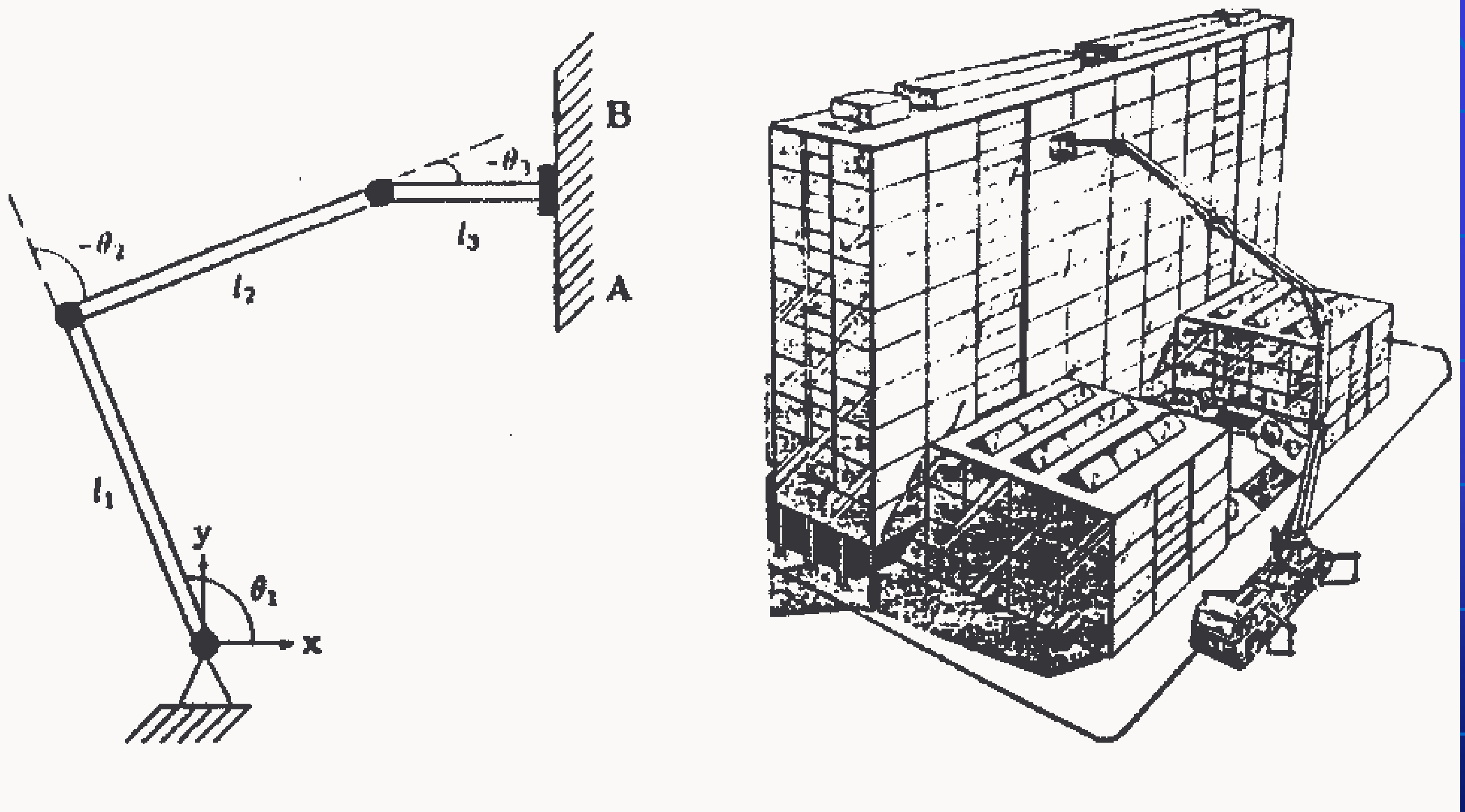


Fig. 1. A three link mobile manipulator [29].

$$\begin{bmatrix} I_3 & 0 & 0 \\ 0 & M_0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \dot{x} = \begin{bmatrix} 0 & I_3 & 0 \\ -K_0 & -D_0 & F_0^T \\ F_0 & 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ S_0 \\ 0 \end{bmatrix} u$$

Example: Perturbation analysis of large systems

Large systems: small parameters are set to zero

$$x_1(k+1) = A_{11}x_1(k) + A_{12}x_2(k) + B_1u(k)$$
$$\varepsilon x_2(k+1) = A_{21}x_1(k) + A_{22}x_2(k) + B_2u(k)$$

Simplified model

$$x_1(k+1) = A_{11}x_1(k) + A_{12}x_2(k) + B_1u(k)$$
$$0 = A_{21}x_1(k) + A_{22}x_2(k) + B_2u(k)$$

$$Ex(k+1) = Ax(k) + Bu(k)$$

Example: interconnected systems

Large systems: collection of interconnected subsystems

$$
\begin{aligned}
x_i(k+1) &= A_i x_i(k) + B_i w_i(k) \\
z_i(k) &= C_i x_i(k) + D_i w_i(k)
\end{aligned}
$$

Overall subsystem equation

$$
\begin{aligned}
x(k+1) &= Ax(k) + Bw(k) \\
z(k) &= Cx(k) + Dw(k)
\end{aligned}
$$

Interconnections:
overall input u(k) and
overall output y(k)

$$
\begin{aligned}
w(k) &= Kz(k) + Mu(k) + Ny(k) \\
y(k) &= Pz(k) + Qu(k) + Rw(k)
\end{aligned}
$$

$$
\begin{aligned}
E\xi(k+1) &= F\xi(k) + Gu(k) \\
y(k) &= H\xi(k) + Ju(k)
\end{aligned}
$$

Obs: A state-space representation may not exist for some interconnected systems

A system with no state equations

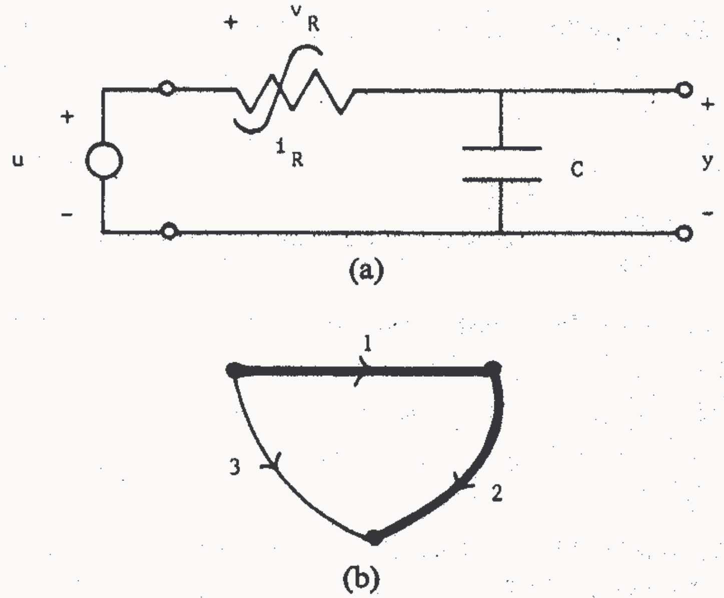


Fig. 7. (a) Circuit with semistate but no state equations. (b) Graph.

$$v_R = -3i_R + i_R^3$$

$$\begin{bmatrix} 0 & C & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}\dot{x} + \left\{ \begin{bmatrix} 0 & 0 & 1 \\ 1 & 1 & 0 \\ 1 & 0 & -3 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ x^3 \end{bmatrix} \right\} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} u$$

$$y = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} x$$

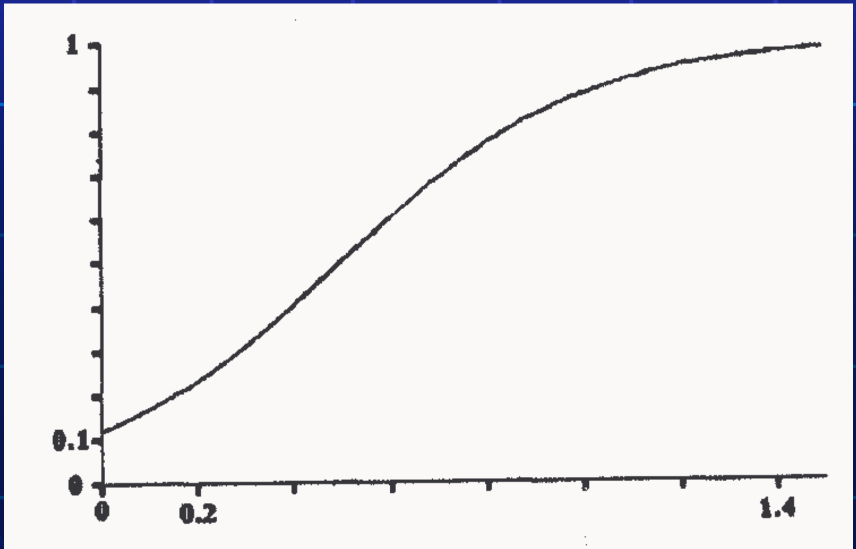
Example 2: system with no state equations

Agricultural production growing curve

$$\dot{\bar{y}}(t)/\bar{y}(t) = \kappa(\bar{y}^* - \bar{y}(t))$$

Logistic function

$$\bar{y}(t) = \bar{y}^* \frac{e^{\kappa \bar{y}^*(t-t^*)}}{1 + e^{\kappa \bar{y}^*(t-t^*)}}$$



3 parts:
* Exponential growth
* Linear growth
* Logaritmic growth

Example 2: system with no state equations

The agricultural production growing curve
is solution of the following singular system

$$
\begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix} \dot{x} =
\begin{bmatrix}
-\bar{s}_1 & -s_1 & \frac{1}{|\alpha|} - \alpha & 1 & \alpha & \alpha & 0 & 0 & 0 \\
a - 1 & 0 & -\bar{a} & -a & 1 - a\alpha & 1 & 0 & 0 & 0 \\
0 & 0 & \alpha - 1 & 0 & -\alpha & -\alpha & \frac{1}{|s_2|} & 1 & 0 \\
0 & 0 & 0 & 0 & -1 & 0 & \frac{1}{|s_2|} - 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & s_2 - 1 & -s_2 & 0
\end{bmatrix} x
+ \begin{bmatrix} 0 & 0 & 0 & 0 & \left(\omega_o^2 \cdot |\alpha| \cdot |a|\right) \end{bmatrix}^T u
$$

$$
y = \begin{bmatrix} |a|^{-1} & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} x
$$

Impulsive Responses

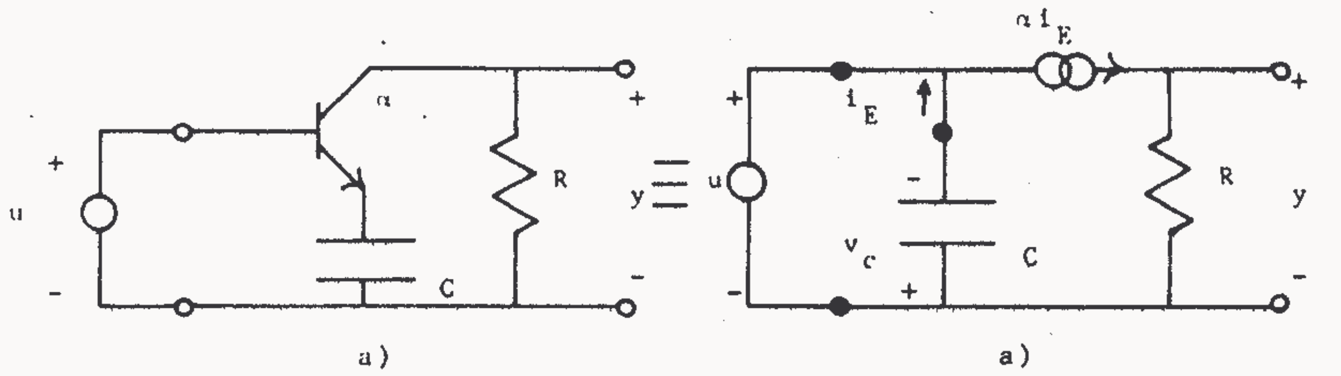


Fig. 10. Circuit for $T(s)$ with pole at infinity.

Transistor model

$$\begin{bmatrix} C & 0 \\ 0 & 0 \end{bmatrix}\dot{x}(t)=\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}x(t)+\begin{bmatrix} 0 \\ 1 \end{bmatrix}u(t),\ t\geq 0,\ x=\begin{bmatrix} v_C \\ i_E \end{bmatrix}$$

$$y=\begin{bmatrix} 0 & \alpha R \end{bmatrix}x$$

In the state space formulation we have information loss (Impulsive solution)

Example: Filtering of non causal system

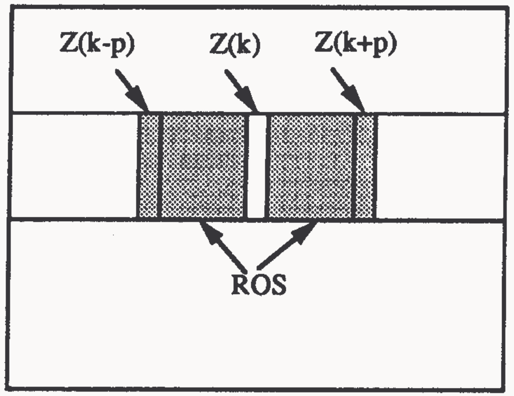


Fig. 1. ROS of noncausal model.

$$Ex(k+1) = Fx(k) + Gu(k)$$
$$z(k) = Hx(k)$$

$$x(k) = \left[z^T(k-p) \quad z^T(k) \quad z^T(k+p)\right]^T$$

$$E = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad F = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ \frac{\rho}{1+\rho^2} & 0 & -1 & 0 & \frac{\rho}{1+\rho^2} & 0 \\ 0 & \frac{\rho}{1+\rho^2} & 0 & -1 & 0 & \frac{\rho}{1+\rho^2} \end{bmatrix}$$

$$G = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T \qquad H = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

Pros and Cons for descriptor modeling

- Riccati equations are related to Hamiltonian extended pencils
  (which are in descriptor form)
- State-space systems are not closed under PID feedback
- Any rational transfer function can be represented by a descriptor system

Pros and Cons for descriptor modeling

- It is a very natural way to model process dynamics.
- It refers much more to the physical behavior of the system and gives more physical insight.
- The interpretation of results is also more simple than in case of the more abstract state space models.

Aplication: Liquid Level Control System

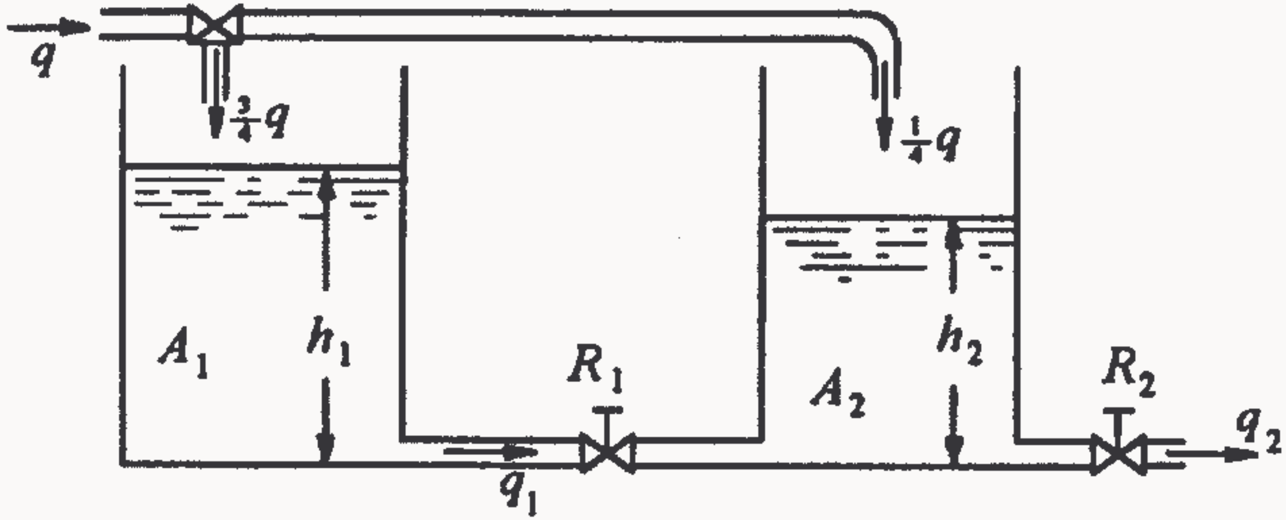


Figure 1: A liquid-level control system

q, q_1, q_2 : rates of the flow of liquid (m^3/sec);

A_1, A_2 : areas of the cross-section of tanks (m^2);

h_1, h_2 : liquid levels (m);

R_1, R_2 : flow resistance (sec/m^2);

Aplication: Liquid Level Control System

State Space Model

$$\begin{bmatrix}\dot{h}_1\\ \dot{h}_2\end{bmatrix}=\begin{bmatrix}-\dfrac{1}{A_1R_1} & \dfrac{1}{A_1R_1}\\ \dfrac{1}{A_2R_1} & -\dfrac{R_1+R_2}{A_2R_1R_2}\end{bmatrix}\begin{bmatrix}h_1\\ h_2\end{bmatrix}+\begin{bmatrix}\dfrac{3}{4A_1}\\ \dfrac{1}{4A_2}\end{bmatrix}q$$

Descriptor Model

$$\begin{bmatrix}A_1 & 0 & 0 & 0\\ 0 & A_2 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\dot{h}_1\\ \dot{h}_2\\ \dot{q}_1\\ \dot{q}_2\end{bmatrix}=\begin{bmatrix}0 & 0 & -1 & 0\\ 0 & 0 & 1 & -1\\ -1 & 1 & R_1 & 0\\ 0 & -1 & 0 & R_2\end{bmatrix}\begin{bmatrix}h_1\\ h_2\\ q_1\\ q_2\end{bmatrix}+\begin{bmatrix}3/4\\ 1/4\\ 0\\ 0\end{bmatrix}q$$

Liquid Level Control System - Closed loop

State feedback

$$q = -K_s x_s = -\begin{bmatrix} K_1 & K_2 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix}$$

$$q = -K_d x_d = -\begin{bmatrix} K_1 & K_2 & 0 & 0 \end{bmatrix} \begin{bmatrix} h_1 & h_2 & q_1 & q_2 \end{bmatrix}^T$$

$$\begin{bmatrix} \dot{h}_1 \\ \dot{h}_2 \end{bmatrix} = \begin{bmatrix} -\dfrac{4+3R_1K_1}{4A_1R_1} & \dfrac{4-3R_1K_2}{4A_1R_1} \\ \dfrac{4-K_1}{4A_2R_1} & -\dfrac{4R_1+4R_2+K_2}{4A_2R_1R_2} \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} \equiv \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix} x_s$$

$$\begin{bmatrix} A_1 & 0 & 0 & 0 \\ 0 & A_2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{h}_1 \\ \dot{h}_2 \\ \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} = \begin{bmatrix} -\frac{3}{4}K_1 & -\frac{3}{4}K_2 & -1 & 0 \\ -\frac{1}{4}K_1 & -\frac{1}{4}K_2 & 1 & -1 \\ -1 & 1 & R_1 & 0 \\ 0 & -1 & 0 & R_2 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ q_1 \\ q_2 \end{bmatrix}$$

The extension of state space results to descriptor systems are not direct.

Example Stability: Classical Result in the Literature

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Ax(t) + Bu(t)$$

$$A^T P + PA + C^T C = 0$$

Descriptor versions

$$E\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Ax(t) + Bu(t)$$

$$A^T PE + E^T PA + E^T C^T CE = 0, P \geq 0$$

$$A^T PE + E^T PA + C^T C = 0, E^T PE \geq 0$$

$$A^T(PE + E_0 Q) + (PE + E_0 Q)^T A + C^T C = 0, P \geq 0$$

(Ishihara et al., 2002)

$$A^T X + XA + C^T C = 0, E^T X = X^T E \geq 0$$

Kalman type Filter for Singular Systems

$$
\begin{aligned}
E_{i+1}x_{i+1} &= F_i x_i + G_i w_i \\
z_{i+1} &= H_{i+1}x_{i+1} + K_{i+1}v_{i+1}
\end{aligned}
\qquad
\operatorname{cov}\left(\begin{bmatrix} w_i \\ v_{i+1} \end{bmatrix}\right) = \begin{bmatrix} Q_i & S_i \\ S_i^T & R_{i+1} \end{bmatrix}
$$

The filtered estimates recursion

$$
\begin{bmatrix} \hat{x}_{i+1|i+1} & P_{i+1|i+1} \end{bmatrix} =
\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ I \end{bmatrix}^T
\begin{bmatrix}
P_{i|i} & & & I & & \\
 & \begin{bmatrix} Q_i & S_i \\ S_i^T & R_{i+1} \end{bmatrix} & & & \begin{bmatrix} I & \\ & I \end{bmatrix} & \\
 & & & \begin{bmatrix} F_i \\ \end{bmatrix} & \begin{bmatrix} G_i & \\ & K_{i+1} \end{bmatrix} & \begin{bmatrix} E_{i+1} \\ H_{i+1} \end{bmatrix} \\
I & & \begin{bmatrix} F_i^T & \end{bmatrix} & & & \\
 & \begin{bmatrix} I & \\ & I \end{bmatrix} & \begin{bmatrix} G_i^T & \\ & K_{i+1}^T \end{bmatrix} & & & \\
 & & \begin{bmatrix} E_{i+1}^T & H_{i+1}^T \end{bmatrix} & & &
\end{bmatrix}^{-1}
\begin{bmatrix}
\hat{x}_{i|i} & 0 \\
\begin{bmatrix} 0 \\ 0 \end{bmatrix} & \\
\begin{bmatrix} 0 \\ z_{i+1} \end{bmatrix} & \\
0 & \\
 & \\
 & -I
\end{bmatrix}
$$

(Ishihara et al., 2005)

Kalman type filter for Singular systems

If $S_i = 0, G_i = I, K_i = I$

The filtered estimates recursion

$$\begin{bmatrix} \hat{x}_{i+1|i+1} & P_{i+1|i+1} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ I \end{bmatrix}^T \begin{bmatrix} P_{i|i} & & & I & & \\ & \begin{bmatrix} Q_i & S_i \\ S_i^T & R_{i+1} \end{bmatrix} & & & \begin{bmatrix} I & \\ & I \end{bmatrix} & \\ & & & \begin{bmatrix} F_i \\ \ \end{bmatrix} & \begin{bmatrix} G_i & \\ & K_{i+1} \end{bmatrix} & \begin{bmatrix} E_{i+1} \\ H_{i+1} \end{bmatrix} \\ I & & \begin{bmatrix} F_i^T & \ \end{bmatrix} & & & \\ & \begin{bmatrix} I & \\ & I \end{bmatrix} & \begin{bmatrix} G_i^T & \\ & K_{i+1}^T \end{bmatrix} & & & \\ & & \begin{bmatrix} E_{i+1}^T & H_{i+1}^T \end{bmatrix} & & & \end{bmatrix} \begin{bmatrix} \hat{x}_{i|i} & 0 \\ \begin{bmatrix} 0 \\ 0 \end{bmatrix} & \\ \begin{bmatrix} 0 \\ z_{i+1} \end{bmatrix} & \\ 0 & \\ & \\ & -I \end{bmatrix}$$

Can be rewritten as

$$\hat{x}_{i+1|i+1} = P_{i+1|i+1} E_{i+1}^T \left(Q_i + F_i P_{i|i} F_i^T \right)^{-1} F_i \hat{x}_{i|i} + P_{i+1|i+1} H_{i+1}^T R_{i+1}^{-1} z_{i+1}$$

$$P_{i+1|i+1} = [E_{i+1}^T \left(Q_i + F_i P_{i|i} F_i^T \right)^{-1} E_{i+1} + H_{i+1}^T R_{i+1}^{-1} H_{i+1}]^{-1}$$

The a priori filter is not equivalent to the a posteriori filter

Robust Filtering

- System with uncertainties :

$$(E_{i+1}+\delta E_{i+1})x_{i+1}=(F_i+\delta F_i)x_i+w_i$$
$$z_i=(H_i+\delta H_i)x_i+v_i$$

$$\delta F_i = M_{f,i}\Delta_i N_{f,i}$$
$$\delta E_{i+1} = M_{f,i}\Delta_i N_{e,i+1}$$
$$\delta H_i = M_{h,i}\Delta_i N_{h,i}$$
$$\|\Delta_i\| \le 1$$

$$\mathrm{E}\left(\begin{bmatrix} x_0 \\ w_i \\ v_i \end{bmatrix}\begin{bmatrix} x_0 \\ w_i \\ v_i \end{bmatrix}^T\right)=\begin{bmatrix} P_0 & & \\ & Q_i\delta_{ij} & \\ & & R_i\delta_{ij} \end{bmatrix}>0$$

$$\Rightarrow \hat{x}_{k|k},\ \hat{x}_{k+1|k},\ \hat{x}_{k-1|k}$$

Kalman-type Robust Filter

$$(E_{i+1} + \delta E_{i+1})x_{i+1} = (F_i + \delta F_i)x_i + w_i$$

$$z_i = (H_i + \delta H_i)x_i + v_i$$

Robust filter

$$\hat{x}_{i+1|i+1} = \{P_{i+1|i+1}[\hat{E}_{i+1}^T\left(\hat{Q}_i + F_i\hat{P}_{i|i}F_i^T\right)^{-1}F_i + \hat{\lambda}_i N_{e,i+1}^T N_{f,i}](I - \hat{\lambda}_i \hat{P}_{i|i} N_{e,i+1}^T N_{f,i})\}\hat{x}_{i|i}$$

$$+ P_{i+1|i+1} H_{i+1}^T \hat{R}_{i+1}^{-1} z_{i+1}$$

$$P_{i+1|i+1}{}^{-1} = \hat{E}_{i+1}^T\left(\hat{Q}_i + F_i\hat{P}_{i|i}F_i^T\right)^{-1}\hat{E}_{i+1} + H_{i+1}^T\hat{R}_{i+1}^{-1}H_{i+1}$$

$$+ \hat{\lambda}_i[N_{h,i+1}^T N_{h,i+1} + N_{e,i+1}^T (I + \hat{\lambda}_i N_{f,i} P_{i|i} N_{f,i}^T)^{-1} N_{e,i+1}]$$

Future work related to PROBRAL

1) Descriptor systems with Markovian jumping

$$E_{\theta(i+1)} x_{i+1} = F_{\theta(i)} x_i + G_{\theta(i)} w_i$$

$$z_i = H_{\theta(i)} x_i + K_{\theta(i)} v_i$$

Already done: array algorithms for filters of Markovian jumping Linear systems

2) other possibilities?

Conclusion & Perspectives

- Wire Less Automated Building
  as NCS Test Bed

- Modelling of Thermal Processes
- Stability Analysis of NCS + Distributed Automation
- Specific Hardware x COTS
  for distributed automation

? UnB + KL ?

Danke! Obrigado!

Wir freuen uns auf die Zusammenarbeit!

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