Advanced Topics in PID Control System Design, Automatic Tuning and Applications

Fundamentals on event-based PID control

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Madrid, Spain

Berlin, 11 July 2020

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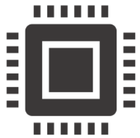
1. Introduction

Traditional control systems

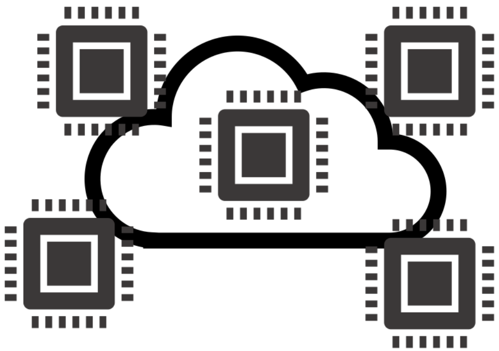
$$\dot{x} = f(x,u)$$

$u = k(x)$ ↑ ↓ x



...if the microprocessor has enough capacity
...if the sensors are accurate enough
...if the actuators are fast enough

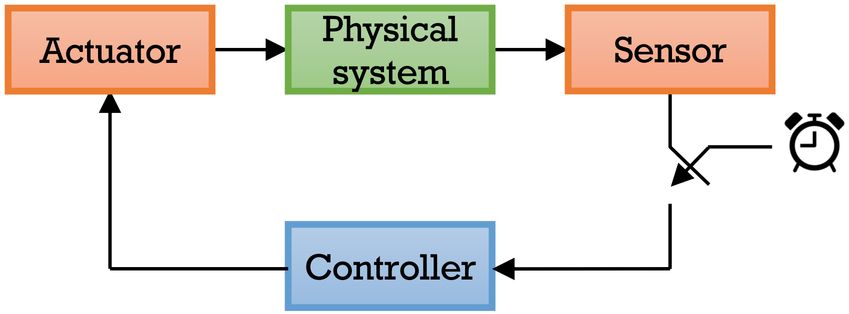
Network control systems



- Reduced communication and computing capabilities
- Limited available power

Integration of control, computing and communication

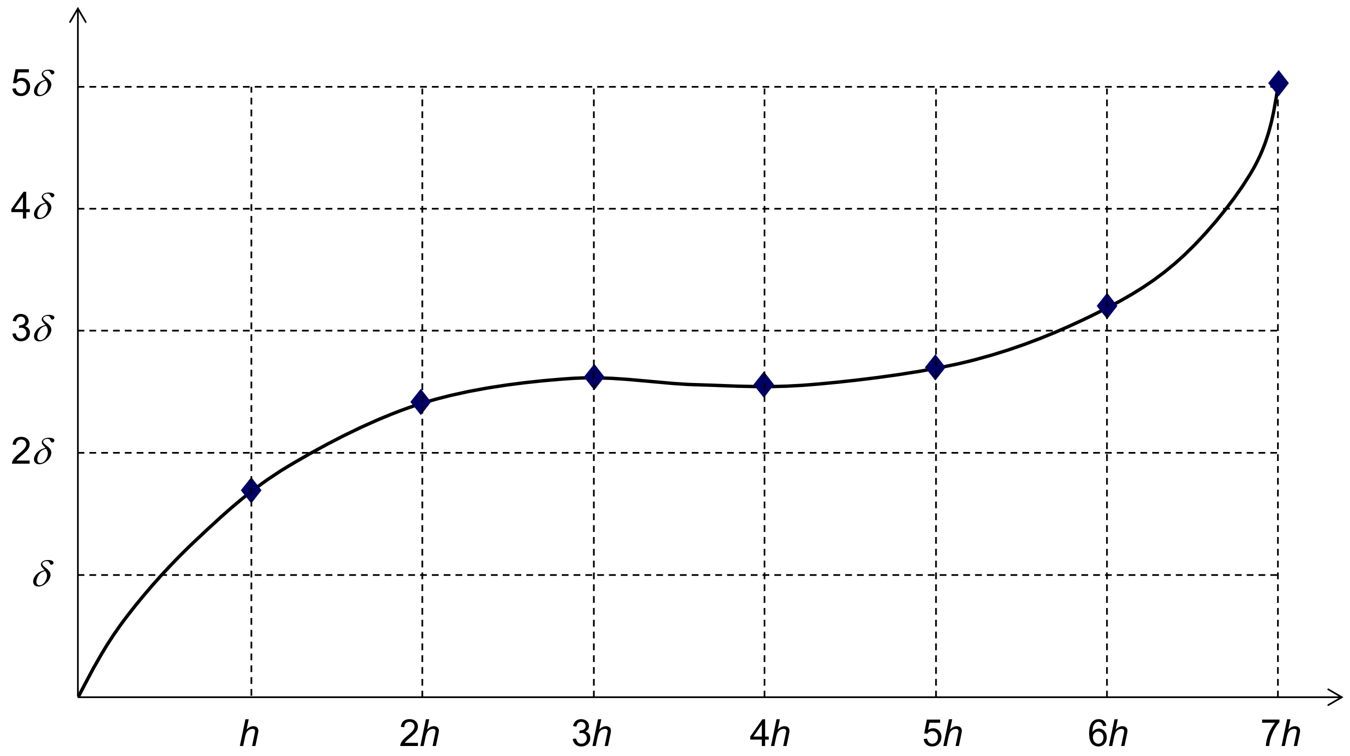
1. Introduction



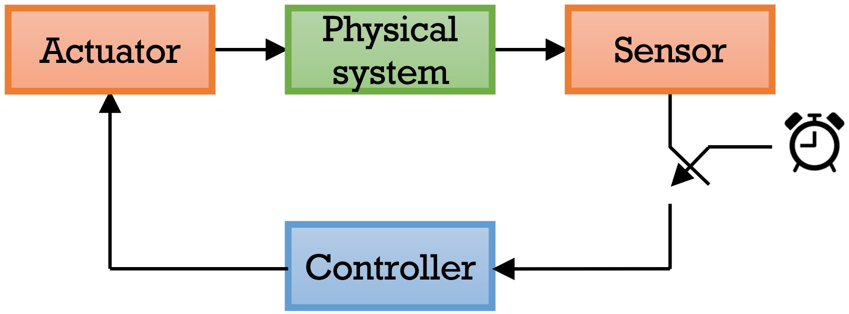
time-triggered control (TTC)

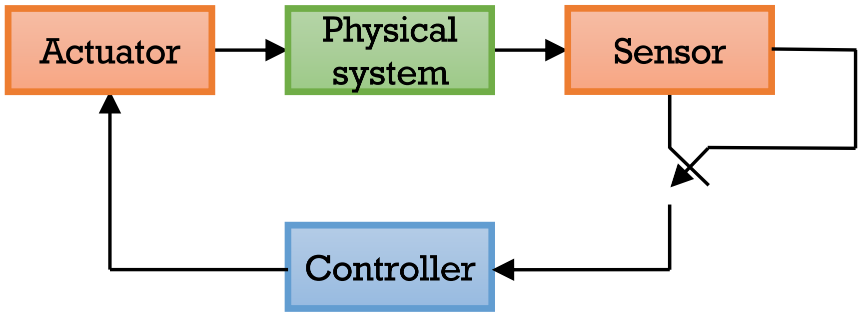
1. Introduction

Time based sampling



1. Introduction



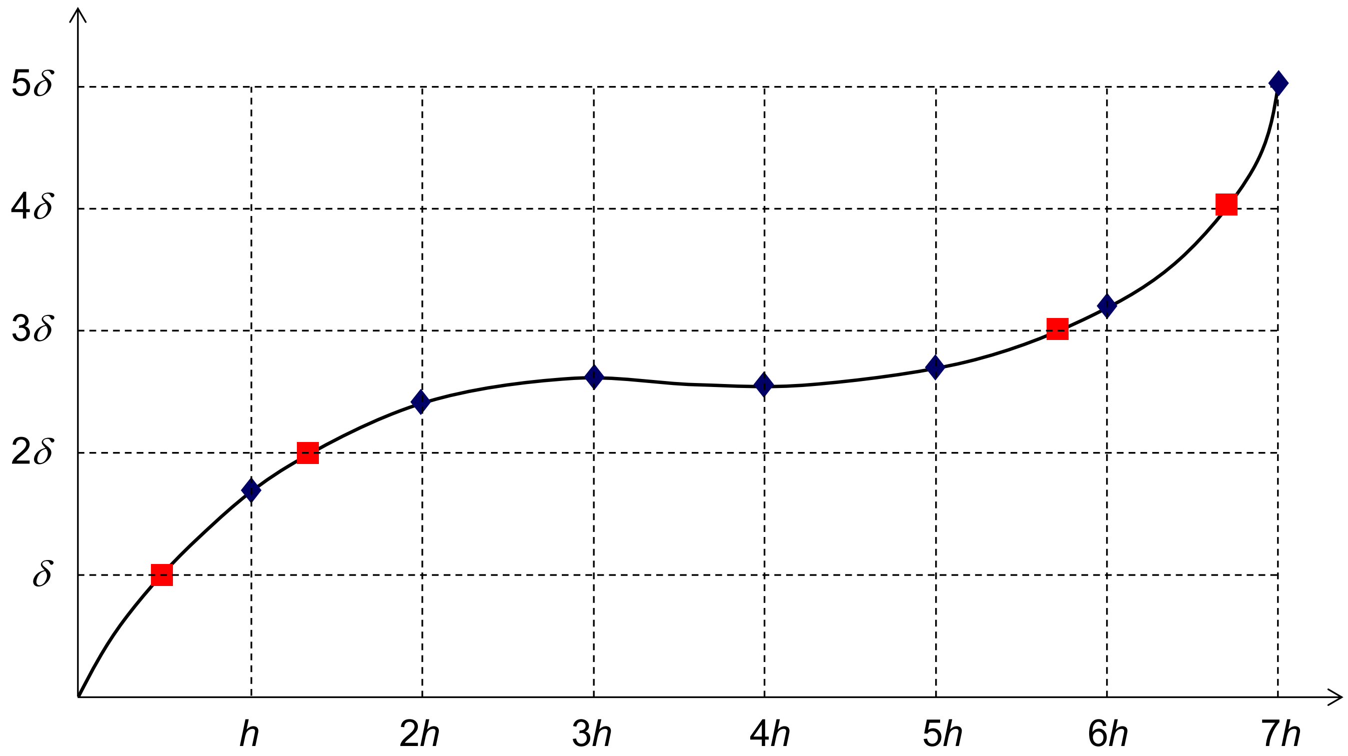


time-triggered control (TTC)

event-triggered control (ETC)

1. Introduction

Event based sampling



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1. Introduction

Time based sampling versus Event based sampling

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

1. Introduction

Dificulties with Time based and Event based sampling

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

1. Introduction

Advantages of event-triggered control

Information is transmitted only when required by the system

- Minimization of energy consumed
- More processor time available
- Better adaptation to the dynamics of the process
- Better response to disturbances and overloads

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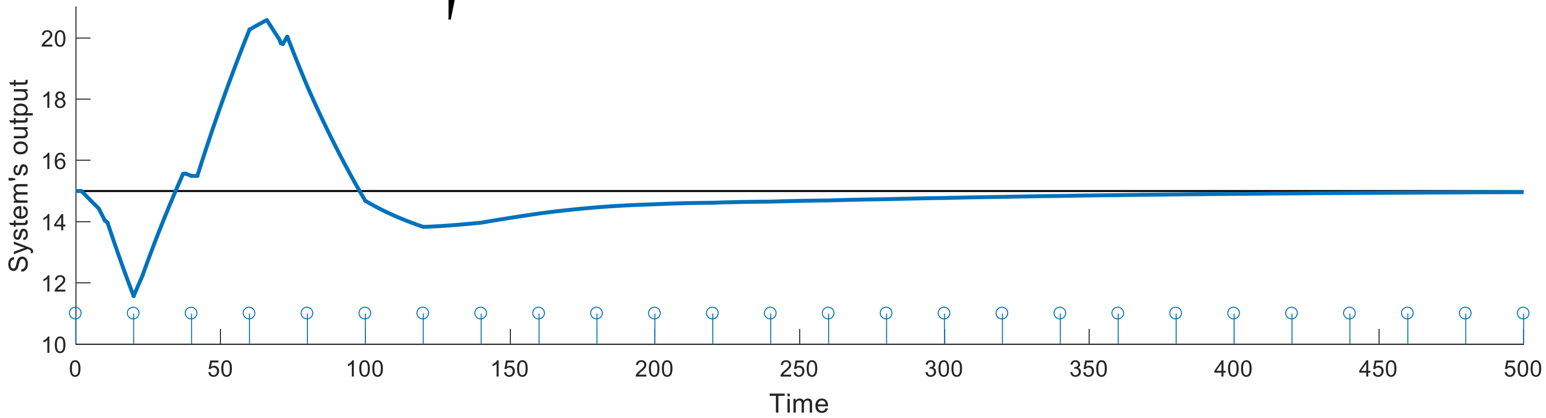

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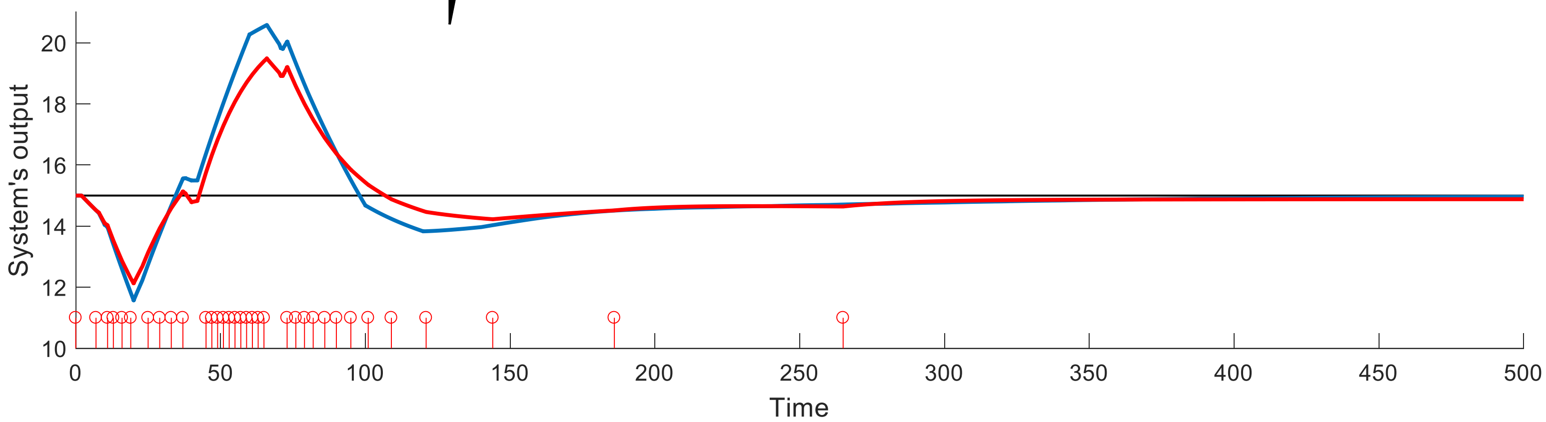

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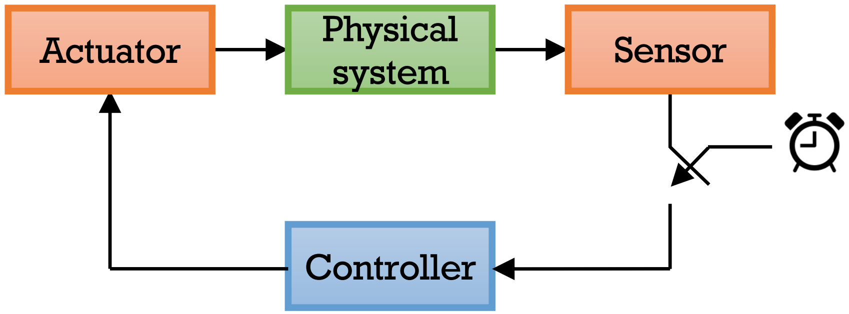
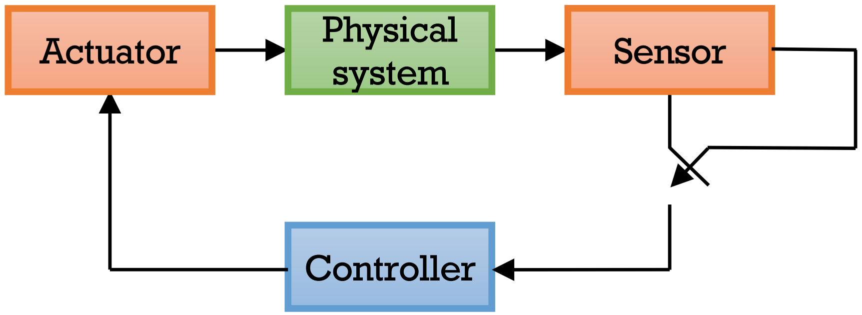
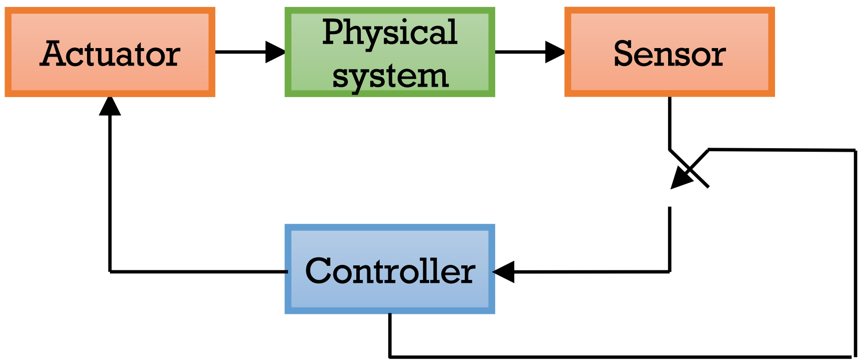
1. Introduction



time-triggered control (TTC)



event-triggered control (ETC)



self-triggered control (STC)

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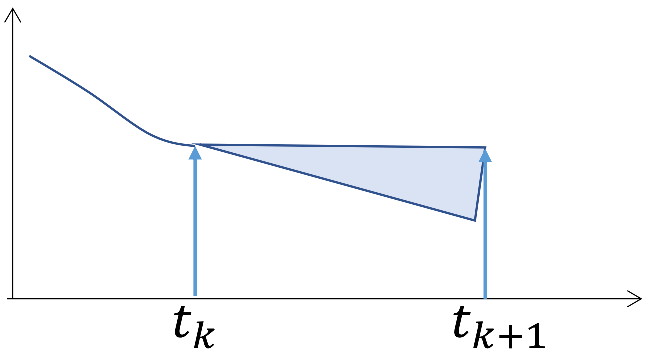
1. Introduction

Self-triggered control (STC)

- Needs:
  - A reliable model of the system
  - More powerful computing resources
- In the sampling instant
  - The output of the plant is transmitted
  - The next sampling time is estimated based on the model and a robustness interval
    - Predicts future plant states
    - Predicts when the trigger condition will cross zero



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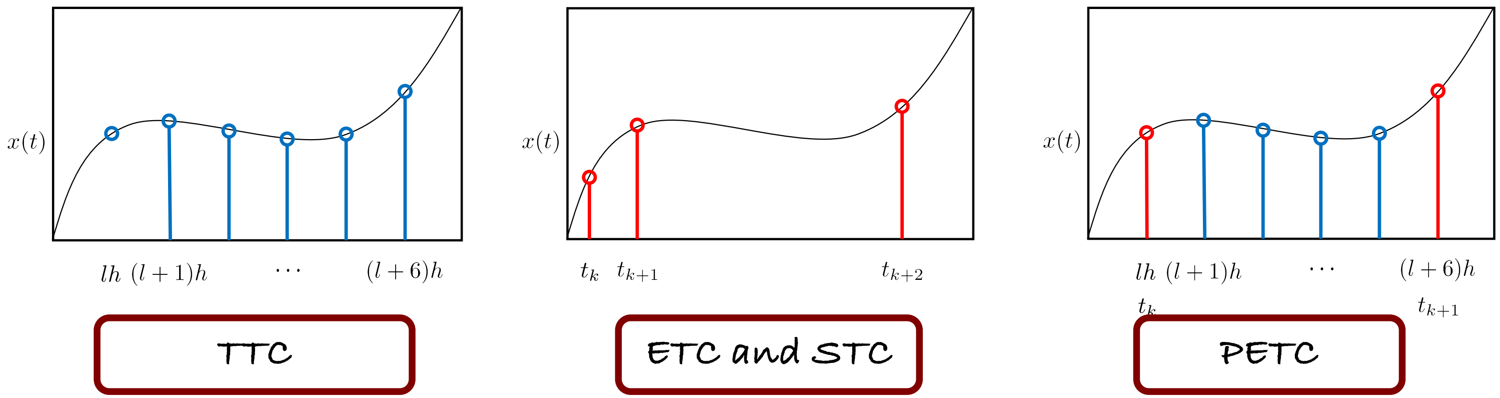
1. Introduction

Periodic-triggered control (PTC)

The event-triggering condition is periodically evaluated

The information is aperiodically sent



In STC t_{k+1} is calculated in t_k

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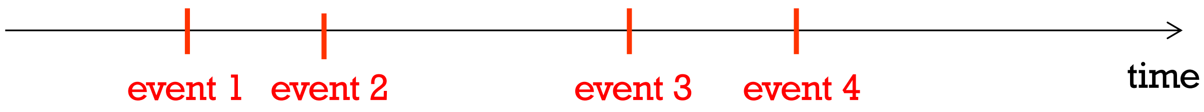
2. What is an event?

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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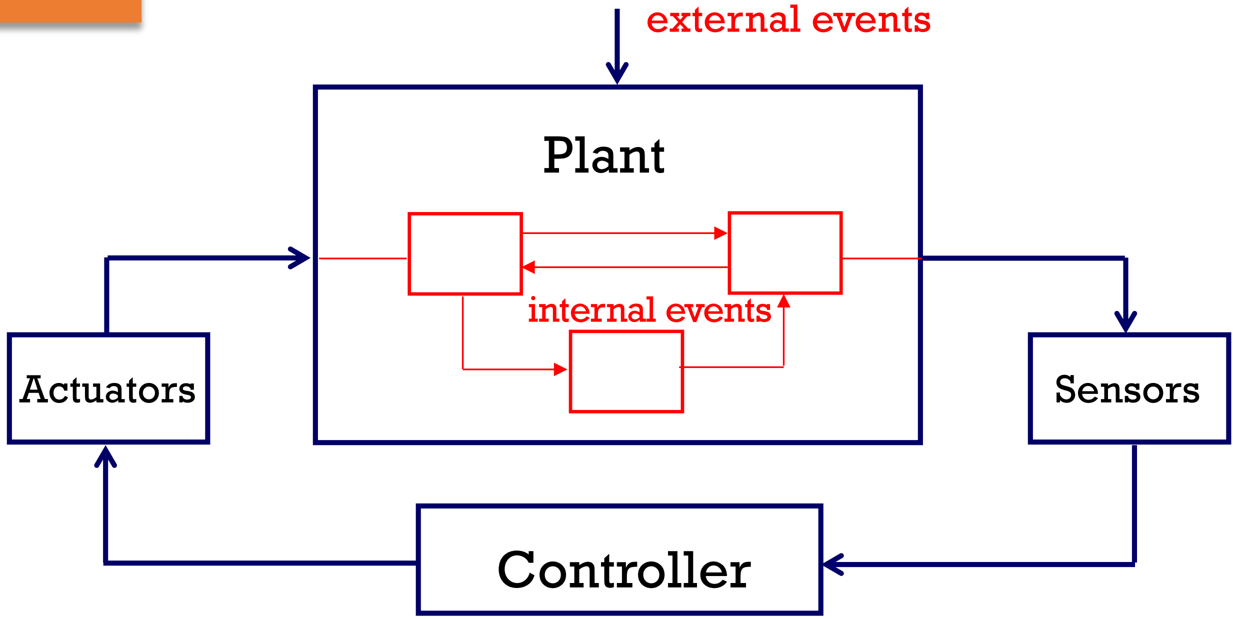
2. What is an event?

Event 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 (TTC)

state events: cannot be scheduled in advance (ETC, STC, PETC)

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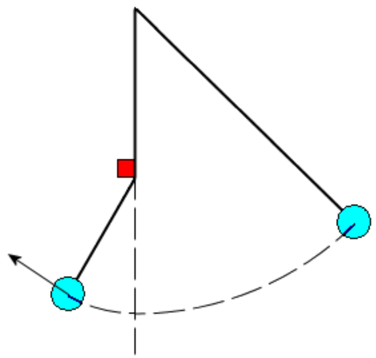
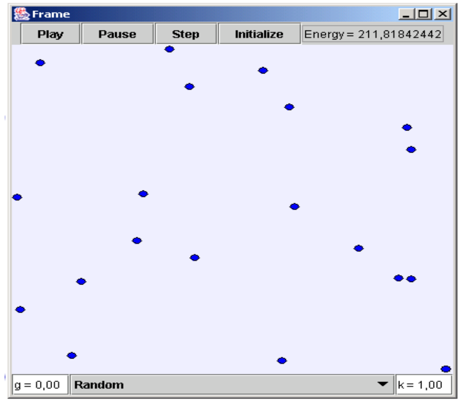
2. What is an event?

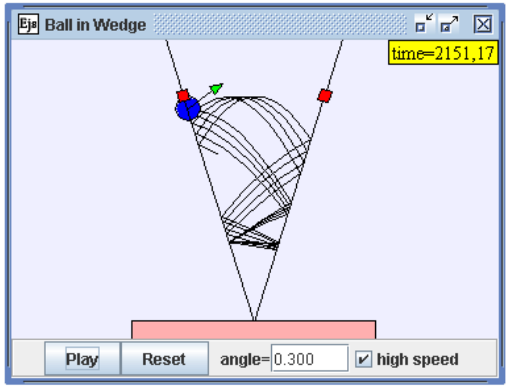
Physical examples: Events plant



Interrupted pendulum



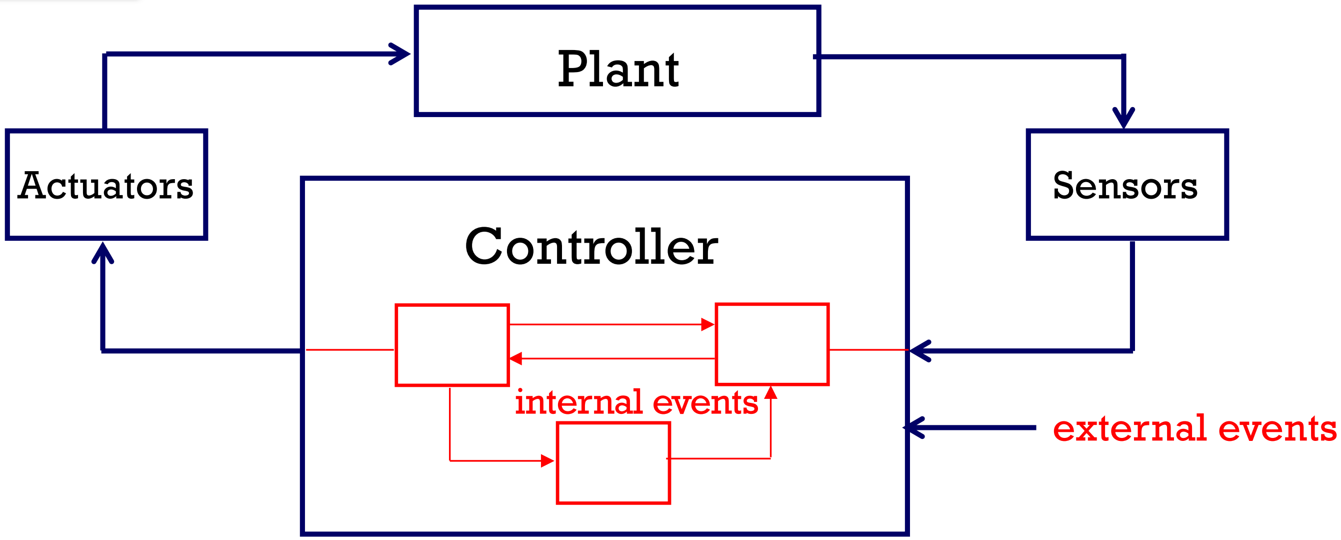
Particles collision



Ball in a wedge

2. What is an event?

Event types



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

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2. What is an event?

How to close the loop

Monitoring the system input/output with a **trigger condition**

- Events occur when $f(\ldots) \geq 0$
- After an event $f(\ldots^{+}) < 0$
- An event is detected when f (the error) reaches a **threshold**
  - Error functions: $e(t) = x(t_k) - x(t), \;\; e(t) = \hat{x}(t) - x(t), \;\; V(x,t)$
  - Thresholds: $c, \;\; \|x(t)\|, \;\; ce^{-\alpha t}, \;\; S(x,t)$

When to evaluate the trigger condition

- Continuously ⇒ Event triggered control (ETC)
- Periodically ⇒ Periodically event triggered control (PETC)
- At predetermined moments ⇒ Self triggered control(STC)

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2. What is an event?

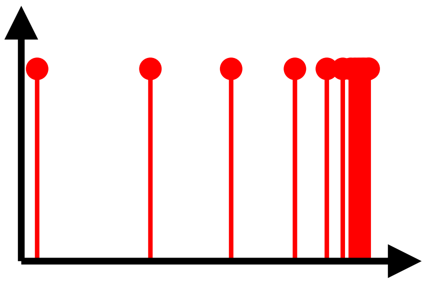
Terminology is not well established

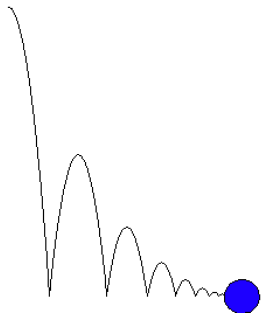
Other terms

- Dead-zone control
- Send-on-delta control
- Intermittent control
- Controlled communication
- Adaptive sampling
- Control monitoring at any time
- Minimum attention control
- Level crossing
- …

Zeno behavior

Occurrence of consecutive events at the same time





Falling ball

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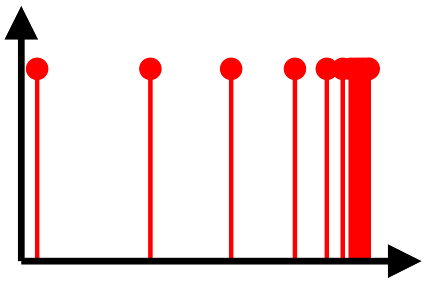
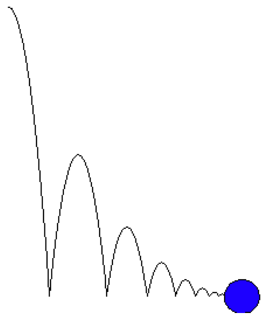
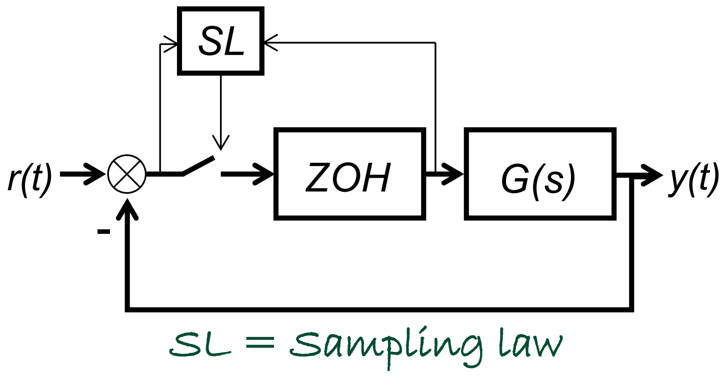


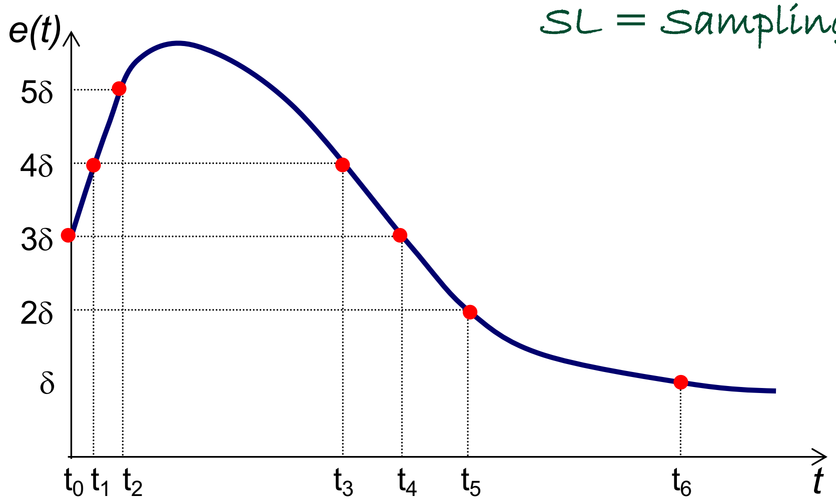


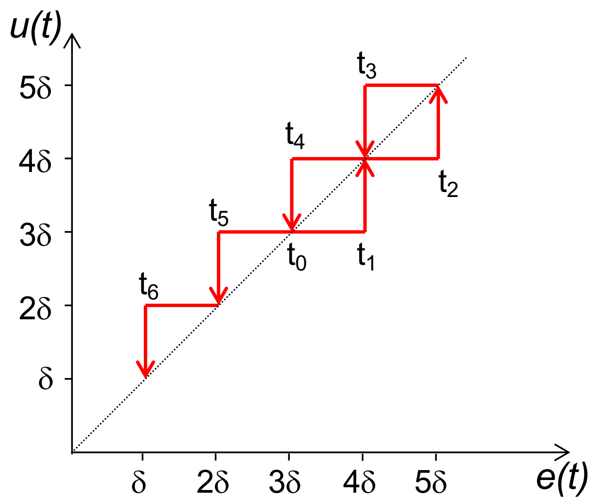
Falling ball

2. What is an event?

The "send-on-delta sampling" criterion: $|e(t)-e(t_i)|=\delta$







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

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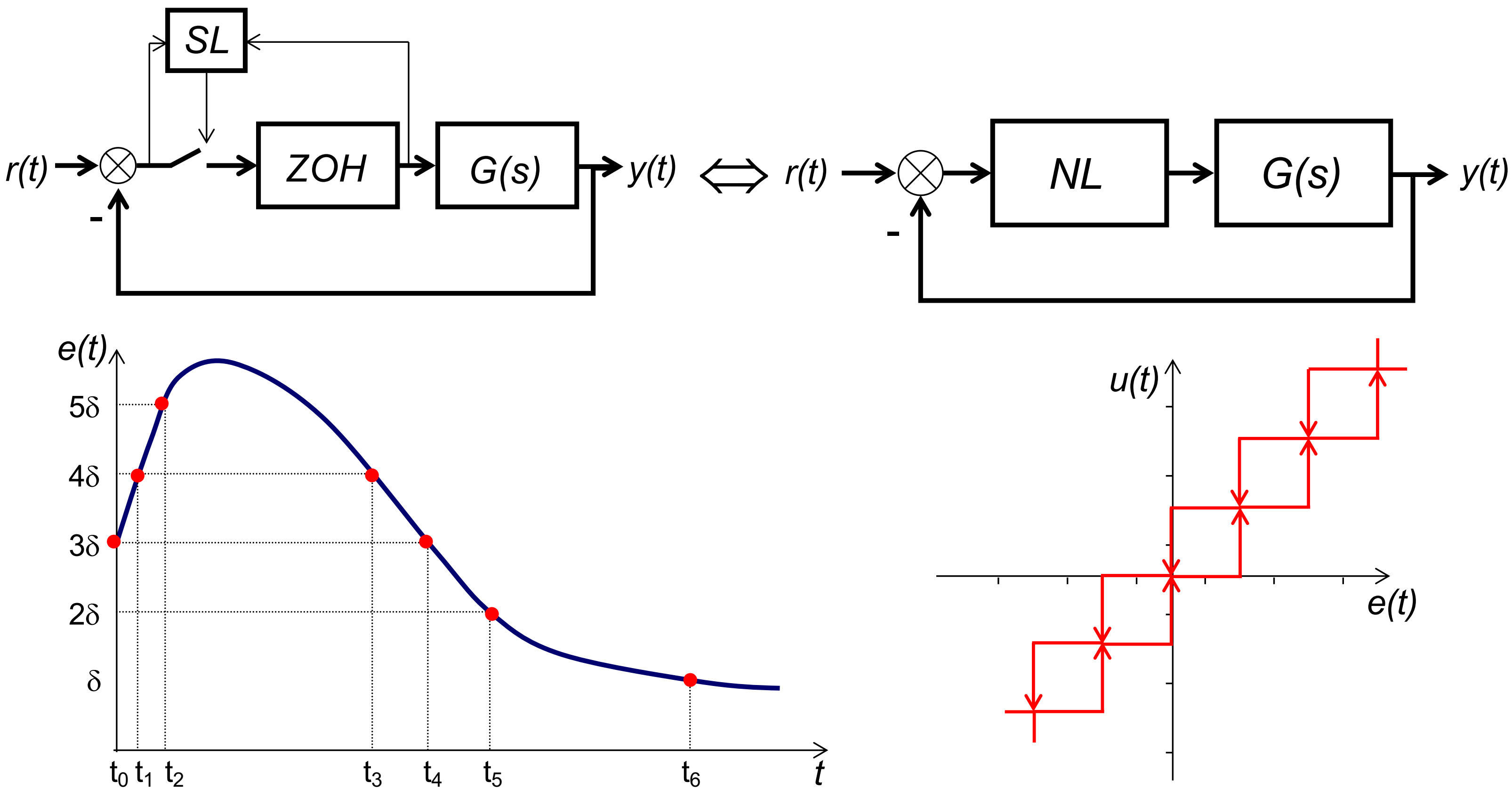

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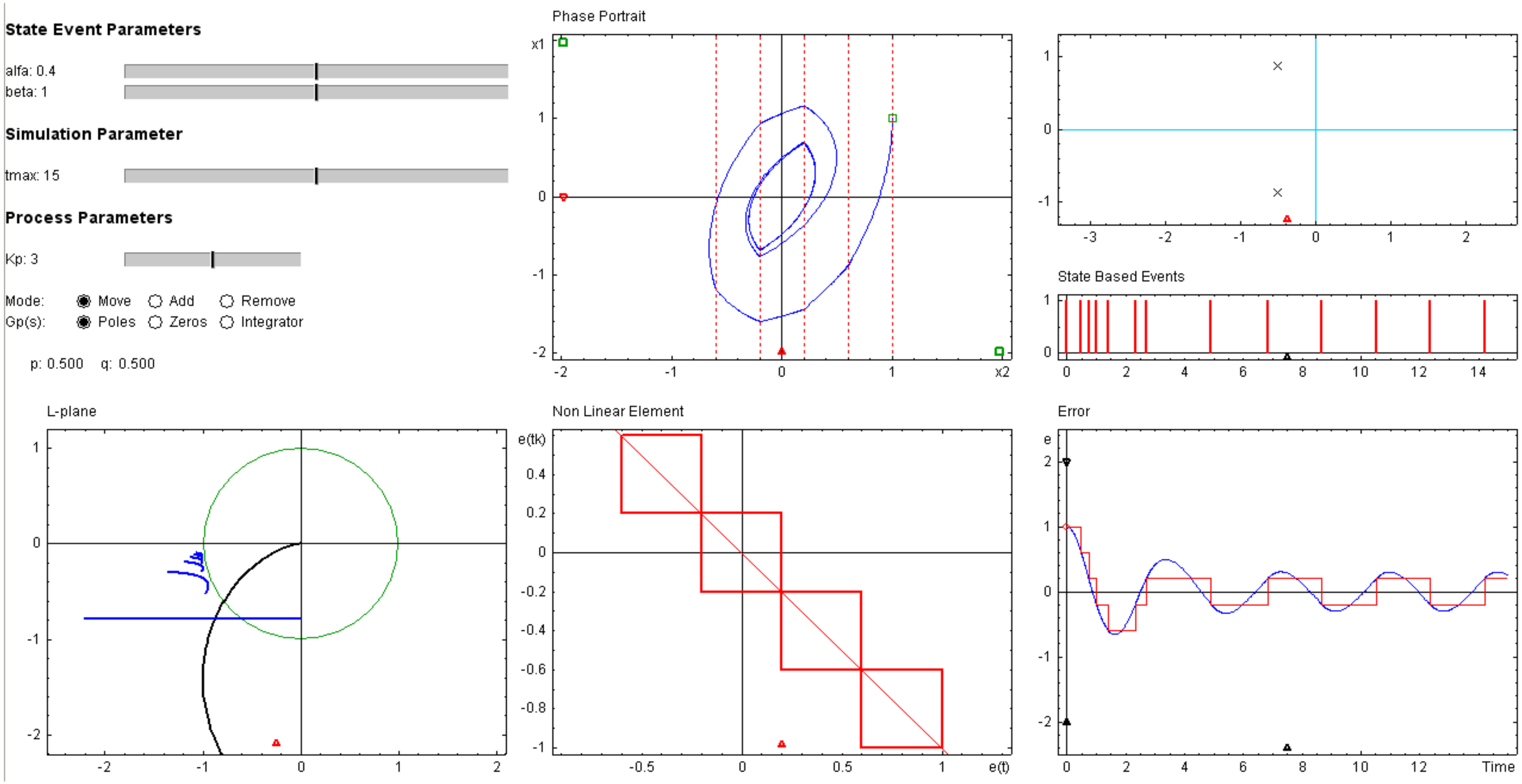

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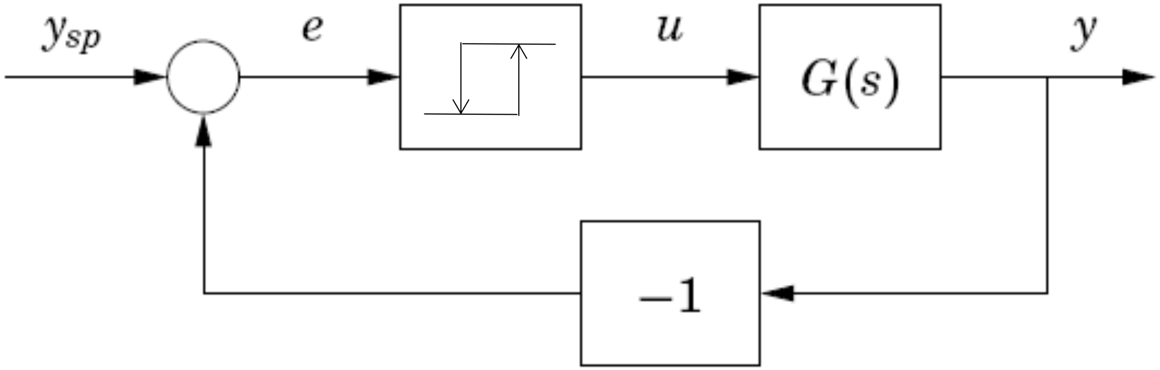
3. Relay control systems

- 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, D-S modulators, Variable structure systems
  - Self-oscillating adaptive systems, Amplifiers
- Relay systems have a rich dynamic behavior

3. Relay control systems

A challenge

To understand the behavior of the system

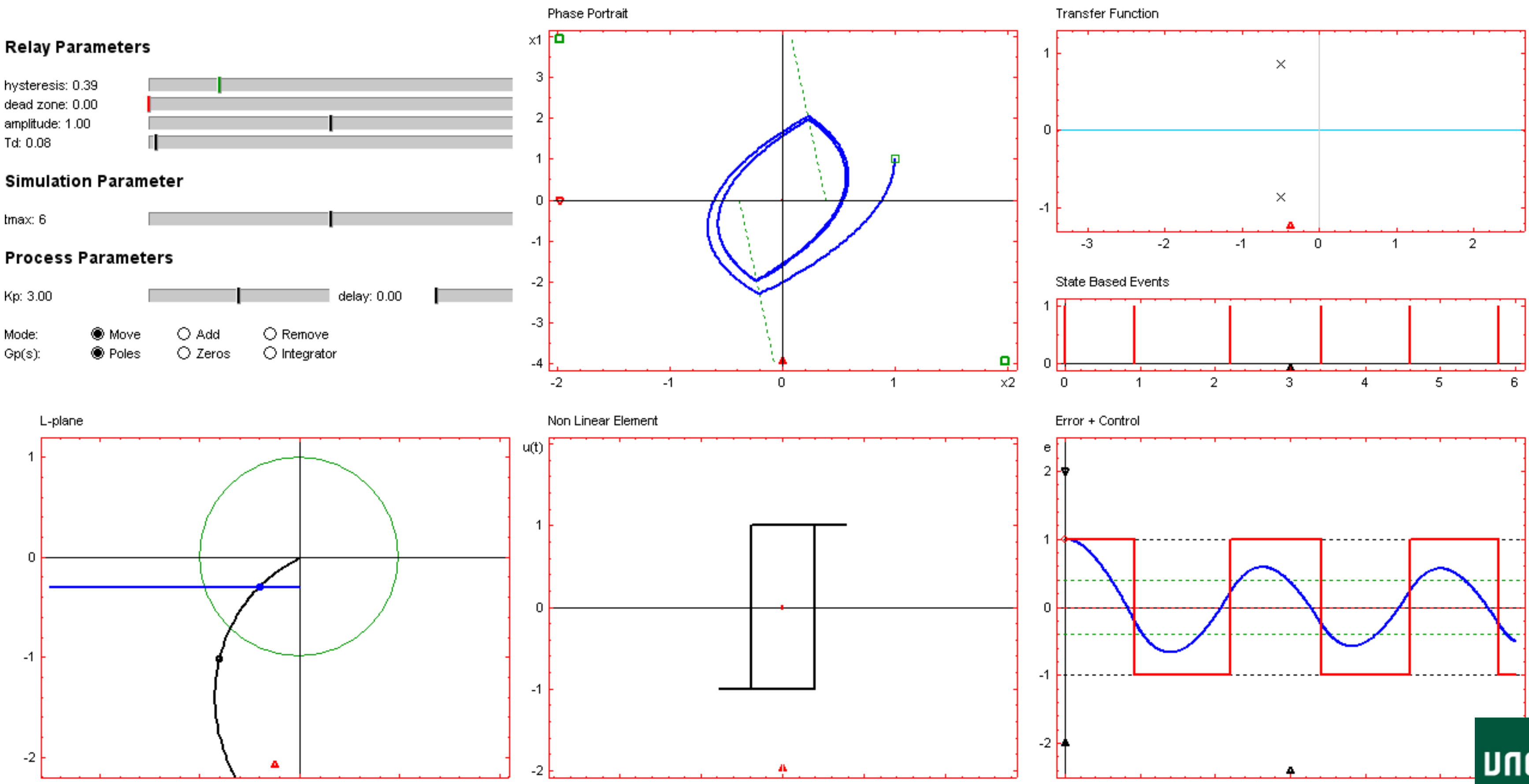


Some things are well known but important problems remain

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

3. Relay control systems

The "relay" toolbox



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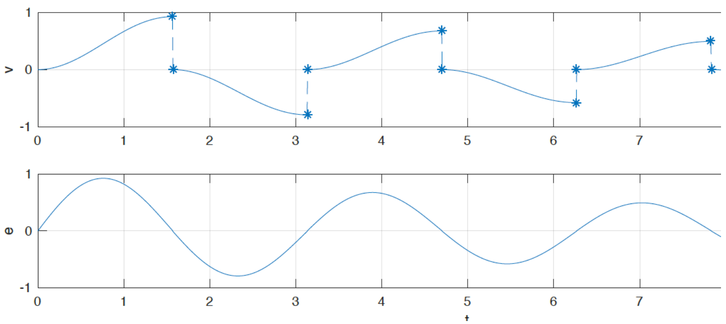
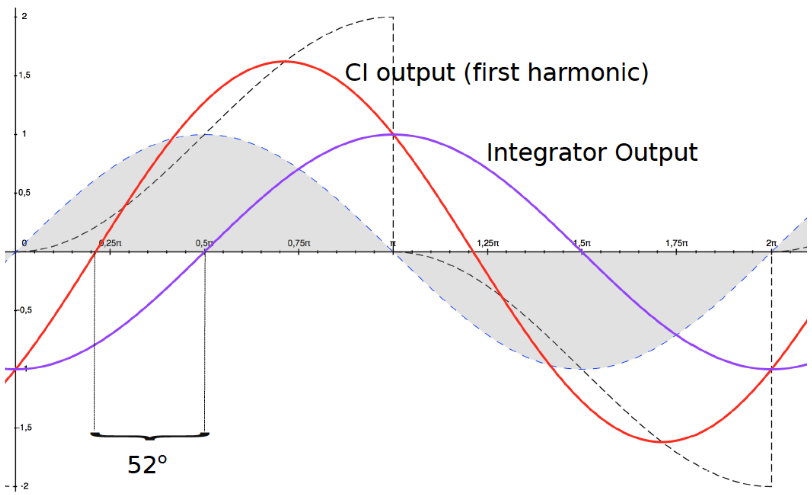
4. Reset control systems

Clegg's integrator

A nonlinear integrator for servomechanisms

Basic idea: The integrator state/output is set to zero (reset) at those instants in which the integrator input is zero.





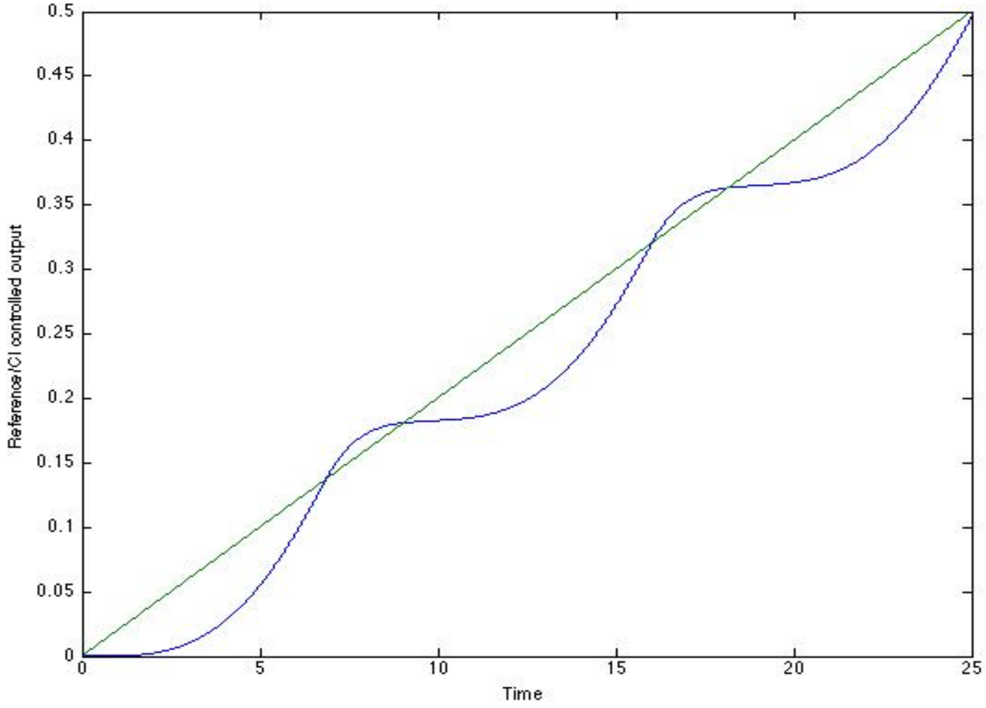
The Clegg integrator represents an attempt to synthesize a nonlinear circuit having the amplitude-frequency characteristic of a linear integrator while avoiding the 90" phase lag associated with the linear transfer function.

J.C. Clegg, A nonlinear integrator for servomechanisms, *Trans. A. I. E. E. m*, Part II 77 (1958) 41–42

4. Reset control systems

Clegg's integrator

…but asymptotic properties of the integrator are lost!



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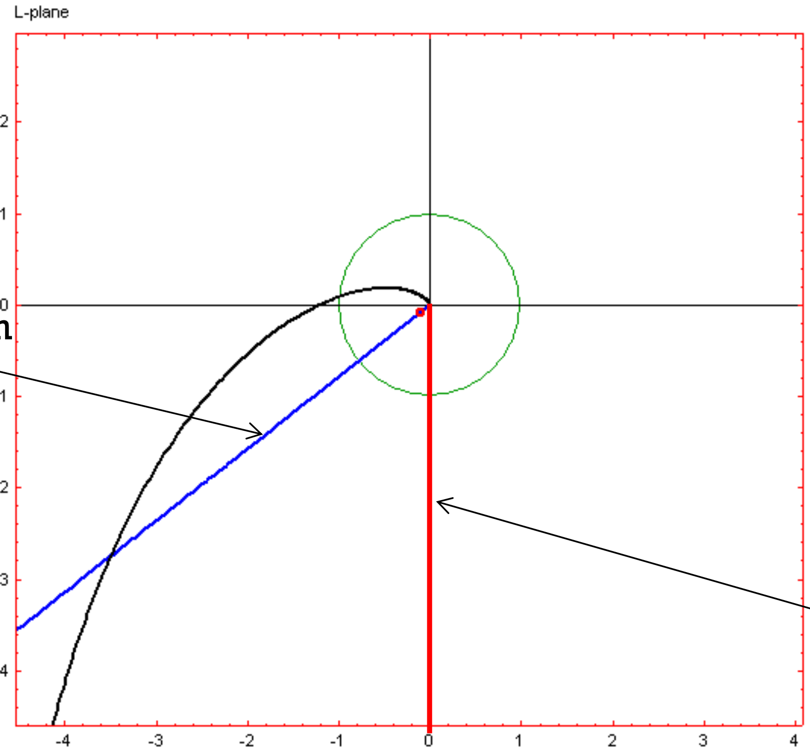
4. Reset control systems

Clegg's integrator

CI gives phase lead over a (linear) integrator

CI describing function

$$CI(j\omega)=\frac{1{,}62}{\omega}e^{-j38{,}1^{o}}$$



$$I(j\omega)=\frac{1}{\omega}e^{-j90^{o}}$$

Linear integrator

J.C. Clegg, A nonlinear integrator for servomechanisms, *Trans. A. I. E. E. m*, Part II 77 (1958) 41–42

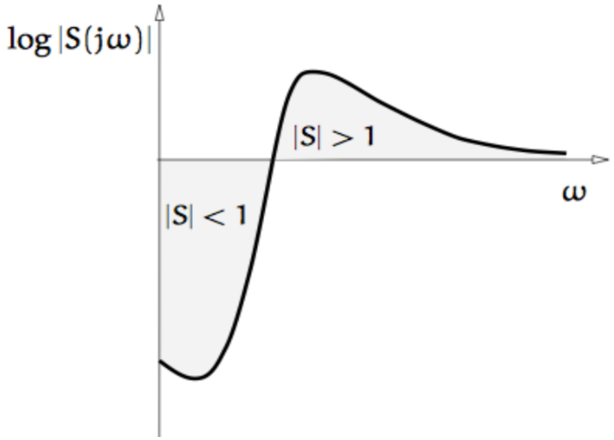
4. Reset control systems

Main motivation of reset control systems

Overcoming fundamental limitations of LTI controllers

Frequency domain:

The "area formula" (Bode)

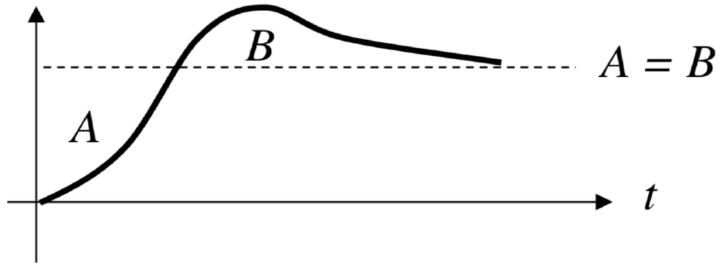


$$\int_0^\infty log|S(j\omega)|d\omega = 0$$

(for L(s) with poles-zeros excess of 2 or more, and no open-loop poles in RHP)

Time domain:

Another "area formula"



$$\int_0^\infty e(t)dt = 0$$

$$lim_{t\to\infty}e(t) = 0$$

(for L(s) having 2 or more integrators)

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4. Reset control systems

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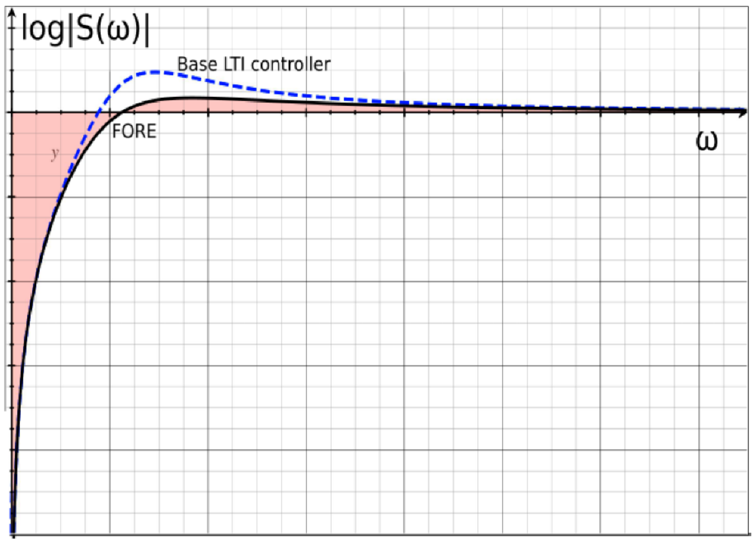
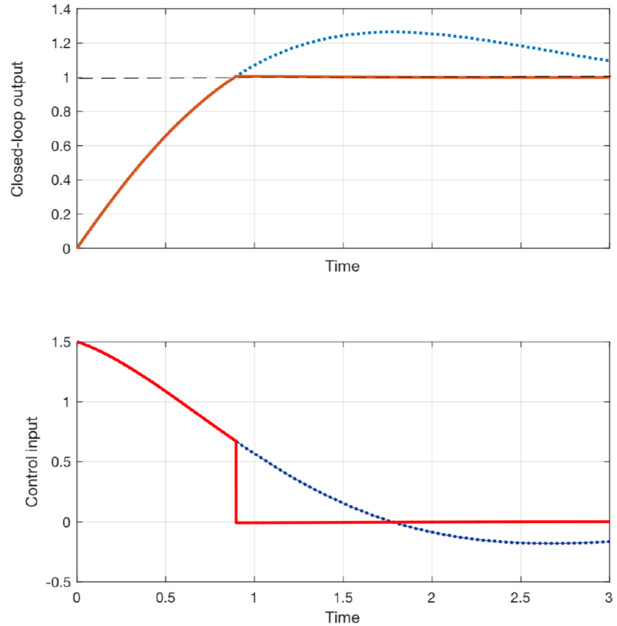
Frequency domain



$$\int_0^\infty log|S(j\omega)|d\omega < 0 \text{ (FORE)}$$

$$\int_0^\infty log|S(j\omega)|d\omega \geq 0 \text{ (any LTI controller)}$$

Time domain



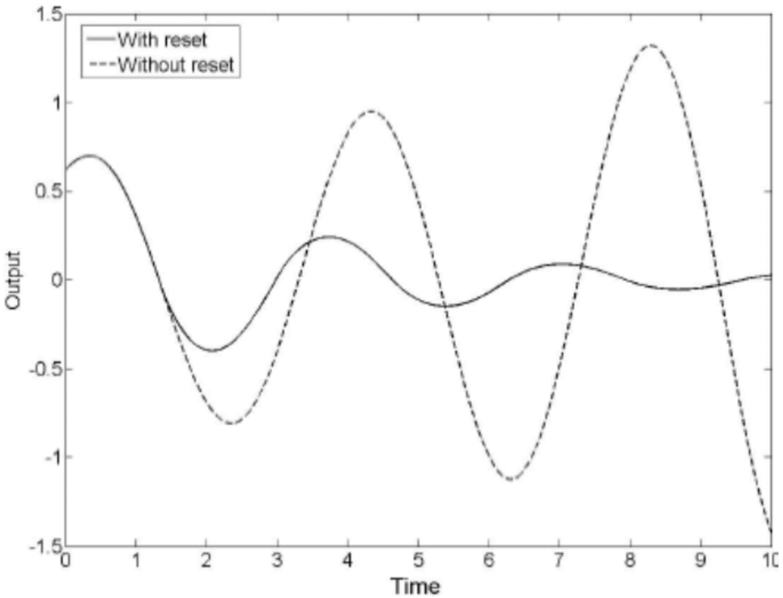
No overshoot (even for fast responses) !
LTI controllers (loop gain with 2 integrators) always prod uce overshoot !

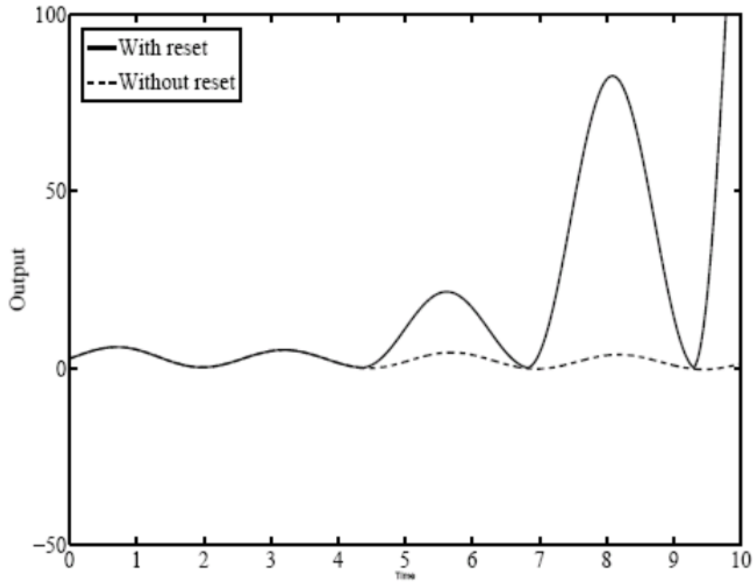
4. Reset control systems

Stability

The problem is non-trivial: reset can stabilize an unstable base system,

… But also can destabilize a stable base system!





Some sufficient conditions for stability:

- independent on the reset instants: H_β -condition (Bekker-Hollot-Chait’2000)

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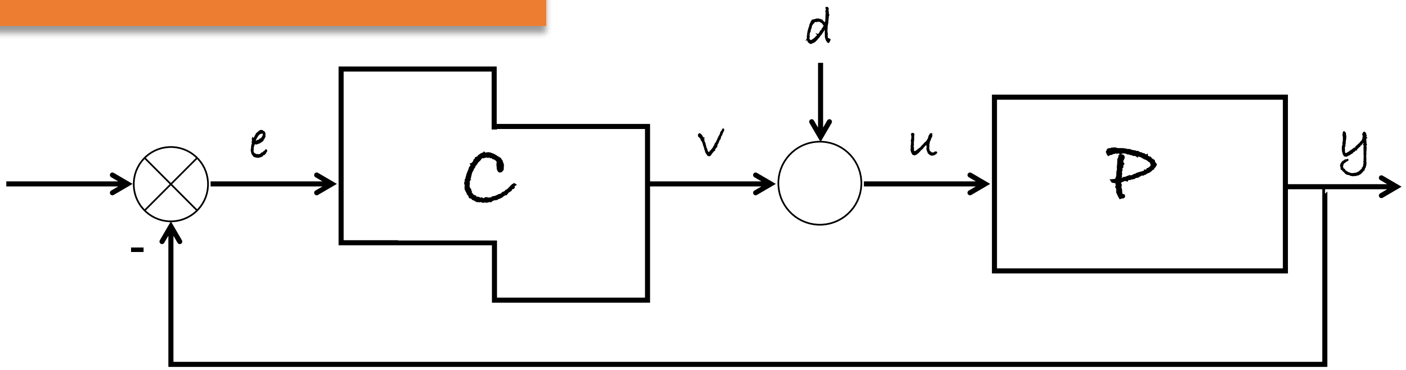
4. Reset control systems

Stability: Problem formulation



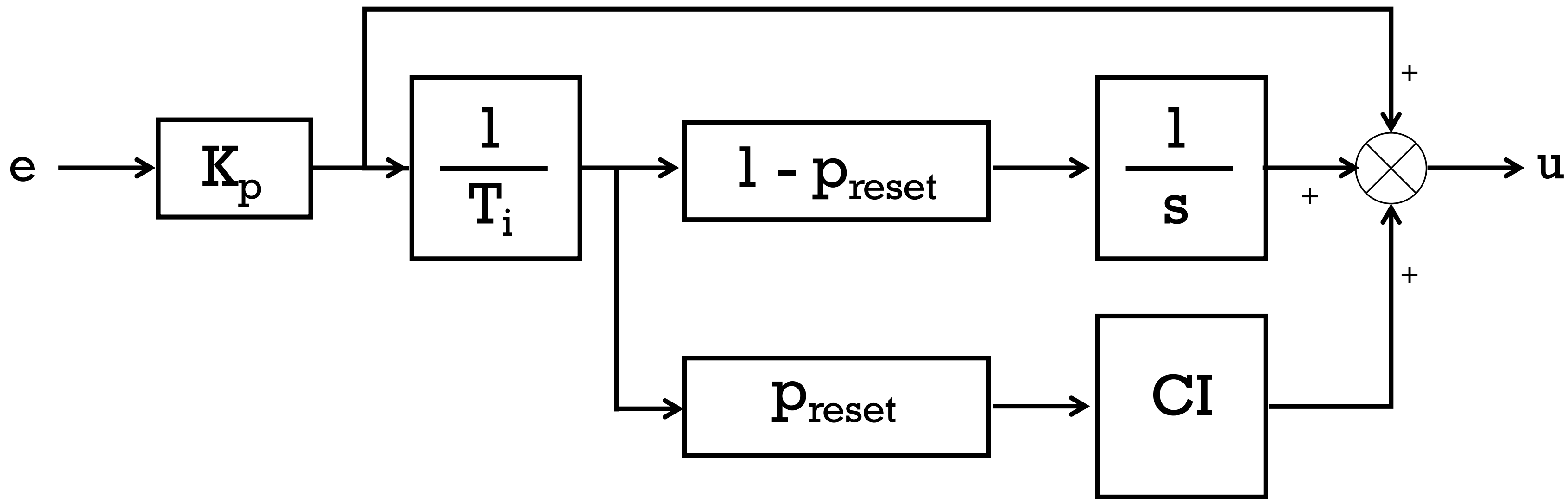
$$\mathcal{C}: \begin{cases} \dot{x}_r = A_r x_r + B_r e, & e \neq 0 \\ x_r^+ = A_\rho x_r, & e = 0 \\ v = C_r x_r \end{cases} \qquad \mathcal{P}: \begin{cases} \dot{x}_p = A_p x_p + B_p u \\ y = C_p x_p \\ u = v + d \end{cases}$$

- 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

4. Reset control systems

PI + CI controller



Baños, A.Vidal: Definition and tuning of a PI + CI reset controller, *European Control Conference*, Kos, Greece, 2007

4. Reset control systems

PI + CI controller: Main characterisics

- A simple structure easily implementable, with few parameters
- Application target: process control
- Good transitory and steady state properties
- LTI base compensator : PI Antiwindup behavior
- "Simple" tuning rules
  - Tune the base PI controller
  - Select the reset percentage to reduce overshoot
- A fast response with no excessive overshoot may be obtained, overcoming LTI compensation limitations.
- Very intuitive for manual tuning: reset is a single parameter p_{reset}
- CI: A "derivative" action without increasing the cost of feedback

Baños, A.Vidal: Definition and tuning of a PI + CI reset controller, *European Control Conference*, Kos, Greece, 2007

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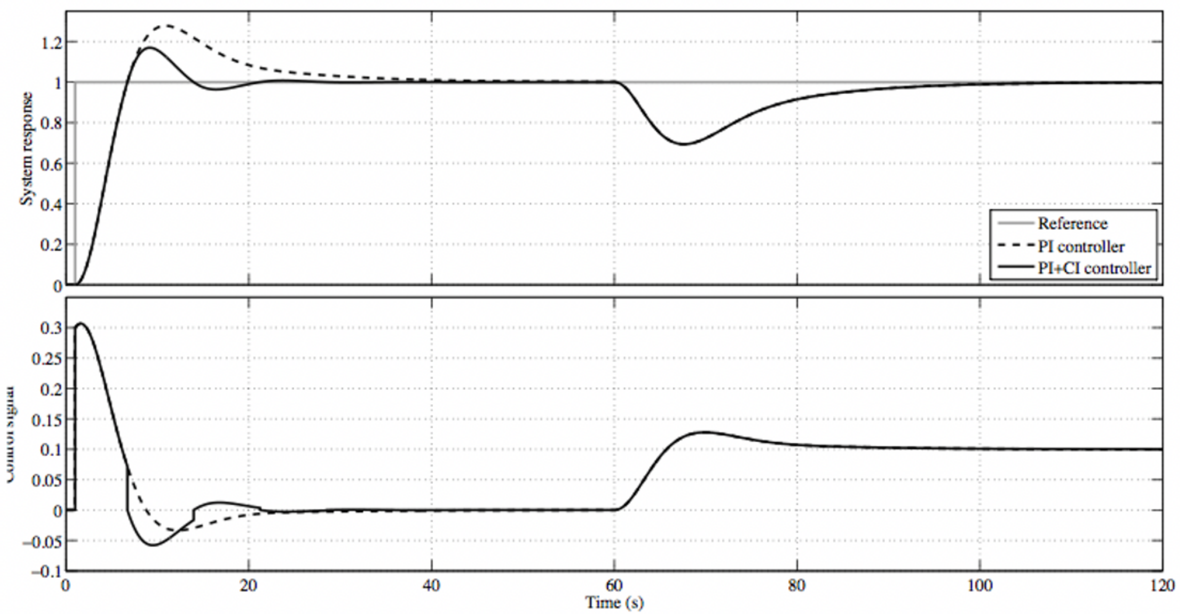
4. Reset control systems

PI + CI controller: Example IPTD system

	Reference		Disturbance		Stability margins	
	IAE (s)	ITAE (s^2)	IAE (s)	ITAE (s^2)	φ_m (°)	A_m (dB)
PI	6.43	62.80	4.48	328.3	48.6	24.28
PI+CI	4.17	20.44	4.48	328.3	48.4	23.9

$$\tilde{P}(s) = \frac{1}{s} e^{-1.69s}$$

PI base (SIMC): $k_p = 0.3, T_i = 13.5$ s



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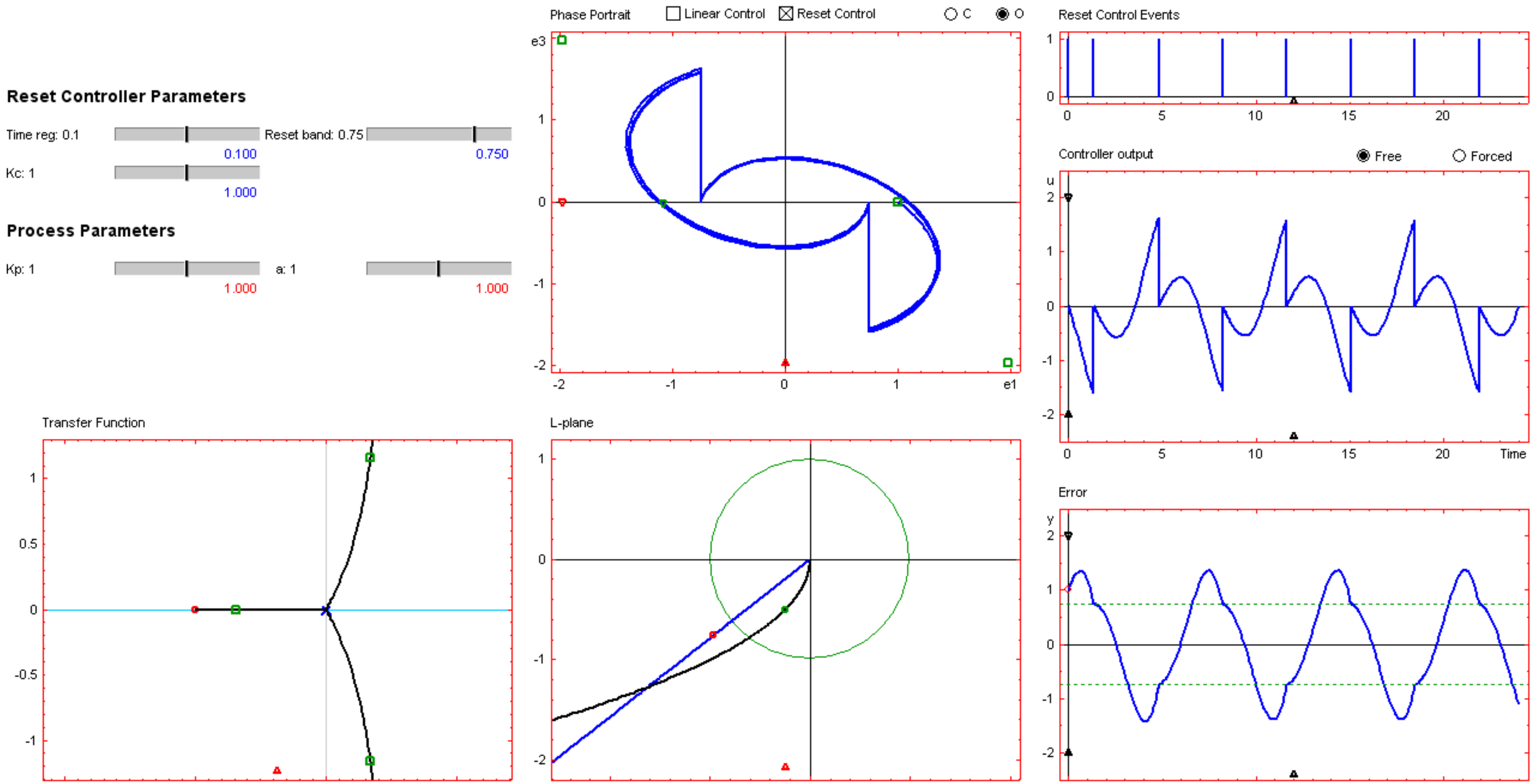
4. Reset control systems

The “reset control” toolbox



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

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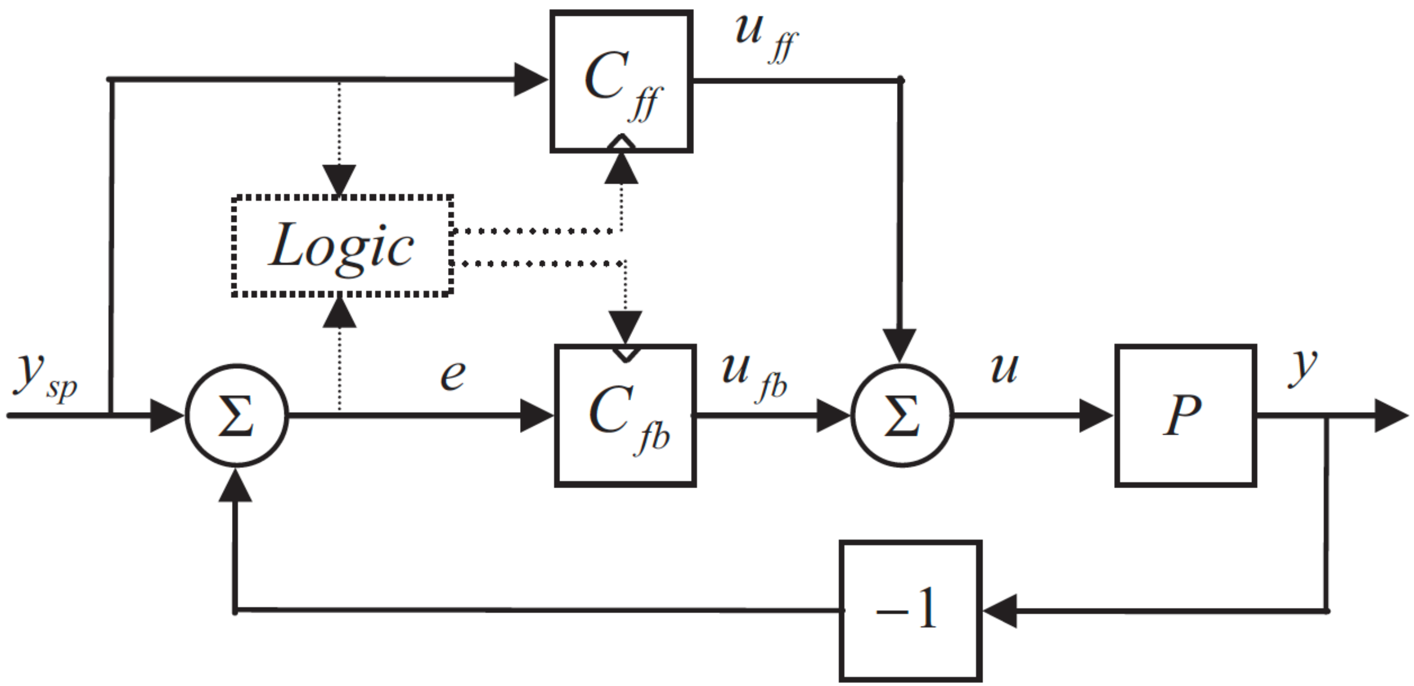
5. A two-degree-of-freedom event-based PI controller

Block diagram of the event-based controller with two degrees of freedom

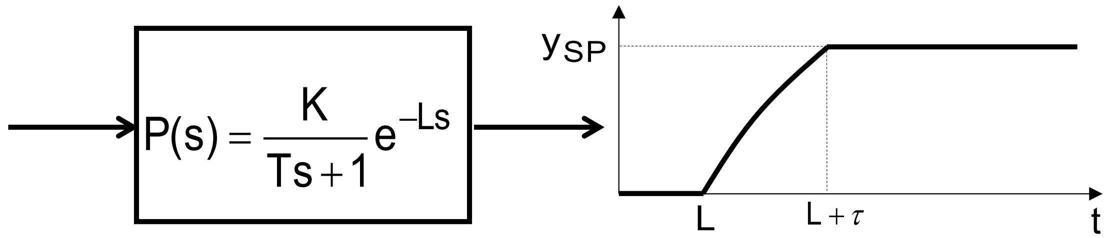


J. Sánchez, A. Visioli, S. Dormido. "A two-degree-of-freedom PI controller based on events", *Journal of Process Control*, vol. 21, pp. 639-651, 2011

5. A two-degree-of-freedom event-based PI controller

Deign of the event-based feed-forward compensator C_{ff}

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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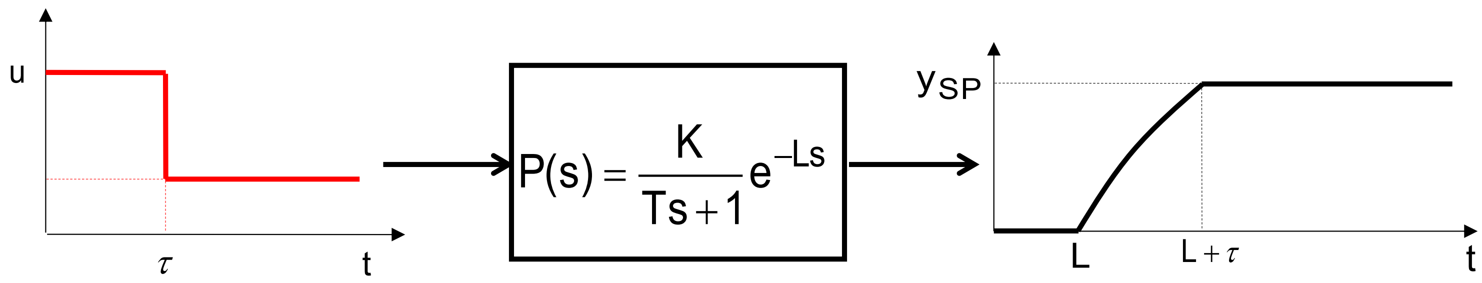


In this case, the following open-loop control action can be applied

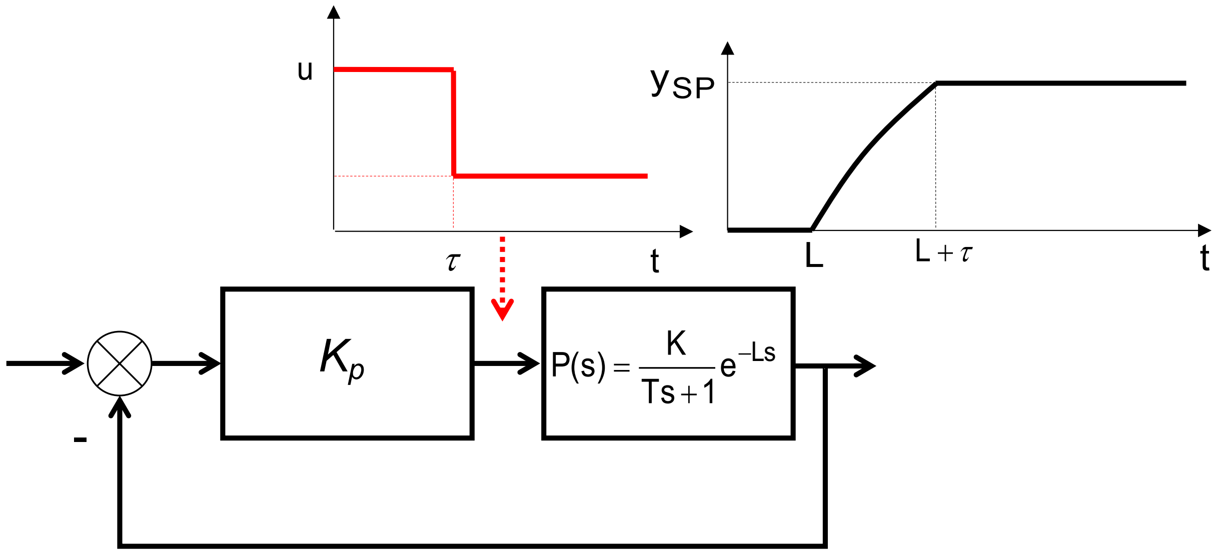
$$u_{\rm ff}(t) = \begin{cases} \bar{u}_{\rm ff} & \text{if } t < \tau \\ \dfrac{y_{\rm sp}}{K} & \text{if } t \geq \tau \end{cases} \qquad \bar{u}_{\rm ff} = \frac{y_{\rm sp}/K}{1 - e^{-\tau/T}}$$

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

5. A two-degree-of-freedom event-based PI controller

Proportional controller

The process to be controlled is modeled as a FOPTD

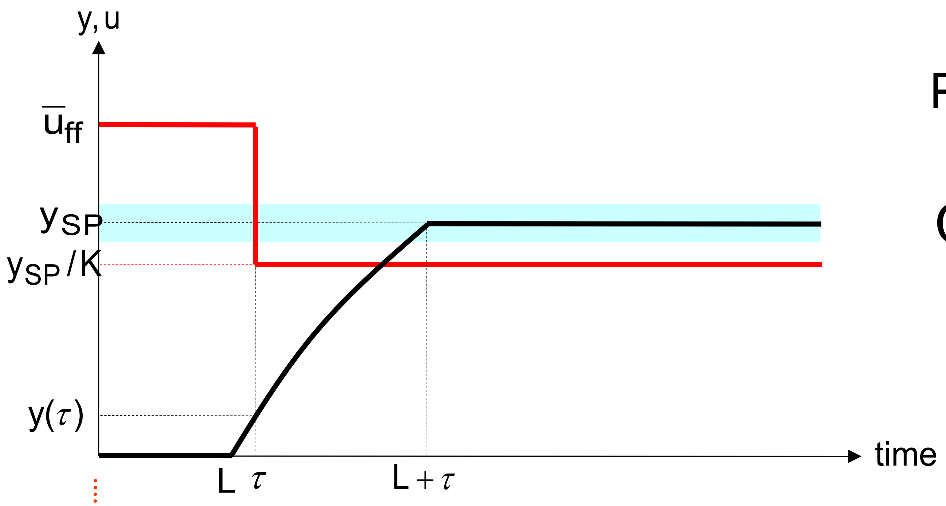


$$u_{ff}(t) = \begin{cases} \bar{u}_{ff} & \text{if } t < \tau \\ \frac{y_{sp}}{K} & \text{if } t \geq \tau \end{cases} \qquad \bar{u}_{ff} = \frac{y_{sp}/K}{1 - e^{-\tau/T}} \Rightarrow \tau = -T \log\left(1 - \frac{y_{sp}}{K\bar{u}_{ff}}\right)$$

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

5. A two-degree-of-freedom event-based PI controller

The process to be controlled is modeled as a FOPTD



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

$$C(s) = K_p$$

$$u_p = K_p y_{SP}$$

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

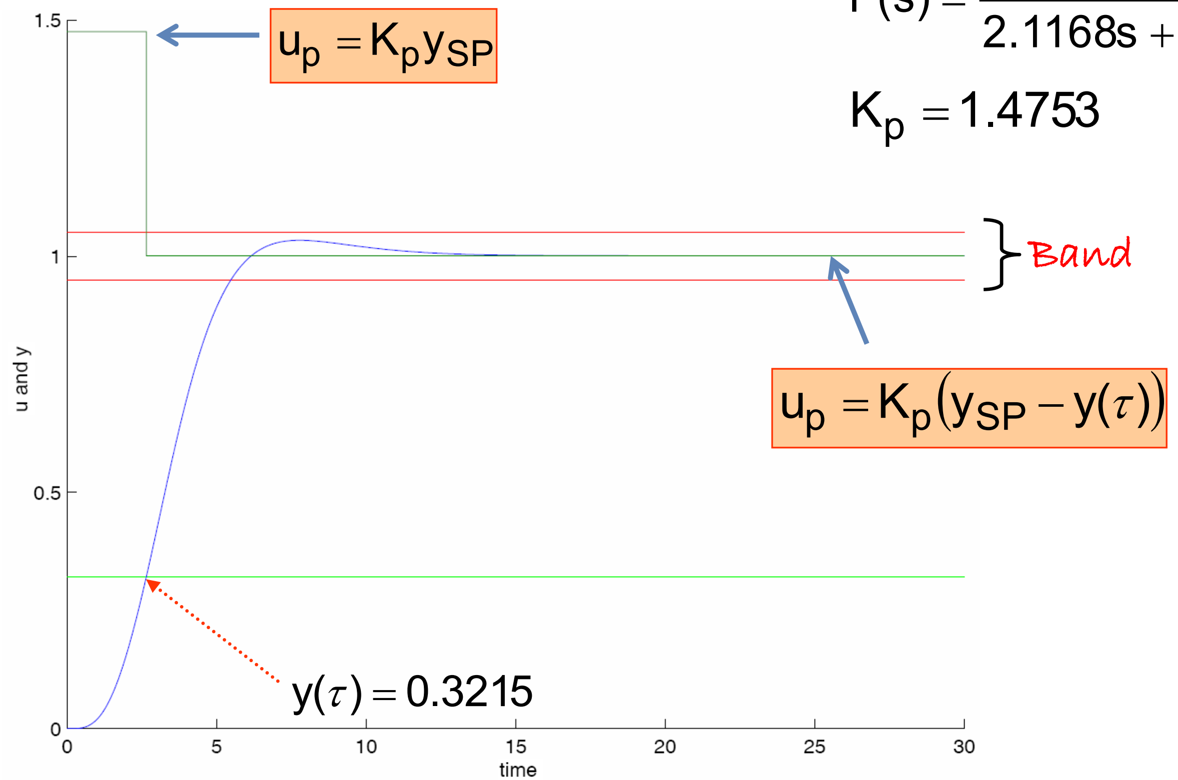
J. Sánchez, A. Visioli, S. Dormido. "A two-degree-of-freedom PI controller based on events", *Journal of Process Control*, vol. 21, pp. 639-651, 2011

5. A two-degree-of-freedom event-based PI controller

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

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

$$K_p = 1.4753$$



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5. A two-degree-of-freedom event-based PI controller

Algorithm of the integral action

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

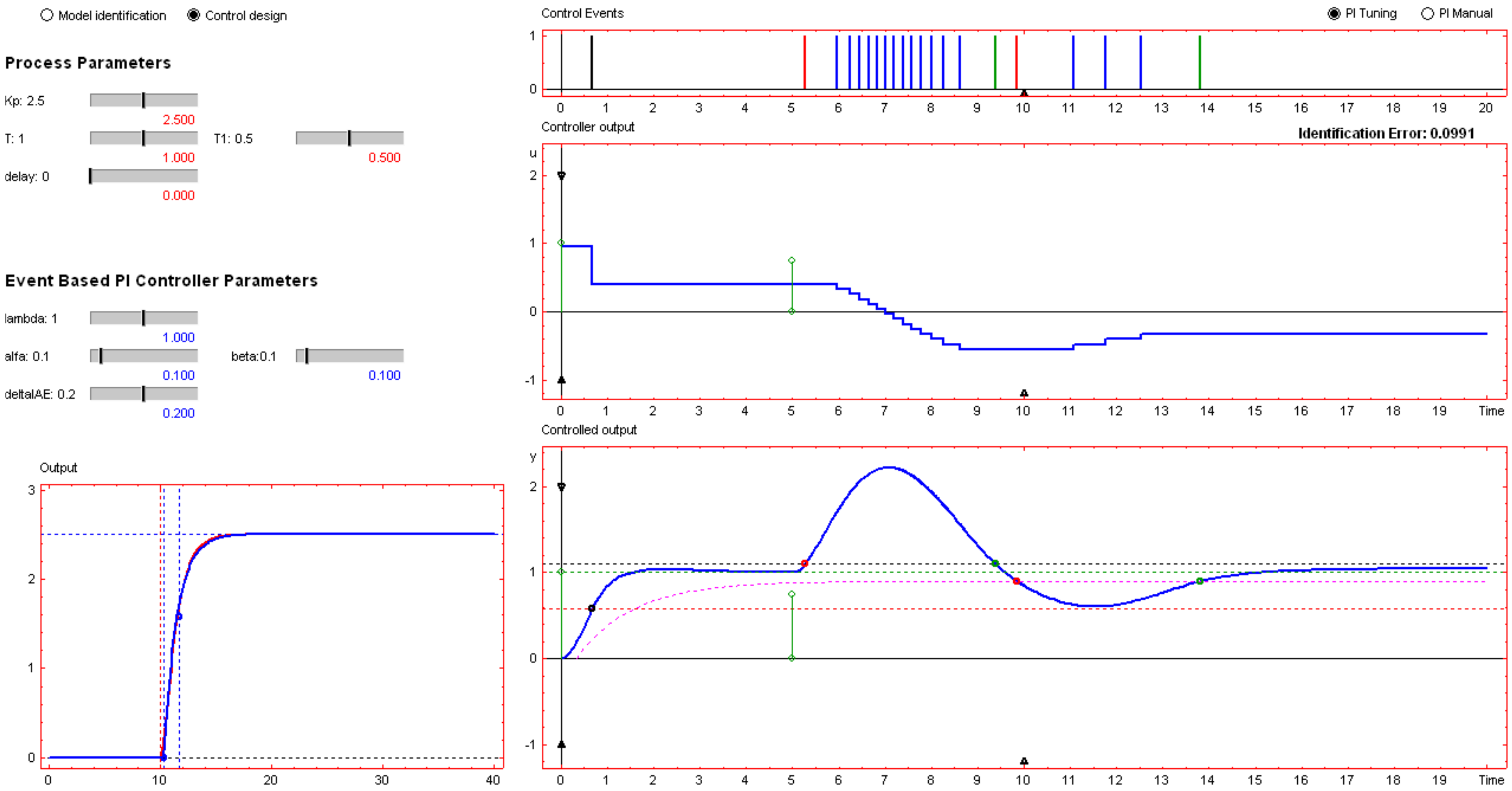
$$a y_{SP} \leq y_{SP} \leq b y_{SP}$$

  - The proportional action is constant: $u_p = K_p(y_{SP} - D_1)$
  - The integrator is enabled.
- When the process leaves the dead-band:
  - The integrator starts calculating the IAE
  - Every time the IAE 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

5. A two-degree-of-freedom event-based PI controller

The "event based PI" toolbox



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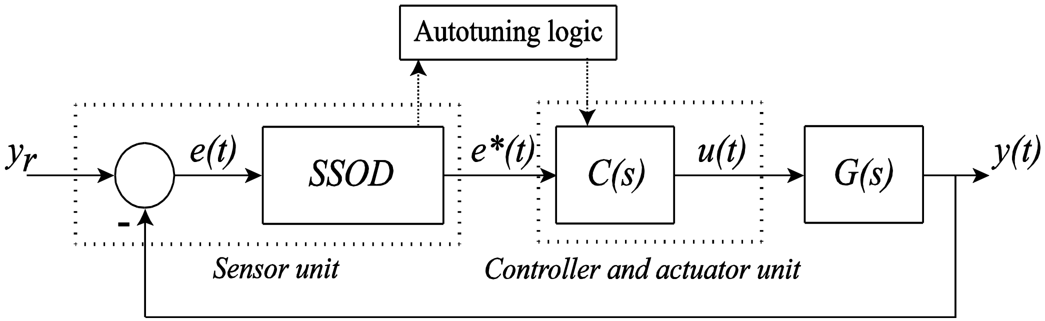
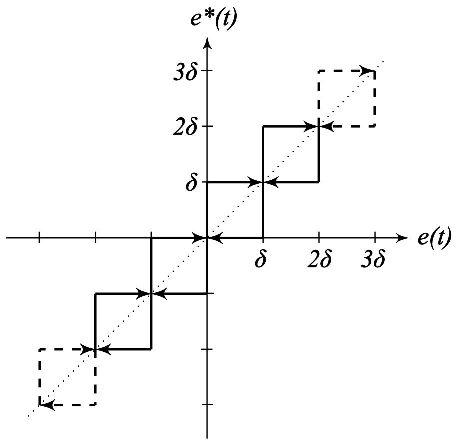
6. Event based model identification

Identification based on the DF of the SSOD



Architecture of the event-based control loop



Relationship between $e(t)$ and $e^*(t)$.

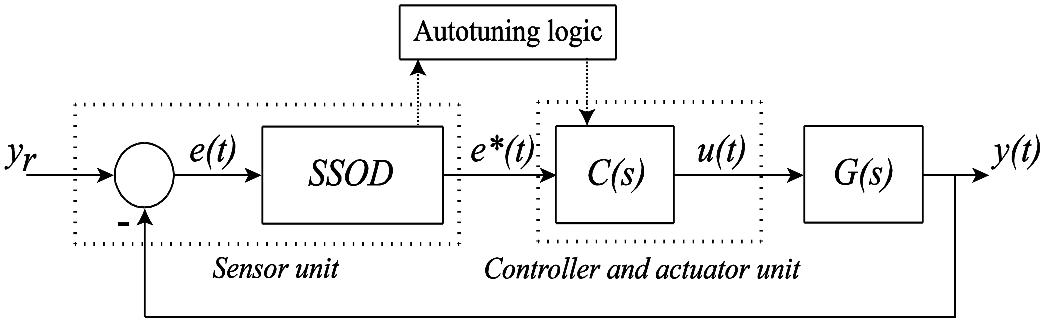
The behaviour of the symmetric send-on-delta sampler can be described as:

$$e^*(t) = \begin{cases} (i+1)\delta & \text{if } e(t) \geq (i+1)\delta \text{ and } e^*(t^-) = i\delta \\ i\delta & \text{if } e(t) \in [(i-1)\delta, (i+1)\delta] \text{ and } e^*(t^-) = i\delta \\ (i-1)\delta & \text{if } e(t) \leq (i-1)\delta \text{ and } e^*(t^-) = i\delta \end{cases}$$

J. Sánchez, Mª. Guinaldo, A. Visioli, S. Dormido. "Identification of process transfer function parameters in event-based PI control loops", *ISA Transactions*, 75, 2018, 157-171.

6. Event based model identification

Identification based on the DF of the SSOD



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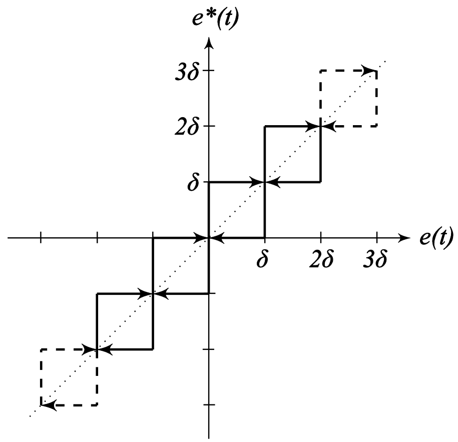
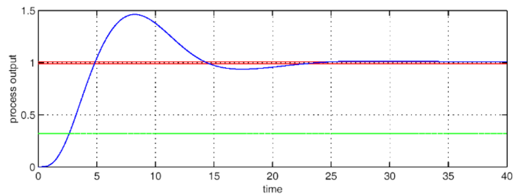
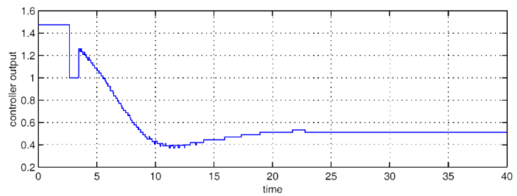


Relationship between $e(t)$ and $e^*(t)$.





In an event control system, events occur due to:

1. Changes in the set point.
2. Disturbances
3. Periodically for safety.

Rest of the time:

- There are no control actions.
- It should not oscillate if it is "fine" tuned.

J. Sánchez, Mª. Guinaldo, A. Visioli, S. Dormido. "Identification of process transfer function parameters in event-based PI control loops", *ISA Transactions*, 75, 2018, 157-171.

6. Event based model identification

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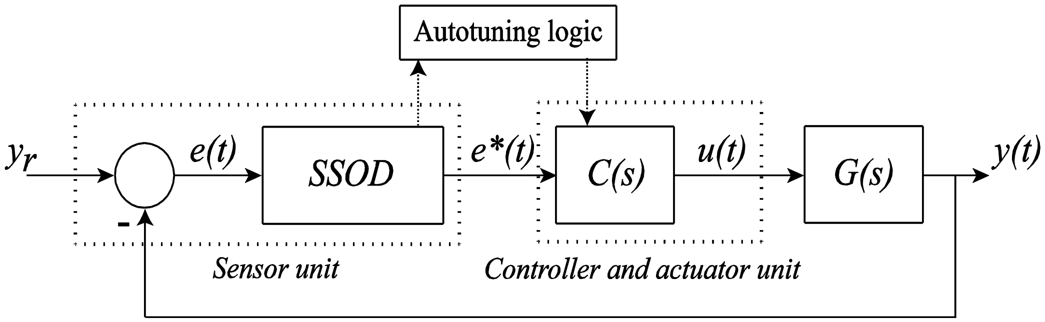

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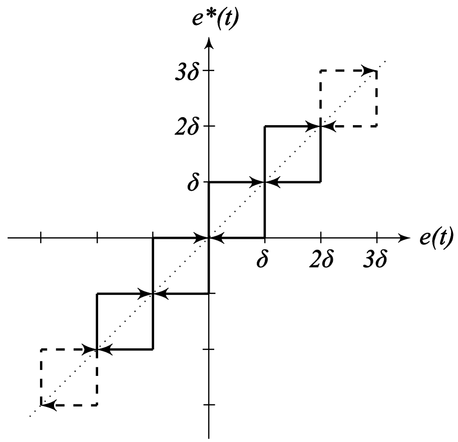

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3. Periodically for safety.

Rest of the time:

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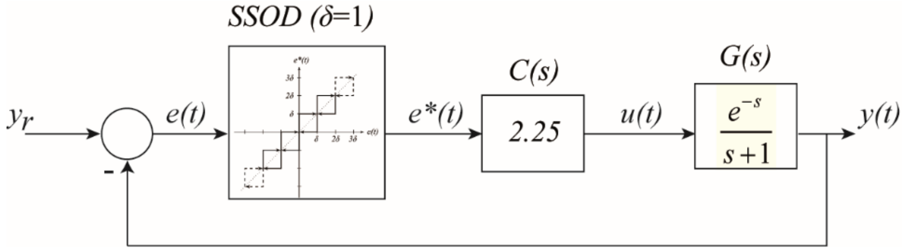
- It should not oscillate if it is "fine" tuned.

The SSOD sampler allows the system to oscillate in a similar way to that produced by a relay with hysteresis with infinite levels δ (i.e., $\pm\ \delta$, $\pm 2\ \delta$, …, $\pm n\delta$)!

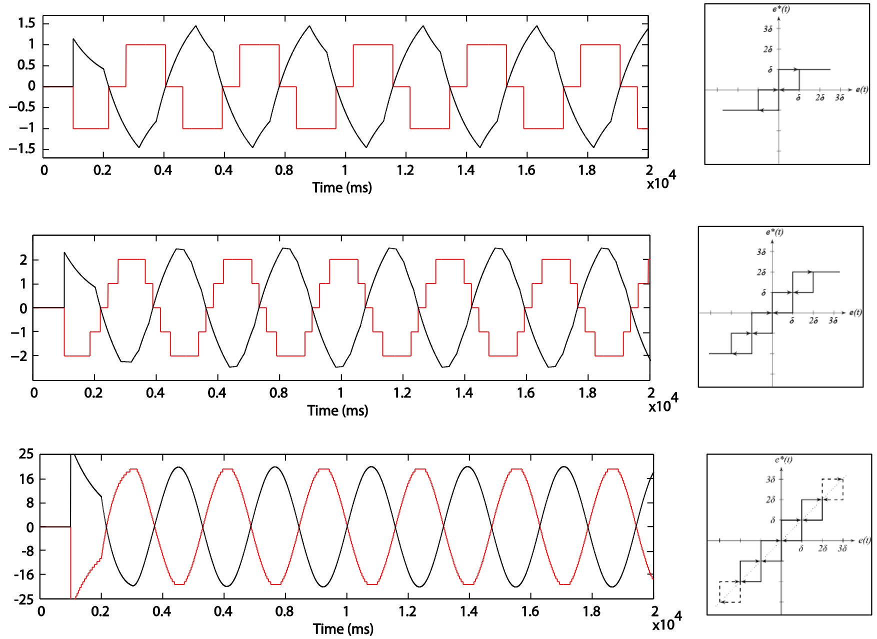
J. Sánchez, Mª. Guinaldo, A. Visioli, S. Dormido. "Identification of process transfer function parameters in event-based PI control loops", *ISA Transactions*, 75, 2018, 157-171.

6. Event based model identification

Identification based on the DF of the SSOD



Different initial conditions produce that the system converges to a **limit cycle** with different amplitude and frequency.



J. Sánchez, Mª. Guinaldo, A. Visioli, S. Dormido. "Identification of process transfer function parameters in event-based PI control loops", *ISA Transactions*, 75, 2018, 157-171.

6. Event based model identification

Identification based on the DF of the SSOD

The *describing function* of the SSOD sampler is given by the following equation:

$$N(A,\delta)=\frac{2\delta}{\pi A}\left[1+\sqrt{1-\left(\frac{\delta}{A}m\right)^2}+2\sum_{k=1}^{m-1}\sqrt{1-\left(\frac{\delta}{A}k\right)^2}\right]-j\frac{2}{\pi}\left(\frac{\delta}{A}\right)^2 m \qquad m=\lfloor A/\delta \rfloor$$

Dormido, S.; Mellado, M. Determinación de ciclos límite en sistemas de muestreo adaptativo. *Revista de Automática* (1975)

Dormido, S.; Mellado, M. A study on fixed-difference sampling scheme. *Applications and Research in Information Systems and Sciences* (1977)

Where the input is a sinusoidal signal of amplitude A.

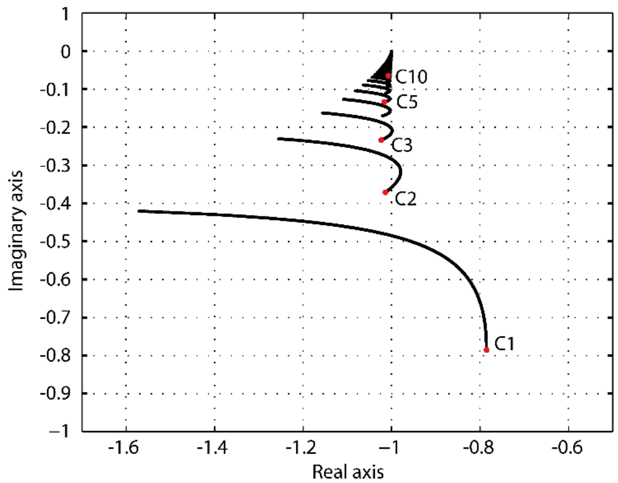
The condition for the existence of limit cycles is given by:

$$G_{ol}(j\omega_{osc})=-\frac{1}{N(A,\delta)}$$

where

$$G_{ol}(j\omega_{osc})=K_{osc}G(j\omega_{osc})$$

A C_i point corresponds to a amplitude of $A = i\delta$



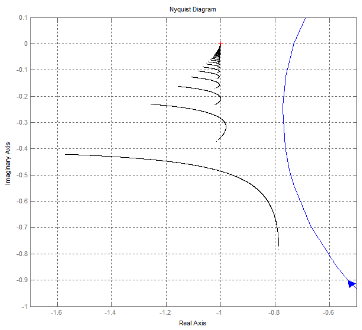
J. Sánchez, Mª. Guinaldo, A. Visioli, S. Dormido. "Identification of process transfer function parameters in event-based PI control loops", *ISA Transactions*, 75, 2018, 157-171.

6. Event based model identification

Identification based on the DF of the SSOD

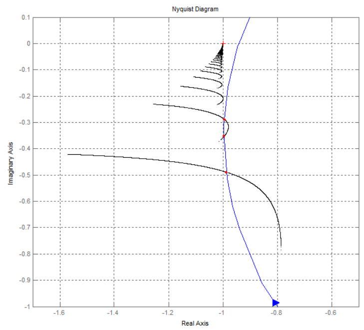
$$G_{ol}(s) = K_{osc}\frac{e^{-s}}{s+1}$$

Example of limit cycles by changing K_{osc}



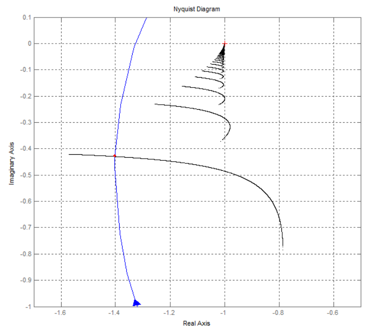
$K_{osc} = 1.65$

Without limit cycle



$K_{osc} = 2.13$

Three possible limit cycle



$K_{osc} = 3$

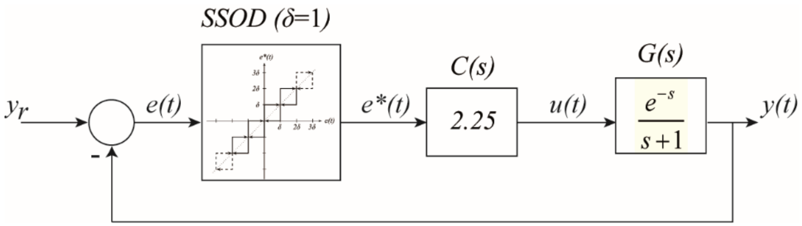
A limit cycle
with possible instability

- The theoretical point of intersection C in the plane of Nyquist does not coincide with the real C', but ...
- The greater the amplitude of the oscillation, the information provided by the experimental data matches much more with the information provided by the describing function.
- The greater the amplitude of the oscillation, the better the identification results.

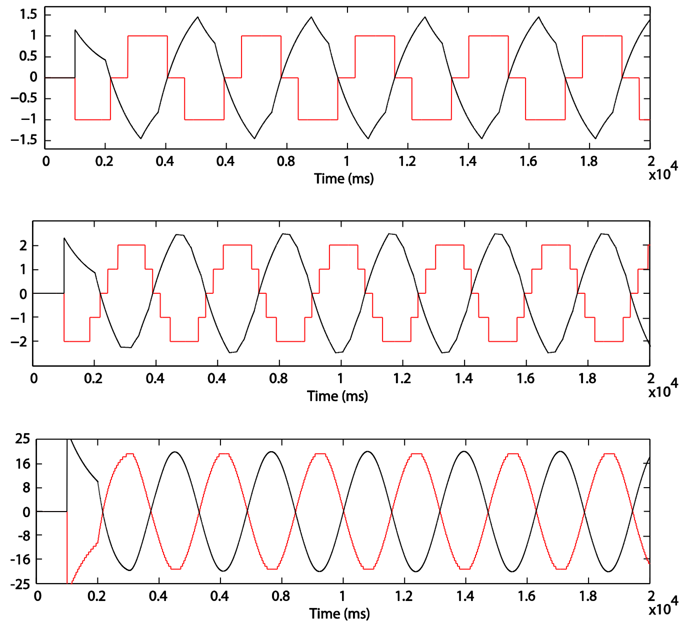
J. Sánchez, Mª. Guinaldo, A. Visioli, S. Dormido. "Identification of process transfer function parameters in event-based PI control loops", *ISA Transactions*, 75, 2018, 157-171.

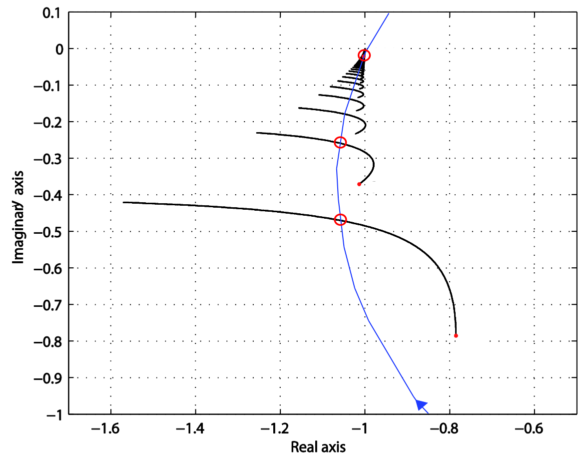
6. Event based model identification

Identification based on the DF of the SSOD



$$\frac{-1}{N(\infty,1)} = C_\infty = \lim_{i\to\infty} C_i = -1$$





J. Sánchez, Mª. Guinaldo, A. Visioli, S. Dormido. "Identification of process transfer function parameters in event-based PI control loops", *ISA Transactions*, 75, 2018, 157-171.

6. Event based model identification

Identification based on the DF of the SSOD

- Obtain expressions of magnitude and argument of the model to be identified:

$$G_{FOPTD}(s)=\frac{Ke^{-Ls}}{Ts+1} \qquad G_{SOPTD-1}(s)=\frac{Ke^{-Ls}}{(Ts+1)^2}$$

$$G_{FOPDTI}(s)=\frac{Ke^{-Ls}}{s(Ts+1)} \qquad G_{SOPTD-2}(s)=\frac{Ke^{-Ls}}{(T_1 s+1)(Ts+1)}$$

$$\Rightarrow \quad |G(j\omega)| \qquad \angle G(j\omega)$$

- We apply a K_{osc} gain to the process so that a stable limit cycle occurs.
- The parameters of the oscillation (ω_{osc} and amplitude A_{osc}) are measured and calculated:

$$C_{osc}=-\frac{1}{N(A_{osc},\delta)} \quad \Rightarrow \quad |C_{osc}| \qquad \angle C_{osc}$$

- The gain of the process K is obtained adding a *bias* (p.e., 0.1δ) to the output of the SSOD:

$$K=\frac{\int_0^{2\pi/\omega_{osc}} y(t)dt}{K_{osc}\int_0^{2\pi/\omega_{osc}} e^*(t)dt}$$

- The expressions of magnitude are matched to obtain T and those of the argument for L:

$$K_{osc}|G(j\omega_{osc})|=|C_{osc}| \quad \Rightarrow \quad \angle G(j\omega_{osc})=\angle C_{osc}$$

J. Sánchez, Mª. Guinaldo, A. Visioli, S. Dormido. "Identification of process transfer function parameters in event-based PI control loops", *ISA Transactions*, 75, 2018, 157-171.

6. Event based model identification

Identification based on the DF of the SSOD

Accuracy of the estimations

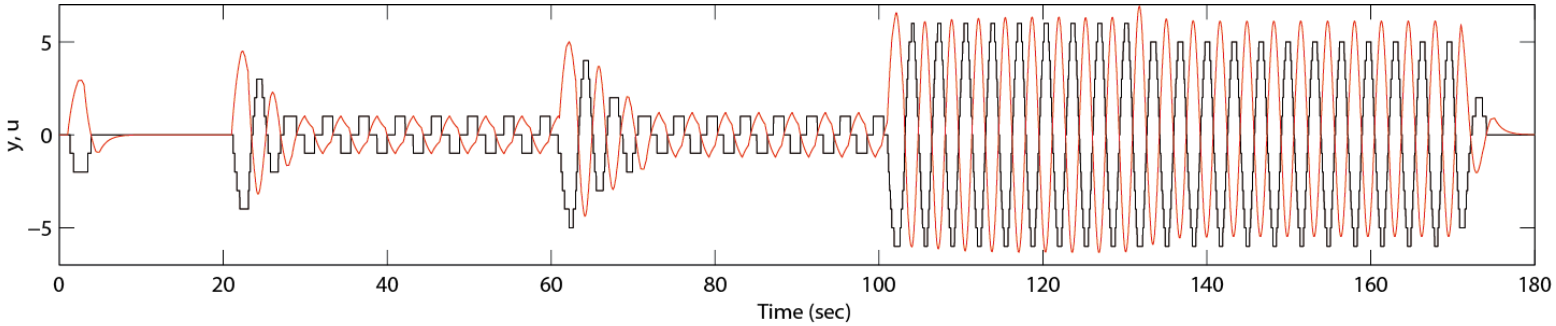
Model	Process	C_1	C_2	C_3
$G_{FOPTD}(s)=\dfrac{Ke^{-Ls}}{Ts+1}$	$\dfrac{e^{-s}}{s+1}$	$\dfrac{e^{-1.10s}}{0.78s+1}$ ω_{osc}=1.4 K_{osc}=1.5 A=1.006	$\dfrac{e^{-0.99s}}{0.93s+1}$ ω_{osc}=1.7 K_{osc}=2.0 A=2.009	$\dfrac{e^{-1.00s}}{0.99s+1}$ ω_{osc}=1.843 K_{osc}=2.14 A=3.02
$G_{SOPTD-1}(s)=\dfrac{Ke^{-Ls}}{(Ts+1)^2}$	$\dfrac{e^{-s}}{(s+1)^2}$	$\dfrac{e^{-0.99s}}{(0.93s+1)^2}$ ω_{osc}=0.96 K_{osc}=1.9 A=1.01	$\dfrac{e^{-1.01s}}{(0.98s+1)^2}$ ω_{osc}=1.13 K_{osc}=2.3 A=2.03	$\dfrac{e^{-1.00s}}{(0.99s+1)^2}$ ω_{osc}=1.19 K_{osc}=2.5 A=3.04

J. Sánchez, Mª. Guinaldo, A. Visioli, S. Dormido. "Identification of process transfer function parameters in event-based PI control loops", *ISA Transactions*, 75, 2018, 157-171.

6. Event based model identification

Identification based on the DF of the SSOD

Example of an identification experiment



- K_{osc} increases in jumps of 0.3 until the oscillation is stable

$$\left| \frac{Tactual - Tprevio}{Tprevio} \right| \leq \varepsilon$$

and of an adequate level (for example, $A_{osc} > 5$).

- A bias of 0.1δ is added in t=130 s. to obtain the process gain: $G_{ol}(0) = KK_{osc} = \dfrac{\int_0^{2\pi/\omega_{osc}} y(t)\ dt}{\int_0^{2\pi/\omega_{osc}} u(t)\ dt}$

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7. 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
- Natural approach for distributed autonomous and multi-agent systems
- Natural for modeling biological systems
- Many interesting open research problems