EBCCSP 2017

3rd International Conference on Event-Based Control, Communication and Signal Processing

A panoramic overview of event based control: A retrospective look from the seventies

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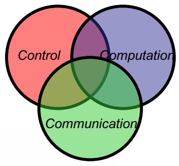

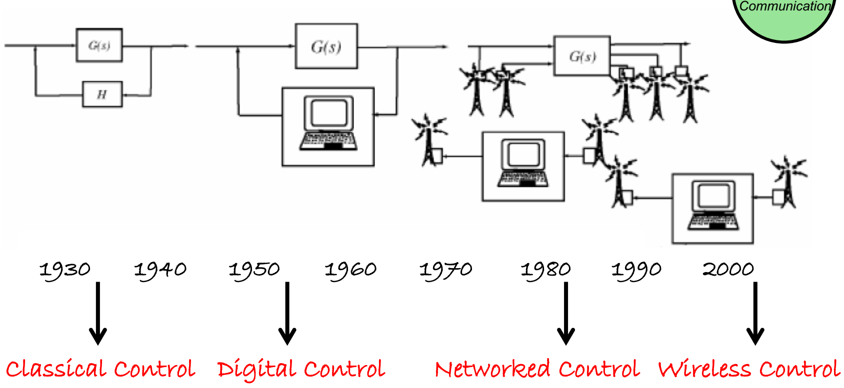

J. Baillieul,, P. Antsaklis, "Control and Communication Challenges in Networked Real-Time Systems", *Proc. IEEE*, january 2007, pp. 9-27

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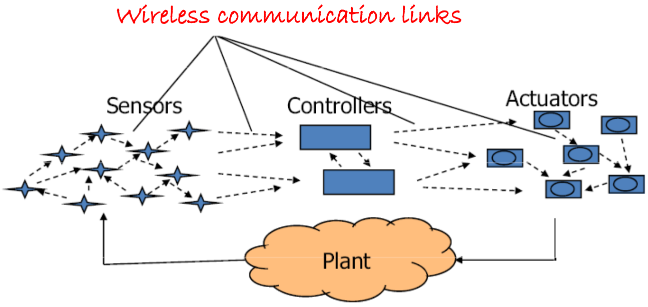
1. Introduction

Control over wireless networks

How to control a plant when sensor, actuator and controller nodes are wireless network devices?



How trade off network resources and control performance?

How move intelligence from central units to local devices?

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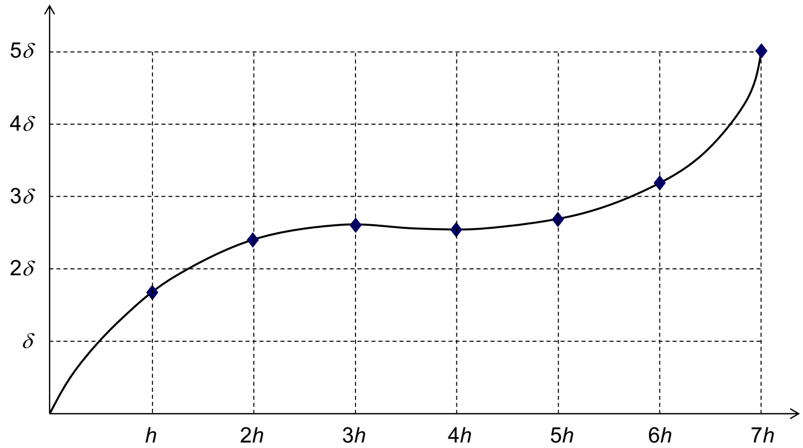
1. Introduction

Time based sampling



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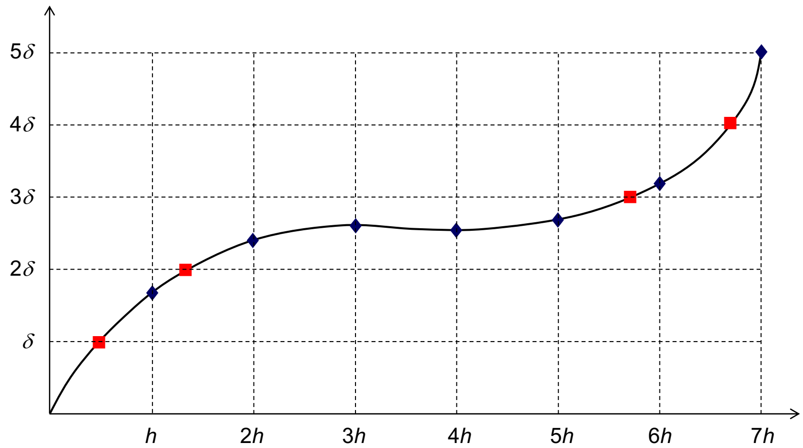
1. Introduction

Time based or event based sampling?



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1. Introduction

Main characteristics

Time based sampling	Event based sampling
▪ Represent $y(t)$ by $\{y(kh)\}$ ▪ Injectivity if $h < 1/f_N$ (Shannon) ▪ LTI systems $\Rightarrow$ periodic systems ▪ Theory developed and mature ▪ Powerful control design methods ▪ Safe implementation ▪ Training oriented	▪ Represent $y(t)$ by $\{t_i\}$; $y(t_i) = n\delta$ ▪ Actuators event based ▪ Sensors event based ▪ δ-Σ, IPFM modulators ▪ Process supervision (SPC) ▪ Pulse feedback systems ▪ Real neurons

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1. Introduction

Dificulties with:

Time based sampling	Event based sampling
▪ Multirate sampling ▪ Distribuited systems: asynchronism ▪ Communication networks ▪ Variable delays ▪ Sampling jitter ▪ Biológical systems–no central clock	▪ Very active research topic

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1. Introduction

Event-Based Control

In an event based control system is the event ocurrence, instead of the pass of time, what decides when a dynamic system must be sampled.

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1. Introduction

Event-Based Control

- Main idea: Act only when needed
  - Save computation and communication resources
  - Act faster once you really have to act
- Main challenges:
  - Difficult, theory under development
  - Too much design freedom

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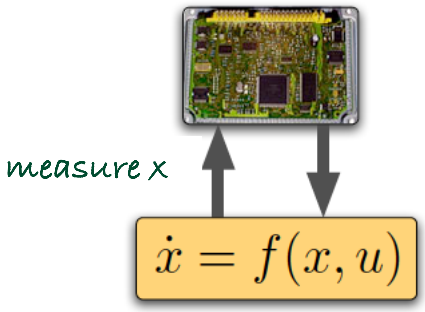
1. Introduction

Feedback control loops are typically implemented on microprocessors



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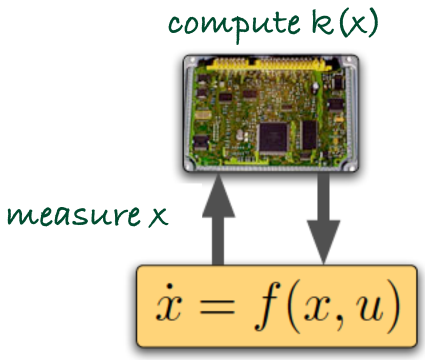
1. Introduction

Feedback control loops are typically implemented on microprocessors



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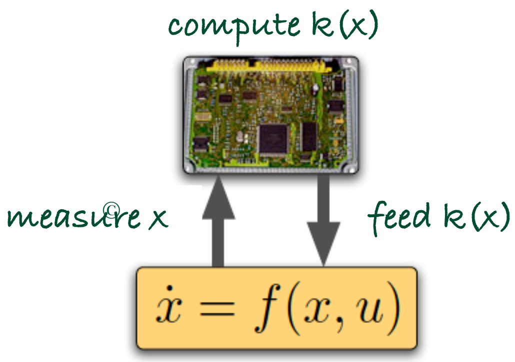
1. Introduction

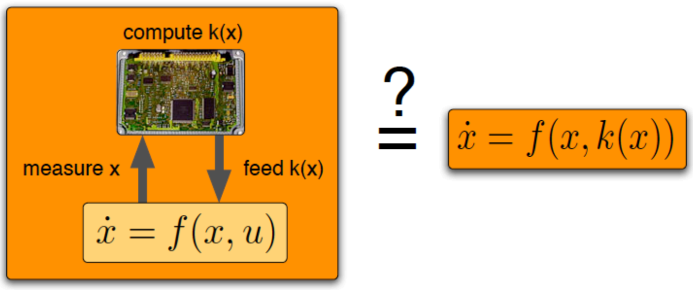
Feedback control loops are typically implemented on microprocessors



1. Introduction

However, most of control theory was developed by ignoring the implementation details.

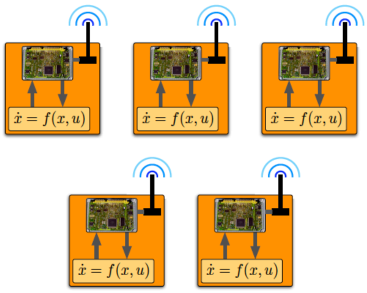
If the computation of k(x) is sufficiently fast, if sensors and actuators are sufficiently accurate.

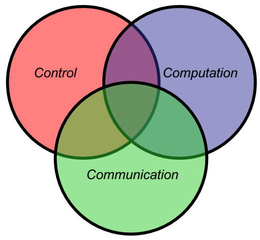


implementation will converge to the specification

1. Introduction

We need a design theory integrating control, computation, and communication





With the advent of networked embedded control systems, we can no longer rely on the assumption of dedicated hardware,

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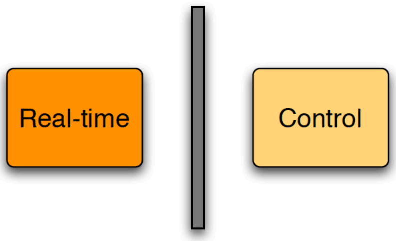
1. Introduction



- The design and implementation of feedback control laws on microprocessors has traditionally been decoupled from real-time scheduling through a "separation of concerns" obtained by treating control tasks as periodic.

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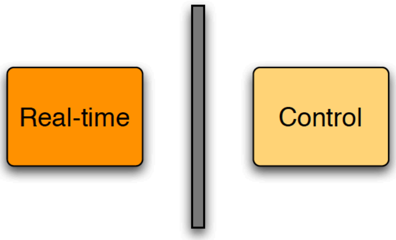
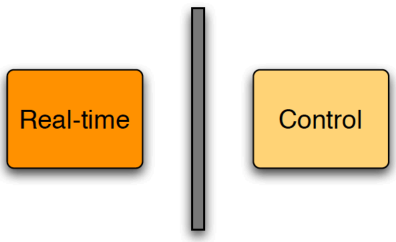
1. Introduction



- The design and implementation of feedback control laws on microprocessors has traditionally been decoupled from real-time scheduling through a "separation of concerns" obtained by treating control tasks as periodic.
  - Control engineers can design controllers while ignoring the implementations details.
  - Software engineers can schedule tasks while ignoring their functionality.

1. Introduction



- Although this "separation of concerns" simplifies the design process, it also results in inefficient usage of resources.
- From a purely theoretical perspective, executing control tasks in a periodic fashion seems unnatural and inconsiderate to the dynamics.
- Even if we accept the periodic paradigm, it is unsettling that we still do not understand how the sampling or execution period should be chosen!.

1. Introduction

Abandon the periodic paradigm in favor of event-triggered and self-triggered control

Why?

- In the context of sensor-actuator networks we would like to execute control tasks as rarely as possible in order to minimize energy consumption due to communication.
- Even if energy is not a concern, the less often control tasks are executed the more processor time is available for other (less) important tasks.
- Ideally, the scheduler should be able to dynamically adjust the quality of control (and implicitly the execution times, deadlines, …) to respond to overloads and other transients.

2. The idea of adaptive sampling

IEEE Control Systems Magazine, 27(4), pp. 19, 2007

This column is the first installment of a new department in which readers are invited to submit technical questions, which will be directed to experts in the field. Please write to us about any topic, problem, or question relating to control-system technology.

The expert we called upon to inaugurate this column is Gene Franklin. Gene is the recipient of the 2005 AACC Richard E. Bellman Control Heritage Award. His acceptance speech can be found in the December 2005 issue of *IEEE Control Systems Magazine*. Gene is a faculty member in the Electrical Engineering Department of Stanford University.

Q. As my first assignment as a control engineer, my supervisor has tasked me with developing specifications for a digital control system. Do you have any advice on how I should select the sampling frequency?

Gene: In general, overall system performance and budgets press to push control engineers to set as low a sampling rate as possible. Within this environment, the following three rules guide sample rate selection:

1) Sample as fast as project managers, technology, and money permit.
2) Follow the guidelines given in standard textbooks, such as Chapter 11 of [1].
3) Select a "reasonable" rate and explore other choices by simulation.

Three major factors influenced by sample rate are aliasing, dynamic response, and disturbance rejection. Aliasing is the name given to the fact that samples from a sinusoid whose frequency is higher than half the sampling frequency are identical with samples taken from an aliased sinusoid at a frequency inside that range. As a result, the sampling rate must be sufficiently high that all frequencies of interest in the closed loop can get by a lowpass filter designed to prevent aliasing. If dynamic response is measured by the step response, a good rule is to sample at least five to ten times per rise time. This rule may be translated to conclude that the sample frequency should be at least 20 times the system bandwidth.

For disturbance rejection and stability margins, one can sketch out a design as if the system is to be continuous time and then set the sample frequency at 20 times the resulting system bandwidth. Afterwards, the design should be recomputed in the discrete domain to be sure the closed-loop poles are properly mapped. Finally, go back to step three and simulate the result since, as the saying goes, "The proof of the pudding is in the eating."

REFERENCE

[1] G.F. Franklin, J.D. Powell, and M.L. Workman, *Digital Control of Dynamic Systems*, 3rd ed. Ellis-Kagle Press, 2006. http://www.digitalcontroldynsys.com/

2. The idea of adaptive sampling

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2. The idea of adaptive sampling

Selection of the sampling period in sampled systems is a fundamental problem. The proper choice depends on the properties of the signal,the reconstruction method and the purpose of the system.

- In a pure signal-processing problem, the purpose is simply to record a signal digitally and to recover it from its samples. A reasonable criterion may be the size of the error between the the original signal and the reconstructed signal. It can be justified to have sampling rates of several hundred samples per period.
- In a closed-loop control system should be based of an understanding of its influence on the performance of the control system. It seems reasonable that the highest frequency of interest should be closely related to the bandwidth of the closed-loop system.

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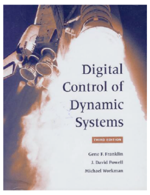
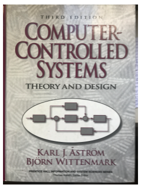
2. The idea of adaptive sampling



"… at least 20 times the closed-loop bandwidth…"



"… at least 4 to 10 times per rise time…"

"… in general, the best sampling which can be chosen for a digital control system is the slowest rate that meets all the performance requirements."

$$\frac{1}{30 f_c} < \mathrm{T} < \frac{1}{5 f_c}$$

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2. The idea of adaptive sampling

The aim of using an adaptive sampling scheme in a sampled-data control system is to improve the sampling efficiency

- The sampling period T_i is allowed to vary from interval to interval in order to reduce the number of samples without sacrificing appreciably the quality of the system response.
- The main design problem is to determine an algorithm (control law) which automatically adjusts T_i based on the time characteristics of the sampled signal $e(t)$ or other signals in the system.

The term "adaptive sampling" was coined by Dorf et al.
In a classical paper published in the sixties

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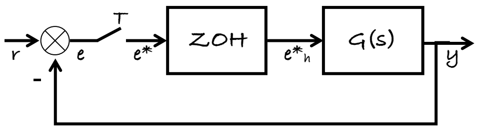
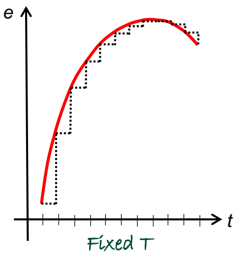
2. The idea of adaptive sampling

R. C. Dorf, M. C. Farren, C. A. Phillips. "Adaptive sampling frequency for sampled-data control systems", *IRE Transactions on Automatic Control*, 38-47, January 1962



Basic sampled-data control system



Fixed T

How to select the sampling period T

$$T_{min} \leq T \leq T_{max}$$

1) T_{max}: Stability considerations

2) T_{min}: It is not necessary to sample with shorter periods than T_{min} since faster sampling provides little information to improve the system response

Input and output of sampler and zero-order hold

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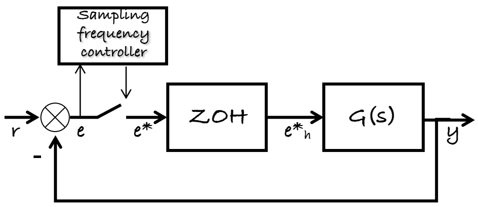
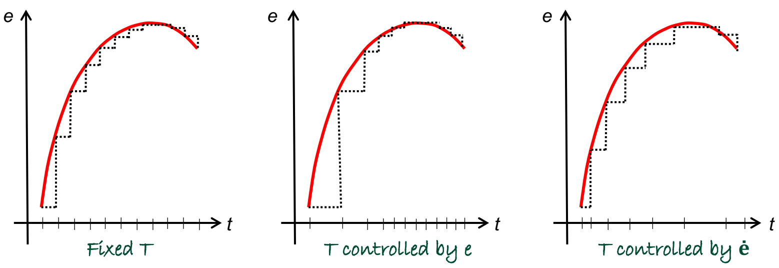
2. The idea of adaptive sampling

R. C. Dorf, M. C. Farren, C. A. Phillips. "Adaptive sampling frequency for sampled-data control systems", *IRE Transactions on Automatic Control*, 38-47, January 1962



Block diagram of adaptive sampling



Fixed T | T controlled by e | T controlled by ė

Input and output of sampler and zero-order hold

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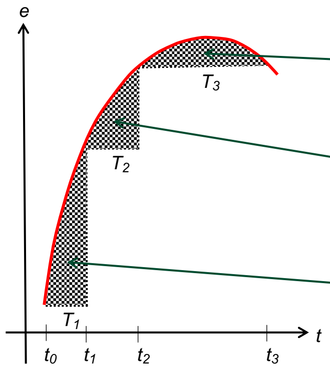
2. The idea of adaptive sampling

The calculation of the sampling law



$$\int_{t_2}^{t_3} (e - e_2^*)dt =$$

$$\int_{t_1}^{t_2} (e - e_1^*)dt =$$

$$\int_{t_0}^{t_1} (e - e_0^*)dt = \frac{C^2}{2}$$

Where C is a constant

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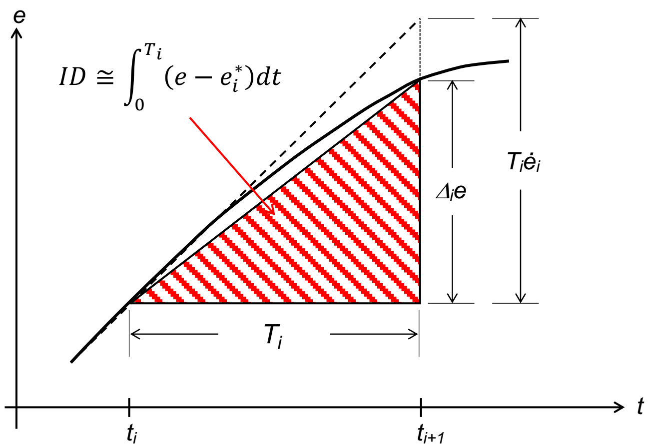
2. The idea of adaptive sampling

The calculation of the sampling law



Input and output of sampler and zero-order hold

Expansion of one sample period showing integral difference ID

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1. Introduction

The calculation of the sampling law

$$ID = \int_{t_i}^{t_{i+1}} (e - e_h^*)dt = \int_0^{T_i} (e - e_i^*)dt \qquad e \cong e_i + \dot{e}_i t$$

$$ID = \int_0^{T_i} (e_i + \dot{e}_i t - e_i^*)dt = \int_0^{T_i} \dot{e}_i t dt = \dot{e}_i \frac{T_i^2}{2}$$

If T_i is made a function of $\dot{\mathbf{e}}_i$ such that: $T_i = \frac{C}{\sqrt{|\dot{e}_i|}}$ (C is a constant)

Then the integral difference per sample period ID will be a constant:

$$ID = \pm \frac{C^2}{2}$$

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1. Introduction

The calculation of the sampling law

$$ID = \int_{t_i}^{t_{i+1}} (e - e_h^*)dt = \int_0^{T_i} (e - e_i^*)dt \qquad e \cong e_i + \dot{e}_i t$$

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If T_i is made a function of $\dot{\mathbf{e}}_i$ such that: $\boxed{T_i = \frac{C}{\sqrt{|\dot{e}_i|}}}$ (C is a constant)

Then the integral difference per sample period ID will be a constant:

$$\boxed{ID = \pm \frac{C^2}{2}}$$

adaptive sampling law

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2. The idea of adaptive sampling

Variable-sampling frequency control

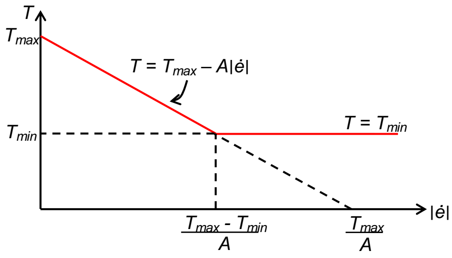
$$T_i = \frac{C}{\sqrt{|\dot{e}_i|}}$$

In the sixties such a function for T_i it was difficult to generate but could be approximated over a wide range by simpler functions

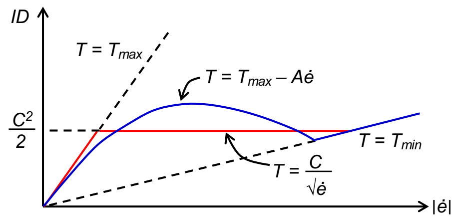
$$T = T(|\dot{e}|)$$

$$T = T_{max} - A|\dot{e}| \quad 0 \le |\dot{e}| \le \frac{T_{max} - T_{min}}{A}$$

$$T = T_{min} \qquad |\dot{e}| \ge \frac{T_{max} - T_{min}}{A}$$



Sampling period T vs $\dot{\mathbf{e}}$



Integral difference per sample period ID vs $\dot{\mathbf{e}}$

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2. The idea of adaptive sampling

Discrete-sampling frequency control

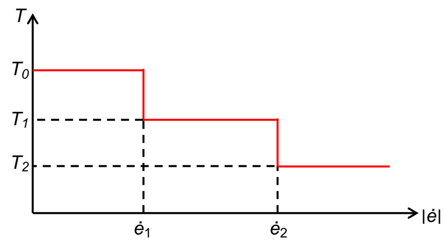
Another method of controlling the sampling frequency is by a number of fixed frequencies which are successi-vely used as $\dot{\mathbf{e}}$ increases

$$T = T(|\dot{e}|)$$

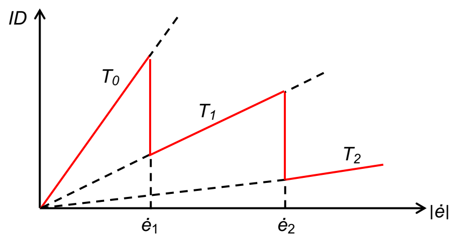
$$T = T_0 \qquad 0 < |\dot{e}| \le \dot{e}_1$$

$$T = T_1 \qquad \dot{e}_1 < |\dot{e}| \le \dot{e}_2$$

$$T = T_2 \qquad |\dot{e}| > \dot{e}_2$$



Sampling period T vs $\dot{\mathbf{e}}$



Integral difference per sample period ID vs $\dot{\mathbf{e}}$

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2. The idea of adaptive sampling

Analytic Design of Adaptive Control Law

The problem of adaptive sampling is to determine an algorithm for T_i ($T_i > 0$) which minimizes a given objective function $J = F(e(t),T_i)$. This algorithm is called the sampling control law

$$J_{ab}(T_i) = \underbrace{\frac{1}{(T_i)^a}\int_{t_i}^{t_i+T_i}(|e(t)-e(t_i)|)^b dt}_{\text{sampling error}} + \underbrace{Ae^{-BT_i}}_{\text{sampling cost}}$$

$T_i > 0$ and a, b are integers with $b > 0$, $b \in \{1,2\}$

$a = 1$ describes the mean value of the integral

$a = -1$ gives a time-weight integral

$a = 0$ yields an unweighted integral

$b = 1, 2$

$A, B > 0$ are positive weighting factors

T. C. Hsia. "Analytic Design of Adaptive Sampling Control Law in Sampled-Data Systems", *IEEE Trans on Automatic Control*, 39-42, february 1974

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2. The idea of adaptive sampling

Analytic Design of Adaptive Control Law

$$J_{ab}(T_i) = \underbrace{\frac{1}{(T_i)^a}\int_{t_i}^{t_i+T_i}(|e(t)-e(t_i)|)^b dt}_{\text{sampling error}} + \underbrace{Ae^{-BT_i}}_{\text{sampling cost}}$$

In practice T_i is bounded as $T_{min} \leqq T_i \leqq T_{max}$ where:

T_{max} Is the stability limit of the constant sampling period for the sampled-data system or it is imposed by the designer based on other considerations

T_{min} Is the largest constant sampling period below which the system response will not improve appreciably , or it is determined by the upper limit of the sampling rate of the sampler

T. C. Hsia. "Analytic Design of Adaptive Sampling Control Law in Sampled-Data Systems", *IEEE Trans on Automatic Control*, 39-42, february 1974

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2. The idea of adaptive sampling

Analytic Design of Adaptive Control Law

$$J_{ab}(T_i) = \underbrace{\frac{1}{(T_i)^a}\int_{t_i}^{t_i+T_i} (|e(t)-e(t_i)|)^b\,dt}_{\text{sampling error}} + \underbrace{Ae^{-BT_i}}_{\text{sampling cost}}$$

Solution for control law

Assuming that T_i is small, $e(t)$ can be approximated by the truncated Taylor series over each sampling interval:

$$e(t) \cong e(t_i) + \dot{e}(t_i)(t - t_i)$$

Approximations used for e^{-Bt_i} are:

Type 1 $\quad e^{-BT_i} \cong 1 - BT_i + B^2T_i^2/2$

Type 2 $\quad e^{-BT_i} \cong 1 - BT_i$

T. C. Hsia. "Analytic Design of Adaptive Sampling Control Law in Sampled-Data Systems", *IEEE Trans on Automatic Control*, 39-42, february 1974

2. The idea of adaptive sampling

Control Laws Derivable from the General Objective Function

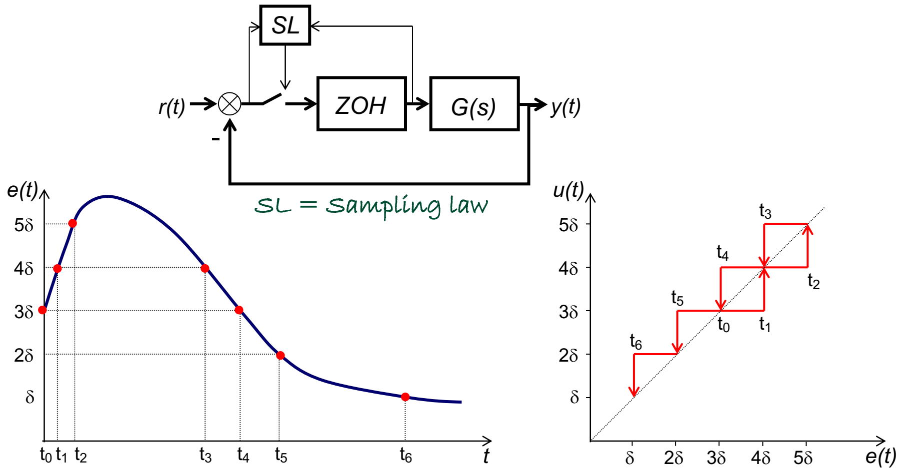
$$J_{ab}(T_i) = \frac{1}{(T_i)^a}\int_{t_i}^{t_i+T_i} (|e(t)-e(t_i)|)^b\,dt + Ae^{-BT_i}$$

Setting $(\partial J_{ab}/\partial T_i) = 0$ One has the minimizing solution of T_i as:

	Objective Function Parameters	Control Law	Control Law Parameters	Type of Approximation
	a=1, b=2	$T_i = \frac{T_{max}}{(\alpha\dot{e}_i)^2+1}$	$\alpha = \frac{2}{3AB^2}$ $B = 1/T_{max}$	Type 1
	a=0, b=2	$T_i = \frac{C_1}{\lvert\dot{e}_i\rvert}$	$C_1 = \sqrt{AB}$	Type 2
	a=-1, b=2	$T_i = \frac{C_2}{(\dot{e}_i{}^2)^{1/3}}$	$C_2 = \frac{\sqrt{3AB}}{2}$	Type 2
	a=1, b=1	$T_i = T_{max} - K\lvert\dot{e}_i\rvert$	$K = 1/2AB^2$ $B = 1/T_{max}$	Type 2
	a=0, b=1	$T_i = \frac{T_{max}}{(\alpha\dot{e}_i)^2+1}$	$\alpha_1 = 1/AB^2$ $B = 1/T_{max}$	Type 1
		$T_i = \frac{C_3}{\lvert\dot{e}_i\rvert}$	$C_3 = AB$	Type 2
	a=-1, b=1	$T_i = \frac{C_4}{\sqrt{\lvert\dot{e}_i\rvert}}$	$C_4 = \sqrt{(2/3)AB}$	Type 1

2. The idea of adaptive sampling

A new criterion of adaptive sampling: $|e(t) - e(t_i)| = \delta$

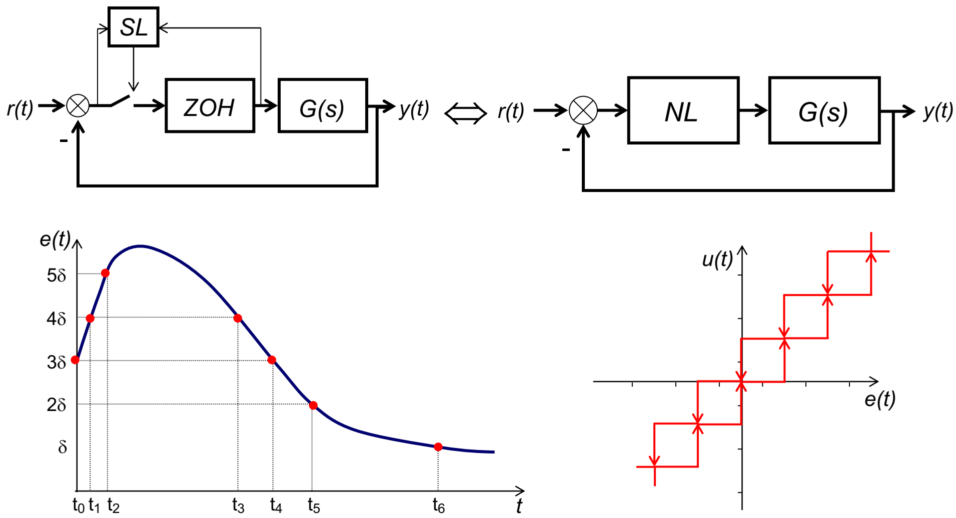


S. Dormido, M. Mellado. "A study on fixed-difference sampling scheme", *Applications and Research in Information Systems and Sciences*, 1973, pp. 480-500

S. Dormido, M. Mellado. "Determinación de ciclos límites en sistemas de muestreo adaptativo", *Revista de Automática*, 26, 21-31, 1975

2. The idea of adaptive sampling

A new criterion of adaptive sampling: $|e(t) - e(t_i)| = \delta$



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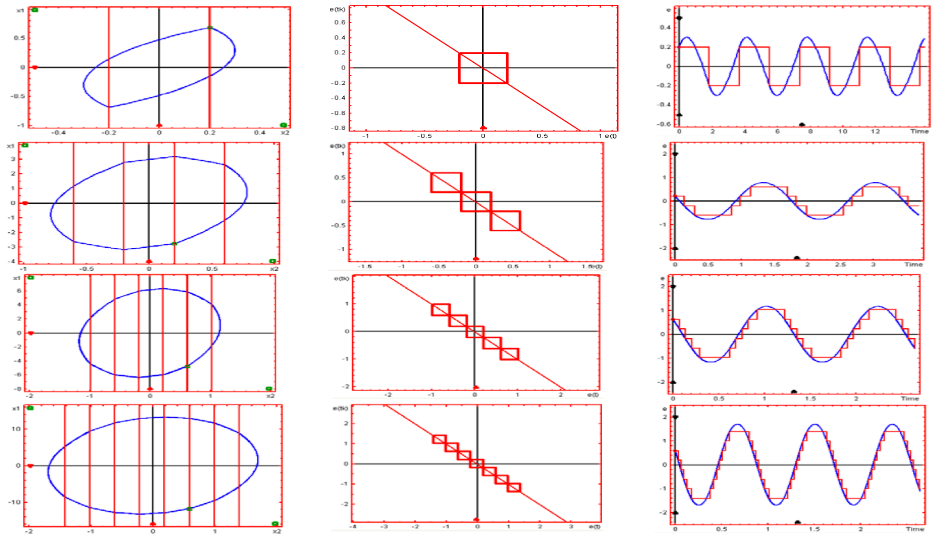
2. The idea of adaptive sampling

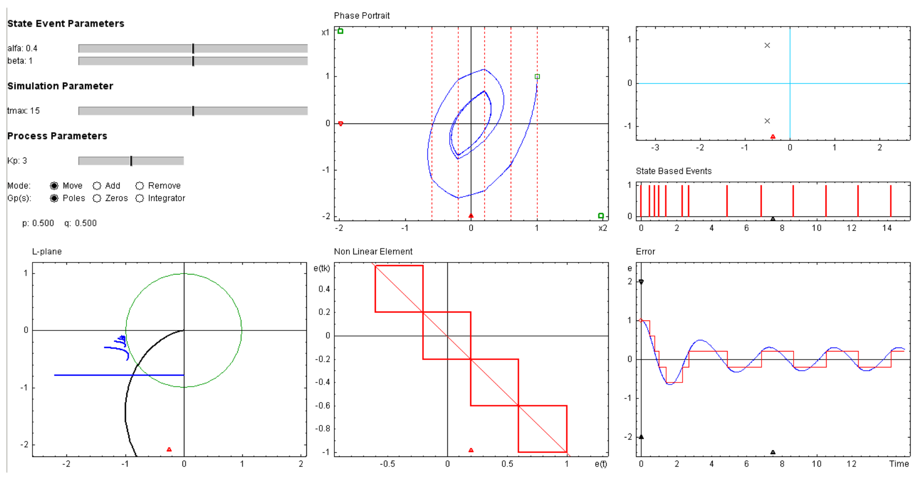
A new criterion of adaptive sampling: $|e(t) - e(t_i)| = \delta$



2. The idea of adaptive sampling

A new criterion of adaptive sampling: $|e(t) - e(t_i)| = \delta$

An interactive application



2. The idea of adaptive sampling

Event based control vs self-triggering control

$$e(t) \cong e(t_i) + \dot{e}(t_i)(t - t_i)$$

Implicit sampling law		Explicit sampling law
$\lvert e(t) - e(t_i) \rvert = \delta$	$\Rightarrow$	$T_i = \dfrac{\delta}{\lvert \dot{e}(t_i) \rvert}$
$\displaystyle\int_{t_i}^{t_{i+1}} \lvert e(t) - e(t_i) \rvert dt = \delta$	$\Rightarrow$	$T_i = \dfrac{\sqrt{2\delta}}{\lvert \dot{e}(t_i) \rvert}$

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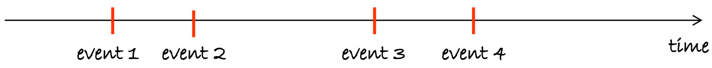
2. What is an event?

Event: Something which occurs instantaneously at a specific time or when a specific condition occurs



Event properties

1. Events are ordered in time (multiple events may occur concurrently)
2. Events take no time
3. There is an event condition for the event to happen
4. There is an action associated with the event

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2. What is an event?

An event is something that happens, especially when it is unusual or important. You can use events to describe all the things that are happening in a particular situation.

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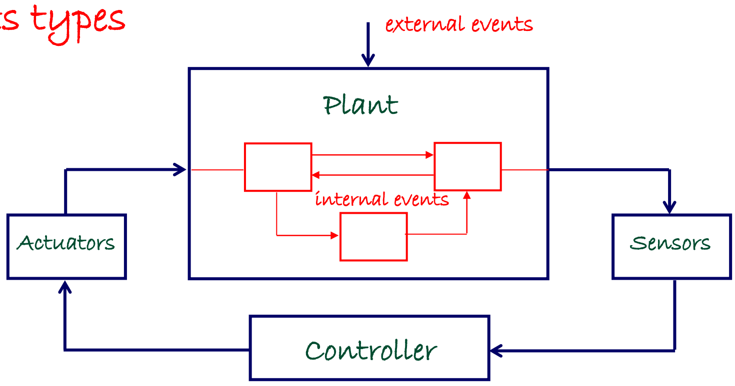
2. What is an event?

Events types



- External: events are related to the input variables
- Internal: events are related to internal model variables in the plant

time events: can be scheduled in advance

state events: cannot be scheduled in advance

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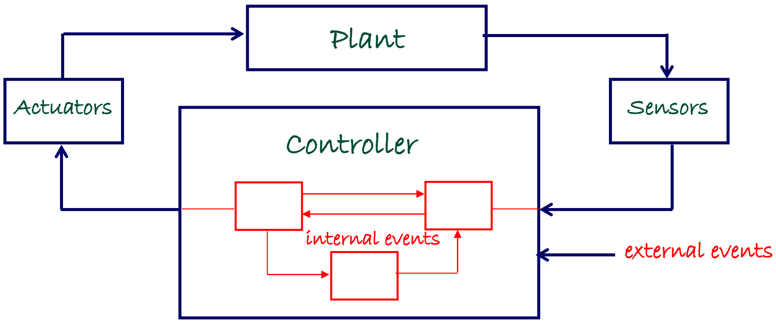
2. What is an event?

Events types



- External: events are related to the input variables
- Internal: events are related to internal model variables in the controller

time events: can be scheduled in advance

state events: cannot be scheduled in advance

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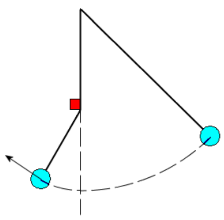
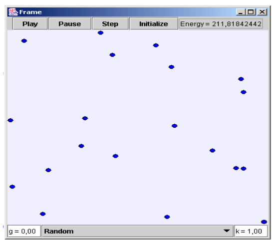
2. What is an event?

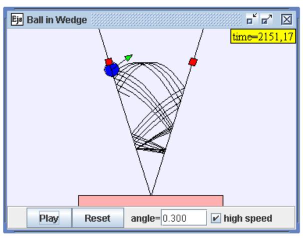
Physical examples: Events plant



Interrupted pendulum



Particles collision



Ball in a wedge

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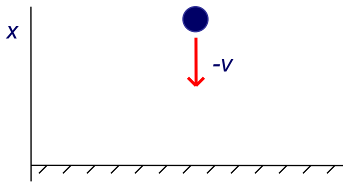
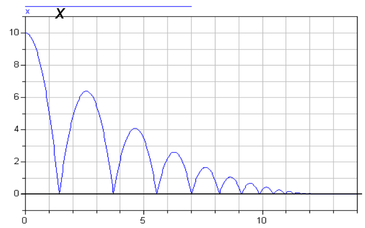
2. What is an event?

Physical examples: Bouncing ball

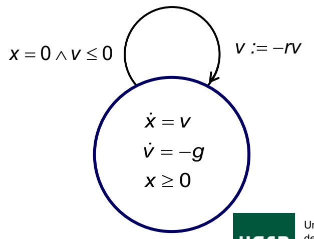




$$\frac{dv}{dt} = \begin{cases} -g & \text{if } x > 0 \\ 0 & \text{if } x \le 0 \end{cases}$$

$$\frac{dx}{dt} = v$$

$$v = -rv \qquad \text{when } x = 0$$



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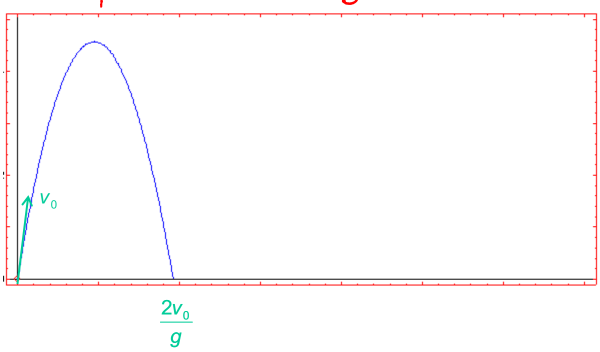
2. What is an event?

Physical examples: Bouncing ball



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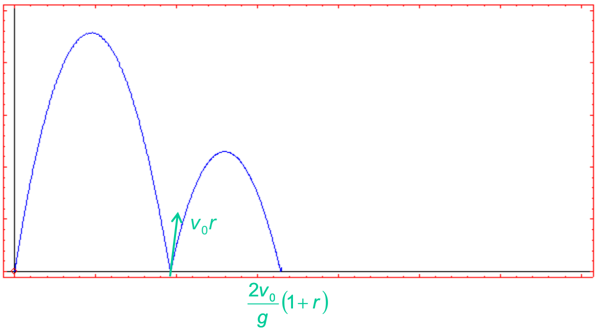
2. What is an event?

Physical examples: Bouncing ball



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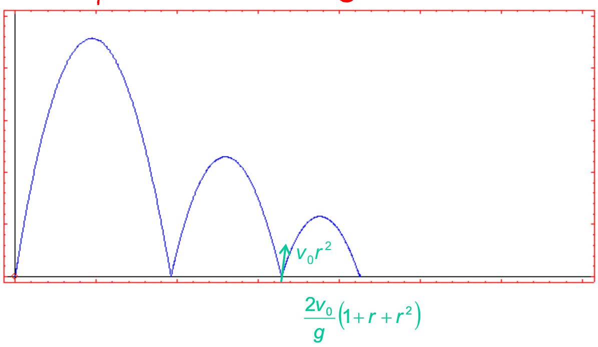
2. What is an event?

Physical examples: Bouncing ball



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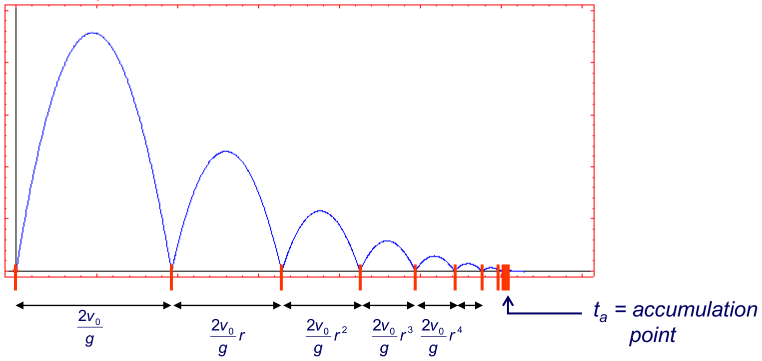
2. What is an event?

Physical examples: Bouncing ball



$$t_a = \frac{2v_0}{g}\sum_{k=0}^{\infty} r^k = \frac{2v_0}{g}\frac{1}{1-r} \qquad \left.\begin{matrix} x(t)\to 0 \\ v(t)\to 0 \end{matrix}\right\} \text{ when } t \to t_a \qquad \left.\begin{matrix} x(t)\equiv 0 \\ v(t)\equiv 0 \end{matrix}\right\} \text{ if } t \ge t_a$$

Infinite state events in a finite interval time are produced (ZENO behavior)

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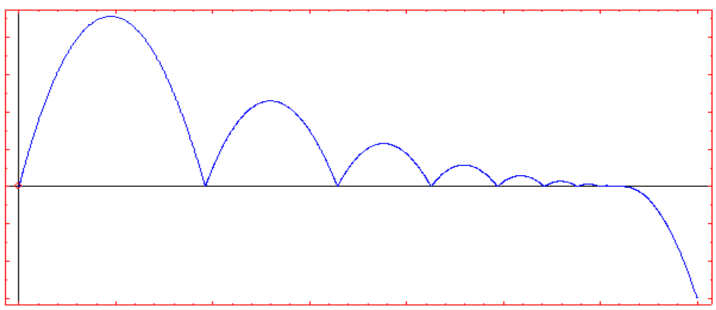
2. What is an event?

Physical examples: Bouncing ball



Why this anomalous and apparently unexpected phenomenon succeeds ?

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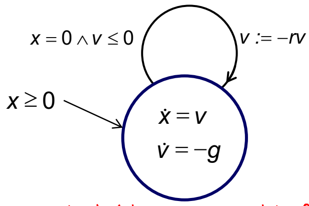
2. What is an event?

Physical examples: Bouncing ball



A hybrid system model of a simple bouncing ball

A bounce happens when the ball touches the ground.and its velocity v is non-positive, meaning either it is still or it is moving towards the ground. However when the following condition holds, $x = 0 \wedge v = 0$, meaning that the ball is at rest on the ground, the supporting force from the ground cancels out the gravity force. Therefore, the acceleration of the ball should be 0 rather than the acceleration of gravity.

A. Ames, H. Zheng, R. D. Gregg, S. Sastry. "Is there Life after Zeno?", ACC, Minneapolis, december 2006

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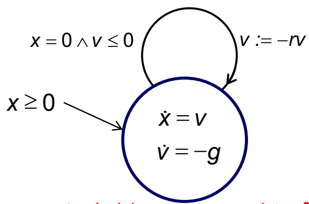
2. What is an event?

Physical examples: Bouncing ball



A hybrid system model of a simple bouncing ball

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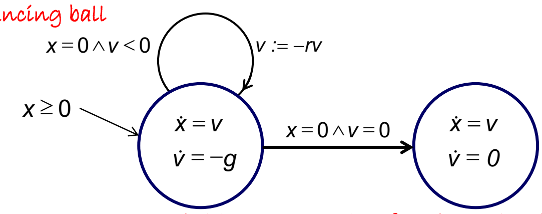

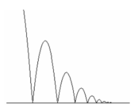

A more complete hybrid system model of the bouncing ball

A. Ames, H. Zheng, R. D. Gregg, S. Sastry. "Is there Life after Zeno?", ACC, Minneapolis, december 2006

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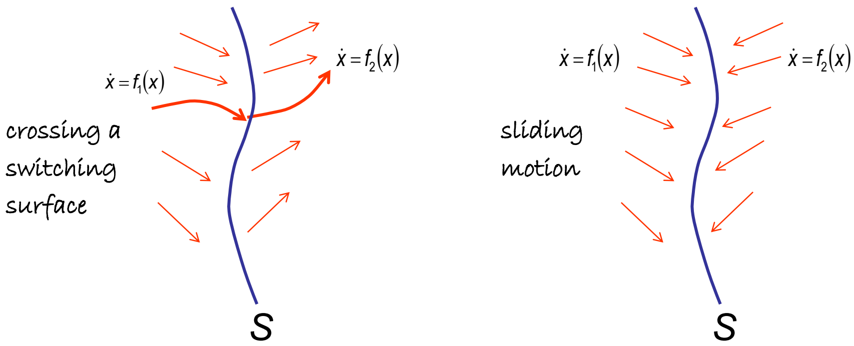
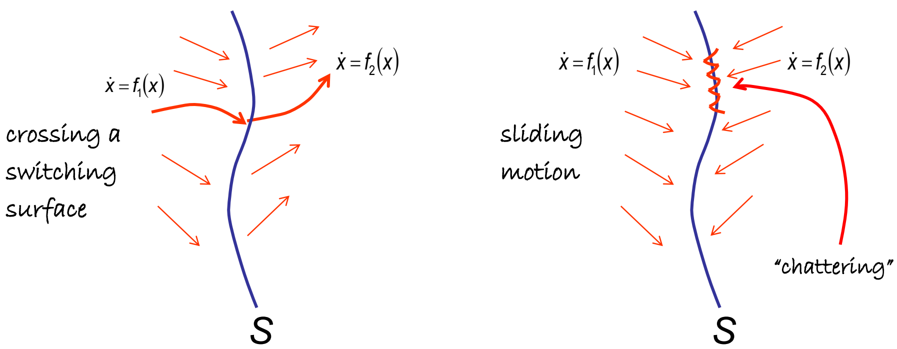
2. What is an event?

Sliding motion



2. What is an event?

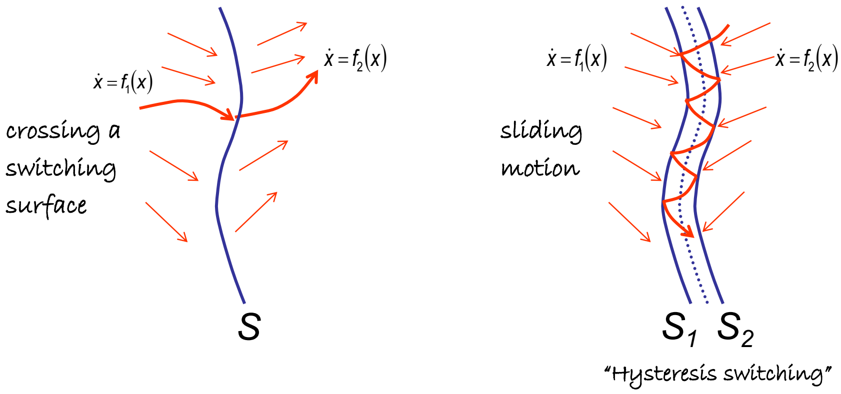
Sliding motion



H. Sira-Ramirez, "Differential geometric methods in variable-structure control", Int. J. Control, 48,4 1988, 1359-1390

2. What is an event?

Sliding motion



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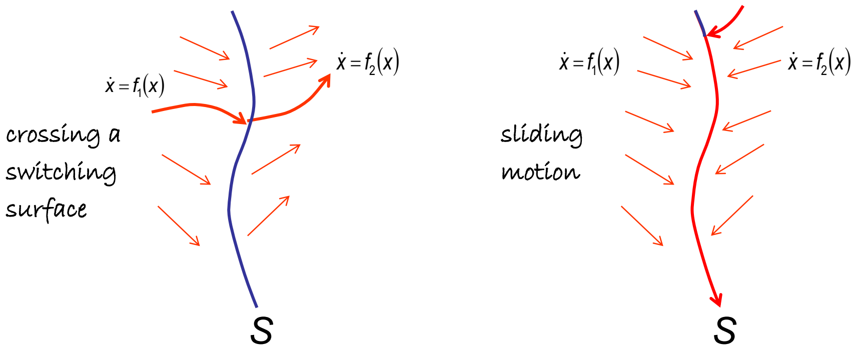
2. What is an event?

Sliding motion



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2. What is an event?

Sliding motion: An example

$$\dot{x} = Ax + B\,\mathrm{sign}(s(x))$$

$$A = \begin{bmatrix} 0 & 1 \\ -p_1 p_2 & p_1 + p_2 \end{bmatrix} \qquad B = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

$$\det(sI - A) = (s - p_1)(s - p_2)$$

$$s(x) = Cx + \rho$$

N. Carrero, R. Costa, S. Dormido, E. Fossas, "Using interactive tools to teach/learn Sliding Mode Control", CDC, Atlanta, december 2010

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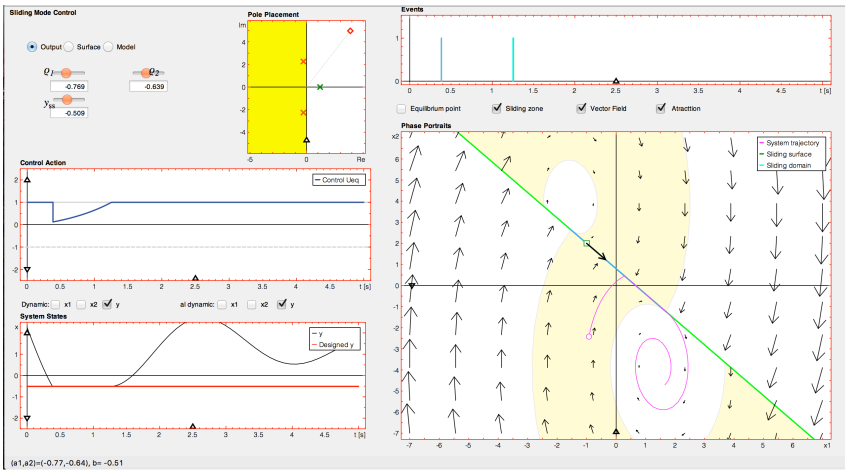
2. What is an event?

Sliding motion: An example



R. Costa, N. Carrero, S. Dormido, E. Fossas. "Teaching, Analyzing, Designing and Interactively Simulating of Sliding Mode Control" IEEE Control Systems, 2017, (submitted)

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3. Relay control systems

- The simplest hybrid and event based control system?
  - Two discrete states
  - Linear continuous behavior
- Relay systems are common
- Relay systems has been studied for a long time
- Relays systems are still widely used
  - DC/DC converters, Relay auto-tuning, Coulomb friction
  - On-off control, Δ-Σ modulators, Variable structure systems
  - Self-oscillating adaptive systems, Amplifiers
- Relay systems have rich behavior

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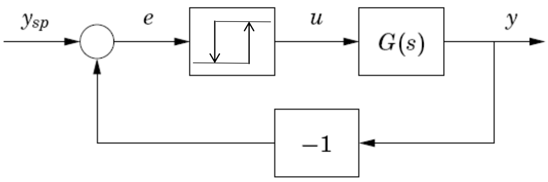
3. Relay control systems

A challenge

To understand the behavior of the system

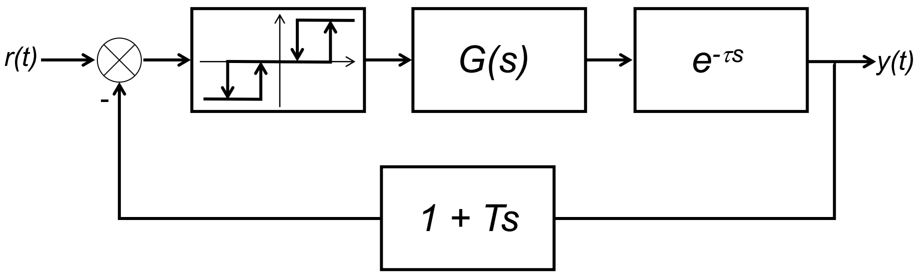


Some things are well known but important problems remain

Find all transfer functions such that there is a stable limit cycle

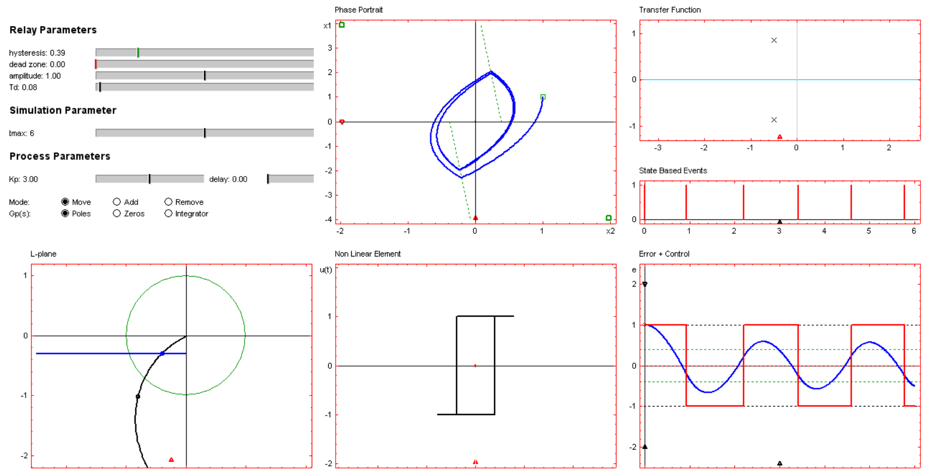
3. Relay control systems

The "relay" toolbox



3. Relay control systems

The "relay" toolbox



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3. Relay control systems

Limit cycles + multi-sliding motion

$$G(s) = k\frac{\left(s^2 + 2\sigma\rho s + \rho^2\right)}{\left(s^2 + 2\zeta\omega s + \omega^2\right)(s+\lambda)} \quad \Rightarrow \quad x = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \in R^3, u \in R, y \in R$$

$$A = \begin{pmatrix} -(2\zeta\omega + \lambda) & 1 & 0 \\ -\left(2\zeta\omega\lambda + \omega^2\right) & 0 & 1 \\ -\lambda\omega^2 & 0 & 0 \end{pmatrix} \quad B = \begin{pmatrix} k \\ 2k\sigma\rho \\ k\rho^2 \end{pmatrix} \quad C = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix}$$

Switching hyperplane $S = \left\{x \in R^3 \middle| x_1 = 0\right\}$

Sliding motion region: $\hat{S} = \left\{x \in R^3 \middle| x_1 = 0, |x_2| < k\right\}$

M. Bernardo, K. Johansson, F. Vasca. "Self-oscillations and sliding in relay feedback systems: Symmetry and bifurcations", Int. J. of Bifurcation and Chaos, Vol. 11, 4, 2001, pp 1121-1140

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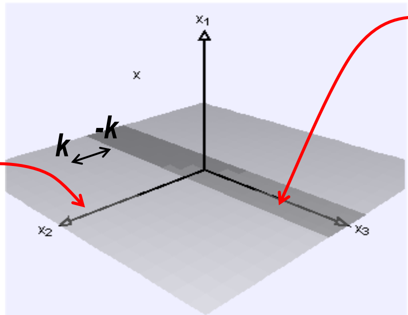
Limit cycles + multi-sliding motion

Switching hyperplane

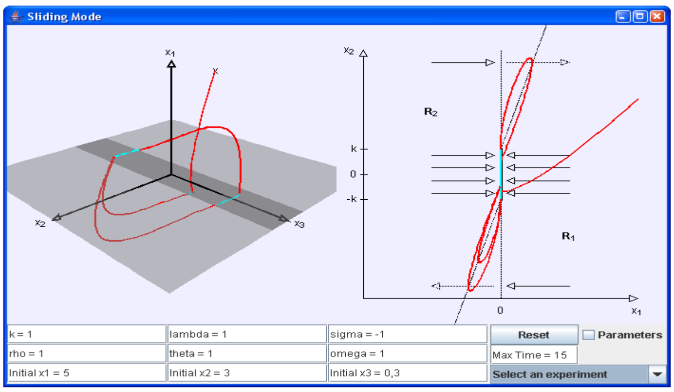
$$S = \{x \in R^3 | x_1 = 0\}$$



Sliding motion region

$$S = \{x \in R^3 | x_1 = 0, |x_2| < k\}$$

Limit cycles + multi-sliding motion



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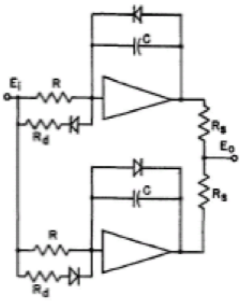
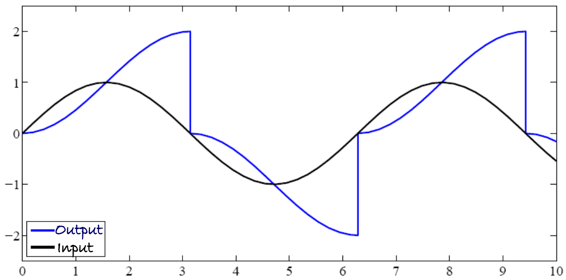
4. Reset control systems

Clegg's integrator (1958)

A nonlinear integrator for servomechanisms





The Clegg integrator represents an attempt to synthesize a nonlinear circuit having the amplitude-frequency characteristic of a linear integrator while avoiding the 90° phase lag associated with the linear transfer function.

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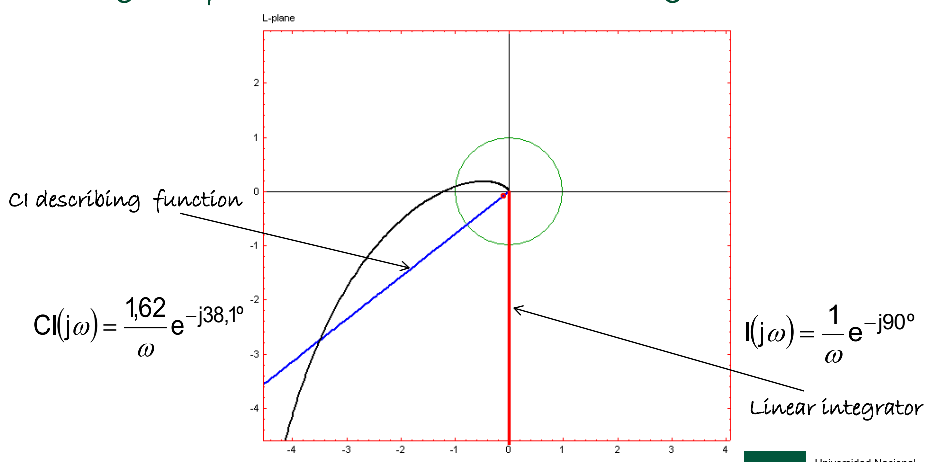
4. Reset control systems

Clegg's integrator (1958)

CI gives phase lead over a (linear) integrator



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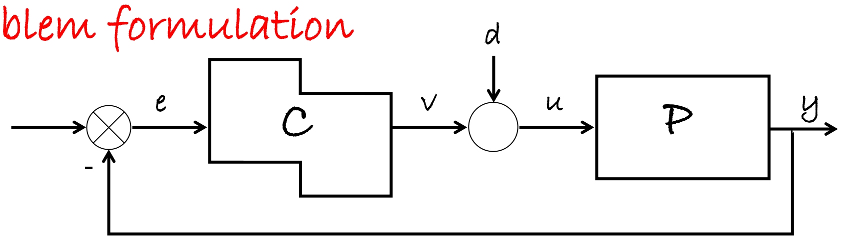
4. Reset control systems

Problem formulation



$$C:\begin{cases}\dot{x}_r = A_r x_r + B_r e, & e \neq 0\\ x_r^+ = A_\rho x_r, & e = 0\\ v = C_r x_r\end{cases}\qquad P:\begin{cases}\dot{x}_p = A_p x_p + B_p u\\ y = C_p x_p\\ u = v + d\end{cases}$$

- The base system is LTI
- The reset instants are defined as the time crossings of the error signal with zero
- Zeno solutions may exist, but are easily removed by time regularization
- Reset actions are events dependent on the (plant and compensator) state

O. Beker, C.V. Hollot, Y. Chait, and H. Han. Fundamental properties of reset control systems. Automatica, 40:905–915, 2004

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4. Reset control systems

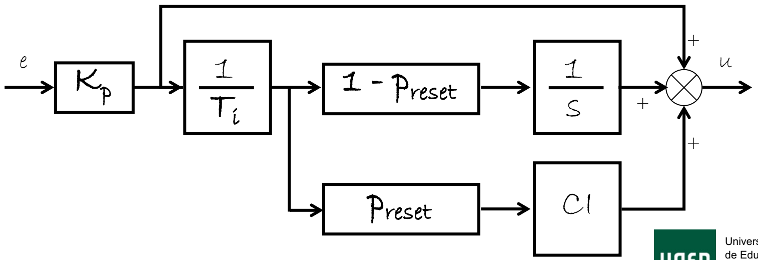
PI + CI

A simple structure easily implementable, with few parameters

Application target: process control

Good transitory and steady state properties

LTI base compensator : PI Antiwindup behavior



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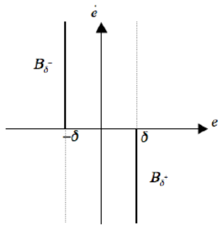
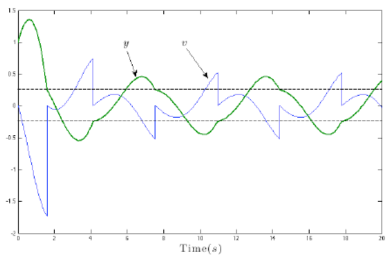
4. Reset control systems

Reset band

$$C:\begin{cases} \dot{x}_r = A_r x_r + B_r e, & (e,\dot{e}) \notin B_\delta \\ x_r^+ = A_\rho x_r, & (e,\dot{e}) \in B_\delta \\ v = C_r x_r \end{cases}$$



Reset instants are defined as the time crossings of the error with zero, when the error signal is entering the error band



A. Baños, S. Dormido, A. Barreiros. "Limit Cycles Analysis of Reset Control Systems with Reset Band", Nonlinear Analysis: Hybrid Systems, vol 5, 2, pp. 163–173, 2011

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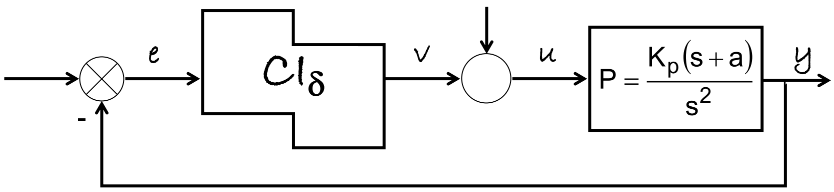
4. Reset control systems

Reset band: Bifurcations



Problem: To study this system with respect to the variation in the parameter "a"

S. Dormido, A. Baños, A. Barreiros. "Interactive Tool for Analysis of Reset Control Systems", 50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC) , Dece 2011

A. Baños, S. Dormido, A. Barreiros. "Limit Cycles Analysis of Reset Control Systems with Reset Band", *Nonlinear Analysis and Hybrid Systems*, vol 5, 2, pp. 163–173, 2011

A. Barreiros, A. Baños, S. Dormido. "Reset Control Systems with Reset Band: Well-posedness and Limit Cycles Analysis", *Systems Control Letters*, 63, 2014, pp. 1–11

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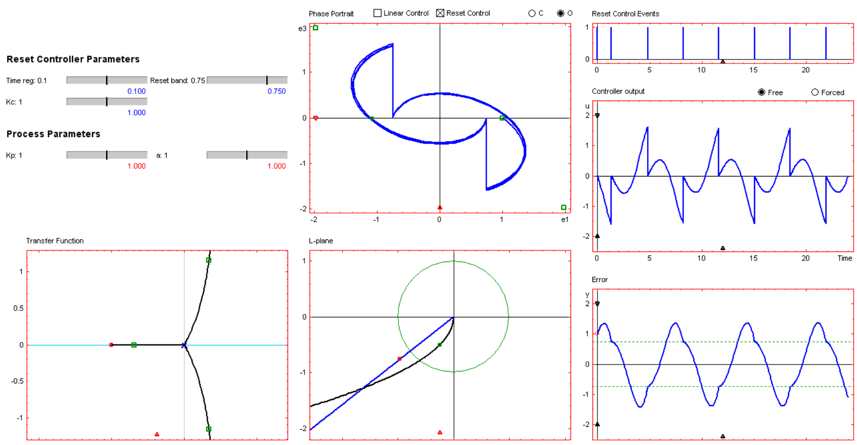
4. Reset control systems

The "reset control" toolbox



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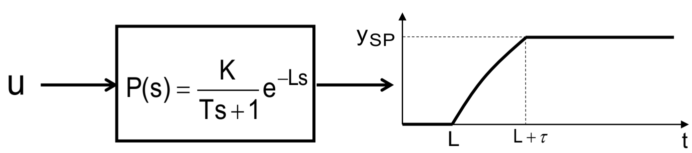
5. Event based PI control

The process to be controlled is modeled as a FOPTD



J. Sánchez, A. Visioli, S. Dormido. "A two-degree-of-freedom PI controller based on events", Journal of Process Control, vol. 21, pp. 639-651, 2011

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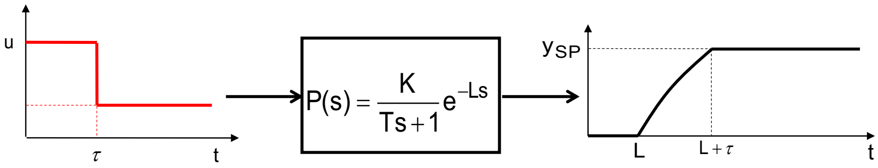
5. Event based PI control

The process to be controlled is modeled as a FOPTD



J. Sánchez, A. Visioli, S. Dormido. "A two-degree-of-freedom PI controller based on events", Journal of Process Control, vol. 21, pp. 639-651, 2011

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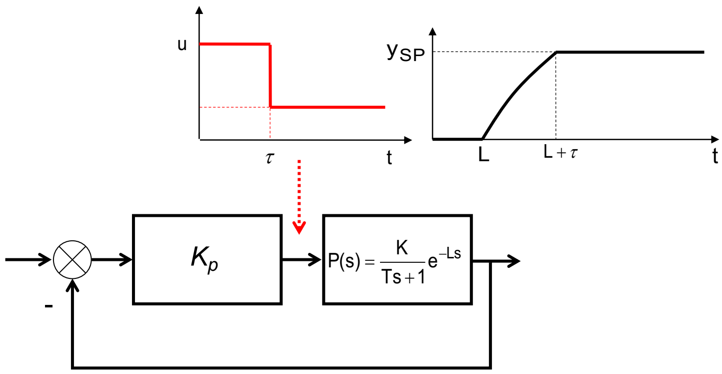
5. Event based PI control

Proportional controller



J. Sánchez, A. Visioli, S. Dormido. "A two-degree-of-freedom PI controller based on events", Journal of Process Control, vol. 21, pp. 639-651, 2011

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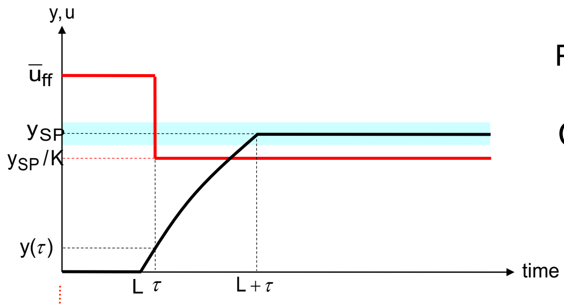
5. Event based PI control

The process to be controlled is modeled as a FOPTD



$$P(s) = \frac{K}{Ts+1} e^{-Ls}$$

$$C(s) = K_p$$

$$\boxed{u_p = K_p y_{SP}} \quad \boxed{u_p = K_p\left(y_{SP} - y(\tau)\right)}$$

J. Sánchez, A. Visioli, S. Dormido. "A two-degree-of-freedom PI controller based on events", Journal of Process Control, vol. 21, pp. 639-651, 2011

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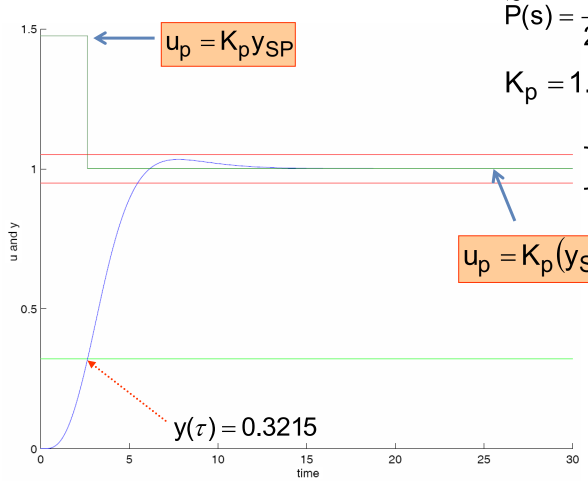
5. Event based PI control

Example: $P(s) = (s+1)^{-4}$

$$\tilde{P}(s) = \frac{e^{-1.8784s}}{2.1168s+1}$$

$$K_p = 1.4753$$



$$\boxed{u_p = K_p y_{SP}}$$

$$\boxed{u_p = K_p\left(y_{SP} - y(\tau)\right)}$$

J. Sánchez, A. Visioli, S. Dormido. "A two-degree-of-freedom PI controller based on events", Journal of Process Control, vol. 21, pp. 639-651, 2011

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5. Event based PI control

Algorithm of the integral action

- Once the process is inside the dead-band, defined as:

$$\alpha y_{SP} \leq y_{SP} \leq \beta y_{SP}$$

  - The proportional action is constant: $u_p = K_p(y_{SP} - \Delta_1)$
  - The integrator is enabled.
- When the process leaves the dead-band:
  - The integrator starts calculating the IAE
  - Every time the integrator exceeds a certain threshold, that is, $IAE \geq \delta_{IAE}$, it produces an integral control action.
- When the process is inside the dead-band:
  - The integrator stops working

J. Sánchez, A. Visioli, S. Dormido. "A two-degree-of-freedom PI controller based on events", *Journal of Process Control*, vol. 21, pp. 639-651, 2011

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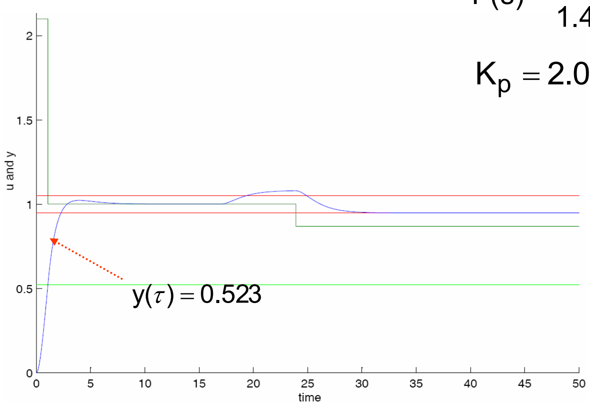
5. Event based PI control

Example: $P(s) = (s+1)^{-2}$

$$\tilde{P}(s) = \frac{e^{-0.5296s}}{1.4707s + 1}$$

$$K_p = 2.0991$$



$\delta_{IAE} = 0{,}1$, deadband $= y_{sp} \pm 0{,}05$, control actions $= 3$

J. Sánchez, A. Visioli, S. Dormido. "A two-degree-of-freedom PI controller based on events", *Journal of Process Control*, vol. 21, pp. 639-651, 2011

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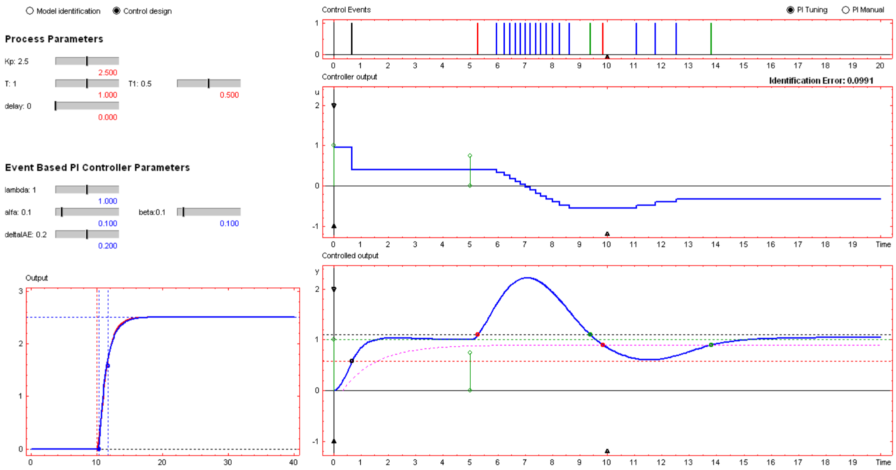
5. Event based PI control

The “event based PI” toolbox



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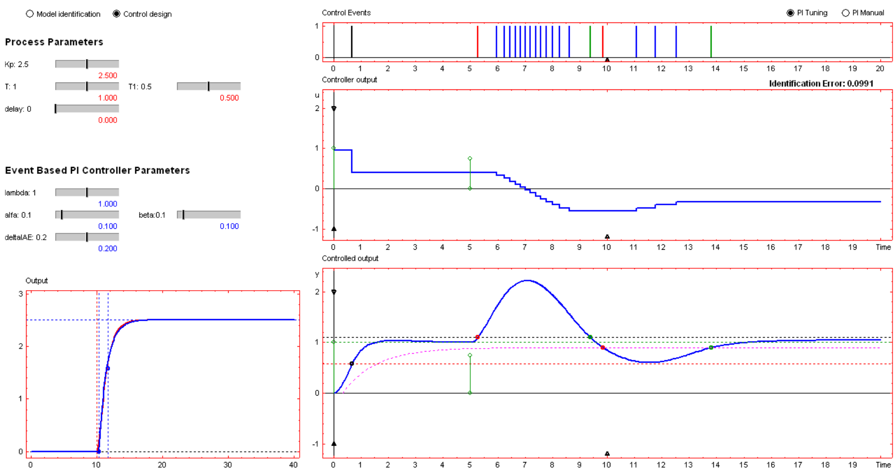
5. Event based PI control

The “event based PI” toolbox



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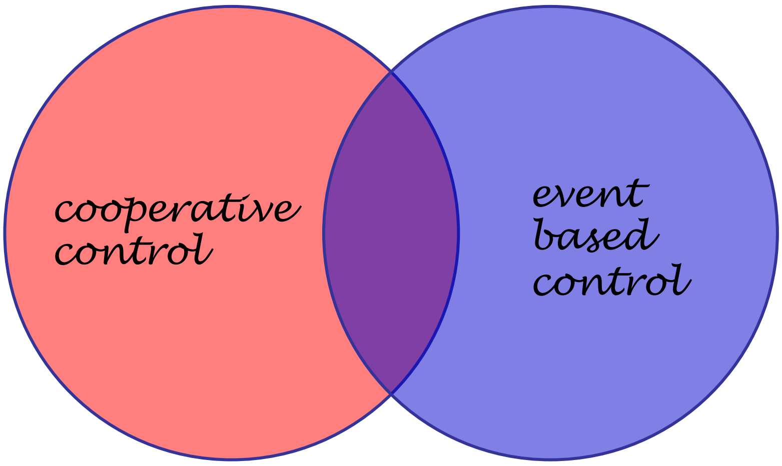
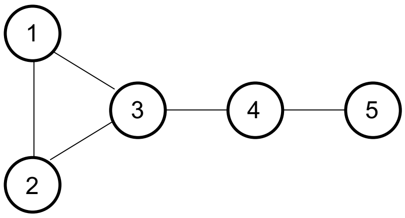
6. Event based cooperative control



6. Event based cooperative control

Fundamentals of algebraic graph theory



$G = \{V, A\}$

Example

Vertices

$V = \{1, 2, 3, 4, 5\}$

Edges

$E = \{(1,2), (2,1), (1,3), (3,1), (2,3), (3,2), (3,4), (4,3), (4,5), (5,4)\}$

If there is an edge (i, j) between nodes i y $j \Rightarrow i$ y j are adjacents

$$E = \{(i, j) \in V \times V : i, j \text{ adjacents}\}$$

Undirected graph: if $(i, j) \in E \Rightarrow (j, i) \in E$

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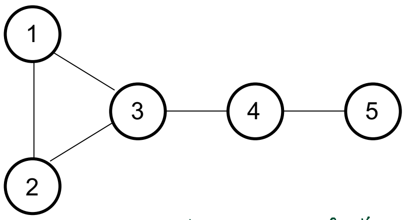
6. Event based cooperative control

Fundamentals of algebraic graph theory



$G = \{V, A\}$

Example

Path: Sequence of adjacents edges

If there is a path between i and $j \Rightarrow (i, j)$ are connected

Adjacency Matrix

$$A = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

Degree Matrix

$$D = \begin{bmatrix} 2 & 0 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Neighbor set

$$N_i = \{j \in V : (i, j) \in E\}$$

$$N_3 = \{1, 2, 4\}$$

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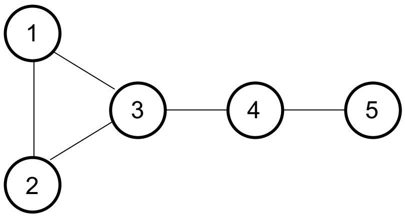
6. Event based cooperative control

Fundamentals of algebraic graph theory



$G = \{V, A\}$

Example

Laplacian Matrix

$$L = D - A = \begin{bmatrix} 2 & -1 & -1 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 \\ -1 & -1 & 3 & -1 & 0 \\ 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix}$$

For undirected graph $\Rightarrow \begin{cases} L = L^T \geq 0 \\ \sum_{j=1}^{n} L_{ij} = 0 \end{cases} \Rightarrow$

$L\mathbf{1} = \mathbf{0}$ $\Rightarrow$ **1** es un vector propio de L

If the graph is connected $\Rightarrow$

$$0 = \underbrace{\lambda_1(G) < \lambda_2(G)}_{\text{algebraic connectivity}} \leq \cdots \leq \lambda_N(G)$$

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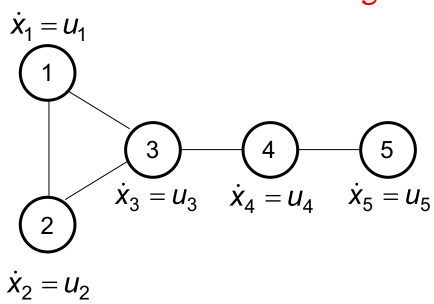
6. Event based cooperative control

Elements to be considered in a multiagent system



1) Agents dynamics
- Single integrators
- Double integrators
- Linear systems
- Non linear systems

2) Communication
- Fixed or variable topology
- Directed or undirected links
- Delays
- Packet losses

3) Control
- Continuous
- Time scheduling
- Event based scheduling
- "Self triggered"

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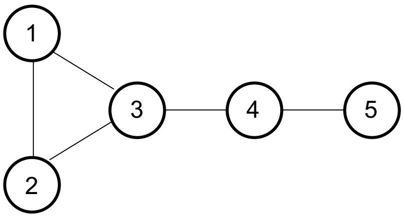
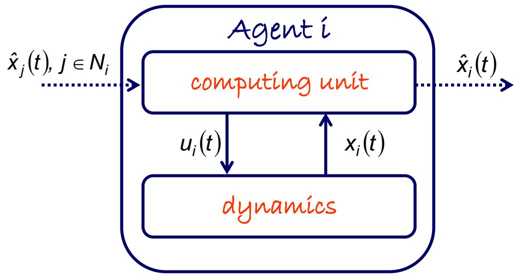
6. Event based cooperative control





R. Olfati-Saber and R. M. Murray, "Consensus problems in networks of agents with switching topology and time-delays", *IEEE Trans. Autom. Control*, vol. 49, no. 9, pp. 1520–1533, Sep. 2004

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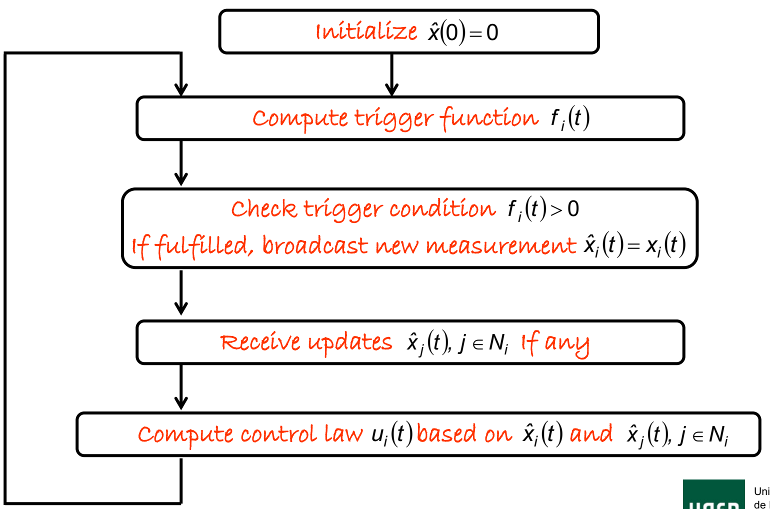
6. Event based cooperative control

Algorithm running in agent i's unit computing



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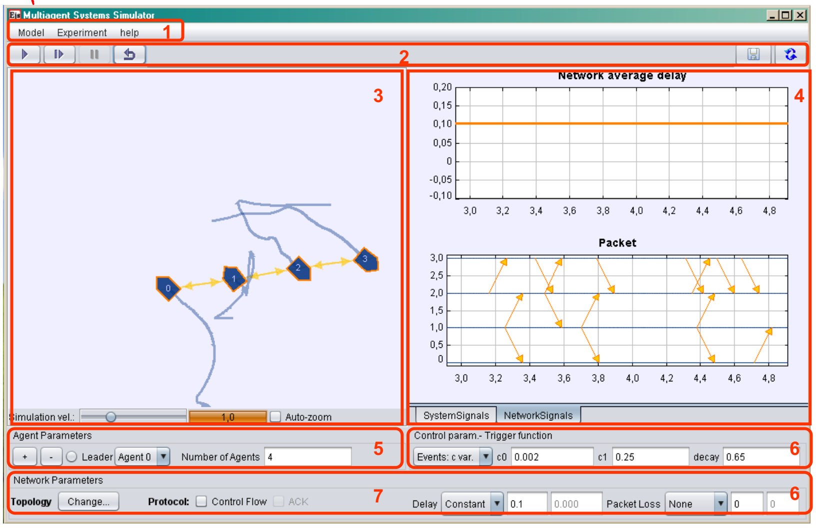
6. Event based cooperative control

GUI of MAS simulator



M. Guinaldo, E. Fabregas, J. Sánchez, S. Dormido-Canto, S. Dormido. "An Interactive Simulator for Networked Mobile Robots", *IEEE Network*,

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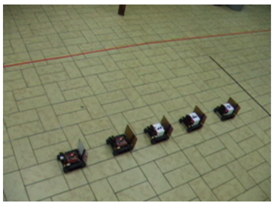
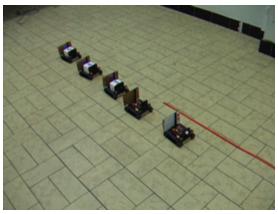
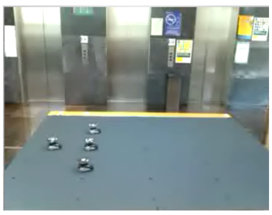
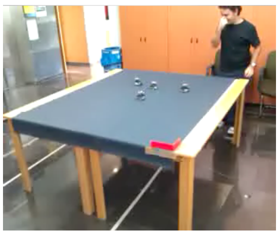
7. Event based cooperative control

Experimental platforms









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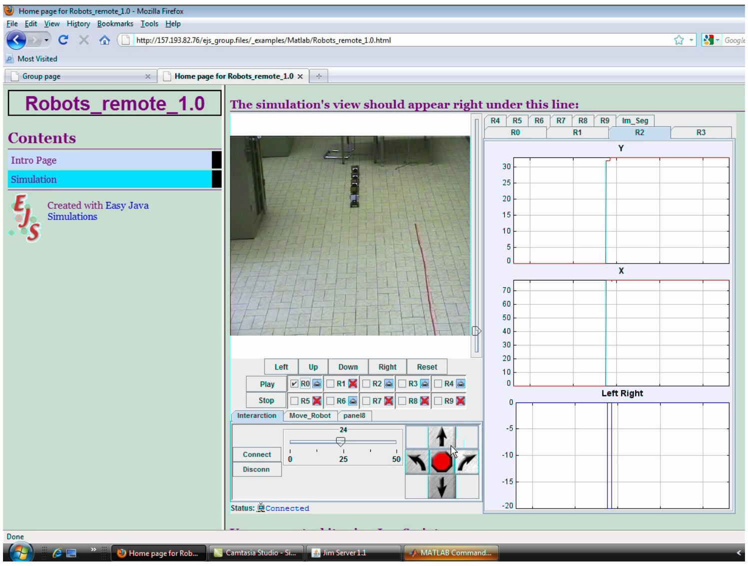
7. Event based cooperative control

Un laboratorio remoto



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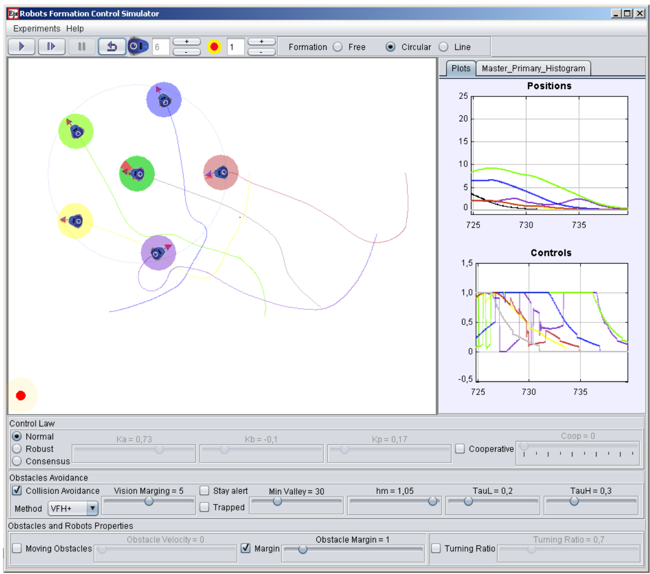
7. Event based cooperative control



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8. Conclusions

Event based control can deal with multi-rate, asynchronism and latency which give difficulties for classical sampled data systems

Simple examples indicate that event based control can give good performance, react quickly to disturbances and do nothing when errors are within the tolerance

Interesting signal form and system structure

- Pulse trains, interval observer and pulse former
- Implication for systems architecture

Natural approach for distributed autonomous systems

Natural for modeling biological systems

Many interesting open research problems

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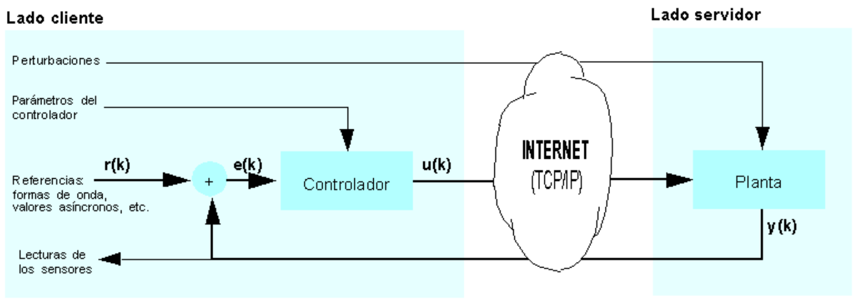
8. Conclusions

Network control system



Controller in the client side

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8. Conclusions

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