Networked Control Systems :

to buff, or not to buff? *

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GDRi DELSYS, 20 November 2013

** Systèmes Contrôlés en Réseau : s'en tamponner, ou pas ?*

NCS: to buff, or not to buff?

Networks such as Internet or Wireless 802.11 present great advantages for flexible and low-cost networking. However, they are not as reliable as CANs, and integrating them in control applications, while preserving some performance, constitutes an interesting challenge.

Using delay models allows for catching many of the effects introduced by the presence of unreliable networks in the control loops. Several theoretical techniques allow for analyzing the resulting systems. Some of them need the delay to be constant, which can be obtained by using waiting strategies involving buffers. Some other tolerate fast varying delays.

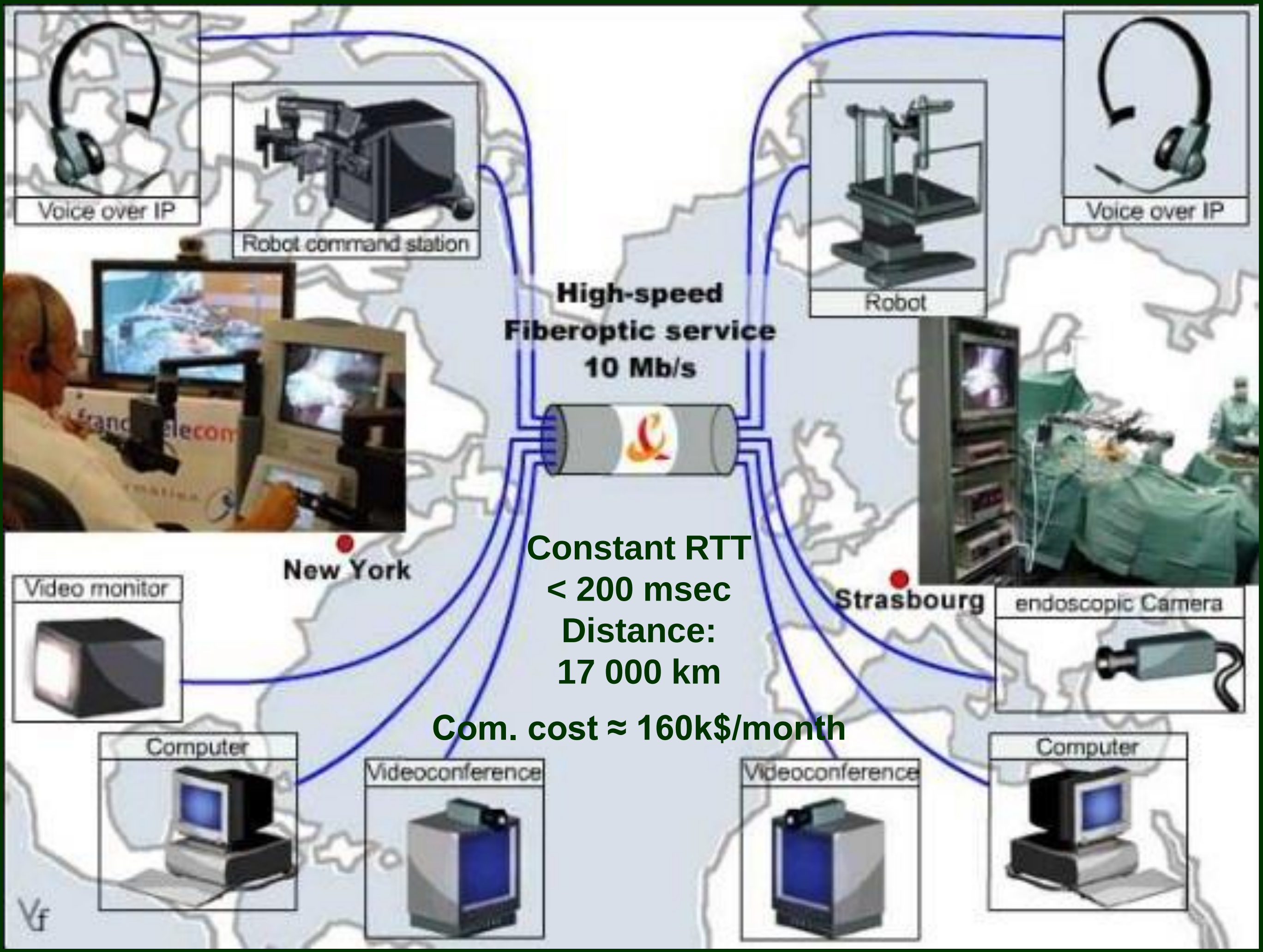
Without entering into many technical details, we'll try to draw a panel of some techniques, in particular the ones we developed at LAGIS.

It will be some story about network effects, sampling and lost packets, time/event -driven solutions, remote observers and bilateral teleoperation...

Overview

- Motivation and examples
- Modelling
- Sampling and delay
- A crude example
- Control : *to buff, or not to buff?* A selection of results
- Conclusions

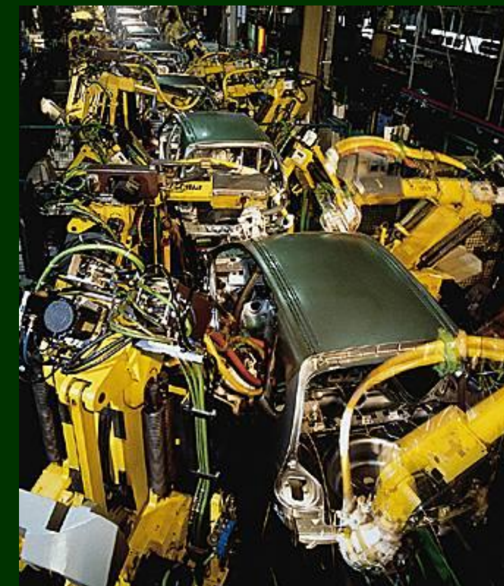
Tele surgery: the Lindbergh operation, 07/09/2001



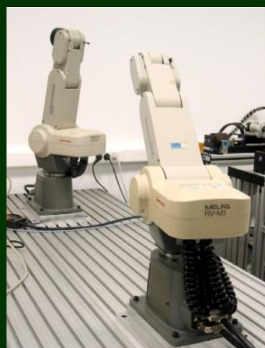
« The only restriction to the development of long-distance tele-surgery as to do, still today, with its cost. For tele-surgery, you must use a transcontinental ATM line, that you have to book during 6 monthes, at the price of about 1 million dollars. » [Prof. J. Marescaux, Le Monde, January 6, 2010]

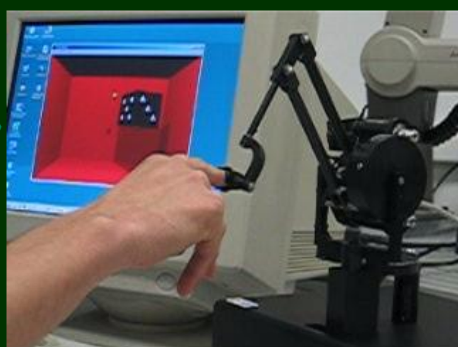
other examples…

Remote Monitoring



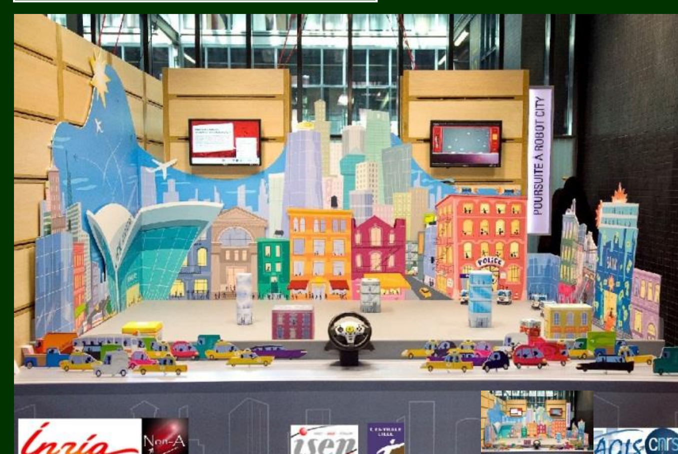
Avoiding electrical cabling



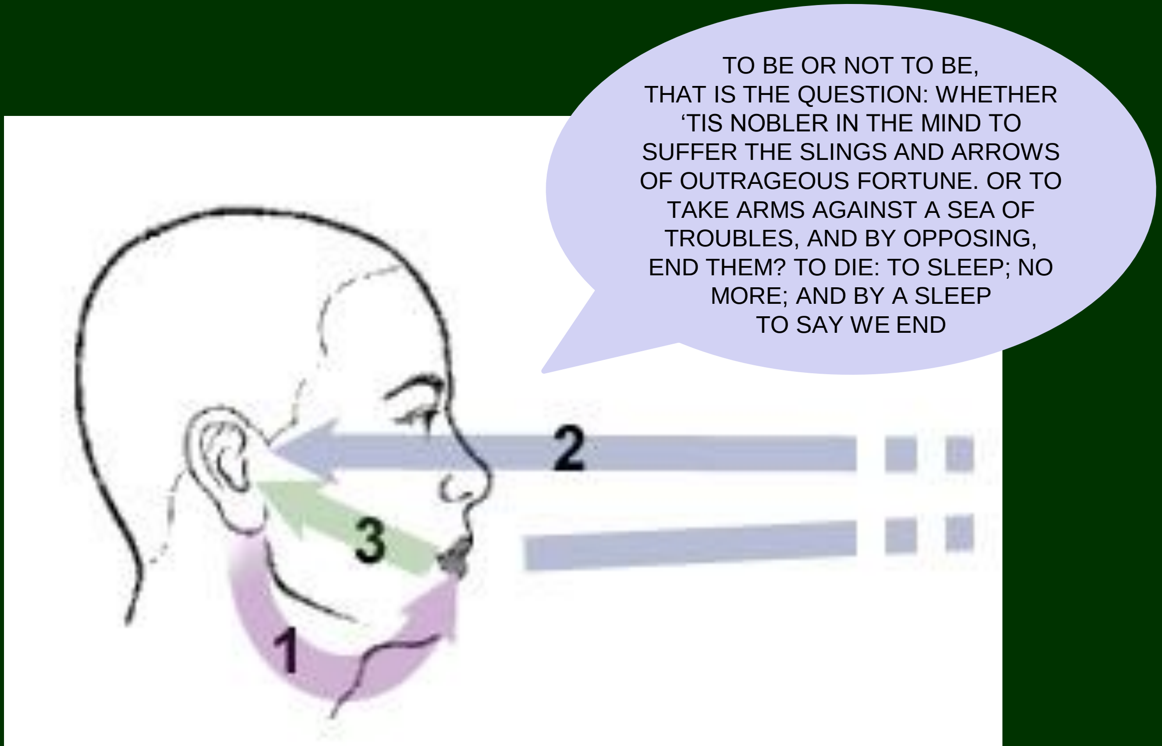


Bilateral Teleoperation

Robot collaboration



and an example from everyday life…



Natural loop of audio-phonatory control

and an example from everyday life…

Networked loop of audio-phonatory ctrl

Some surveys…

- Control methodologies in Networked Control Systems
  Y. Tipsuwan, M.Y. Chow, Control Eng. Practice 11, 1099-111, **2003**

- Networked Control System: a brief survey
  T.C. Yang, IEE Proc. Control Theory Appl., 153 (4), **2006**

- Control over Wireless Networks
  K.H. Johansson, 25th Benelux Meeting on S&C, The Netherland, **2006**

- A survey of recent results in Networked Control Systems
  J.P. Hespanha, P. Naghshtabrizi, Y. Xu, Proc. of the IEEE, 95 (1), **2007**

  nice (wrt 2007)

- Trends in Networked Control Systems
  S. Zampieri, 17th IFAC World Congress, Seoul, **2008**

  not that bad, too

- A switched system approach to exponential stabilization through com. network
  A.Kruszewski, WJ.Jiang, E.Fridman, J.P.Richard, A.Toguyeni, IEEE CST, 20 (4) **2012**

not forgetting…

C. Canudas de Wit, T. Divoux, P. Fraisse, D. Georges, J.P. Georges,
G. Juanole, A. Lelevé, F. Lepage, F. Michaut, G. Mouney, W. Perruquetti,
J.P. Richard, E. Rondeau, O. Sename, A. Seuret, E. Wittrant.

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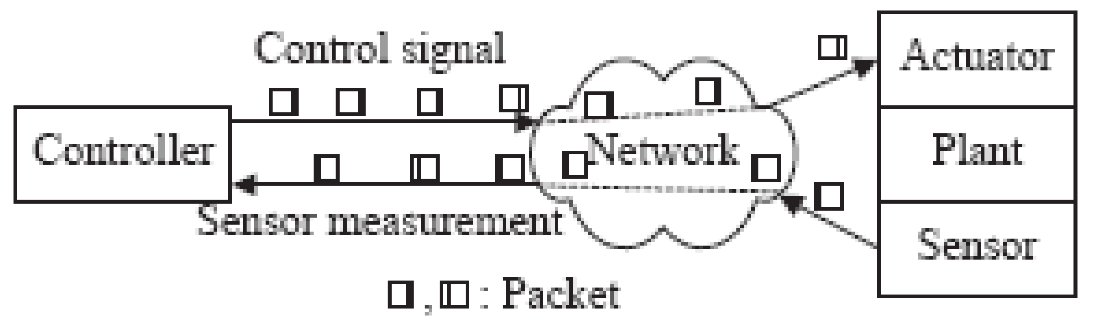
Single-loop NCS



Tipsuwan 2003
Fig. 1. NCS in the direct structure.

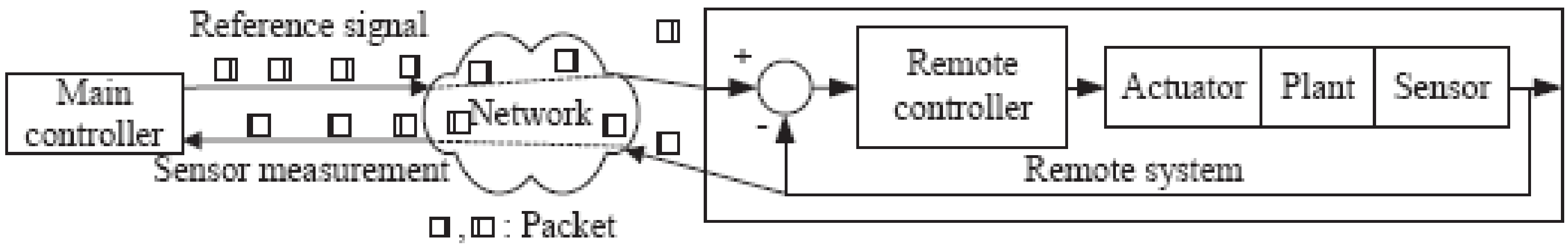


Fig. 2. NCS in the hierarchical structure.
Tipsuwan 2003

What about multi-loop?

Multiple-loop NCS according to [Yang 2006]:

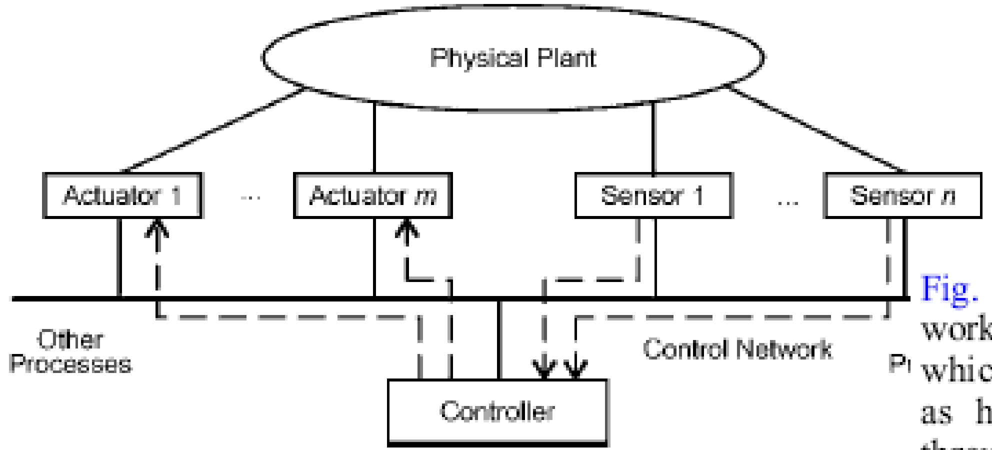
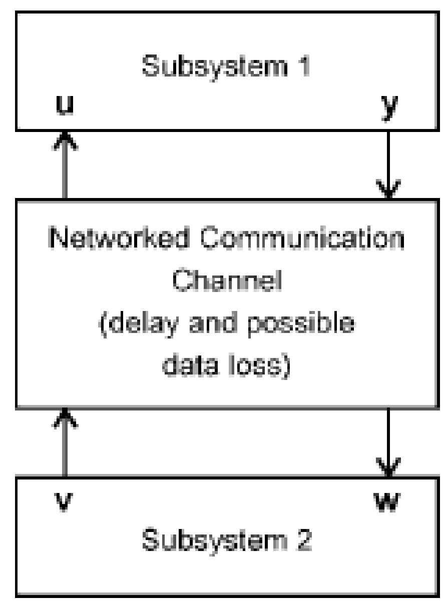


Fig. 1 *Typical NCS setup and information flows*

Yang 2006

Fig. 2 is a block diagram, representing a general framework for the study of networks and control. An NCS, which is the main topic of this paper, can be considered as having two subsystems interacting with each other through networked communication channels. Here, it is



Yang 2006

Fig. 2 *General framework for networks and control*

Multiple-loop NCS according to [Hespanha 2007]:

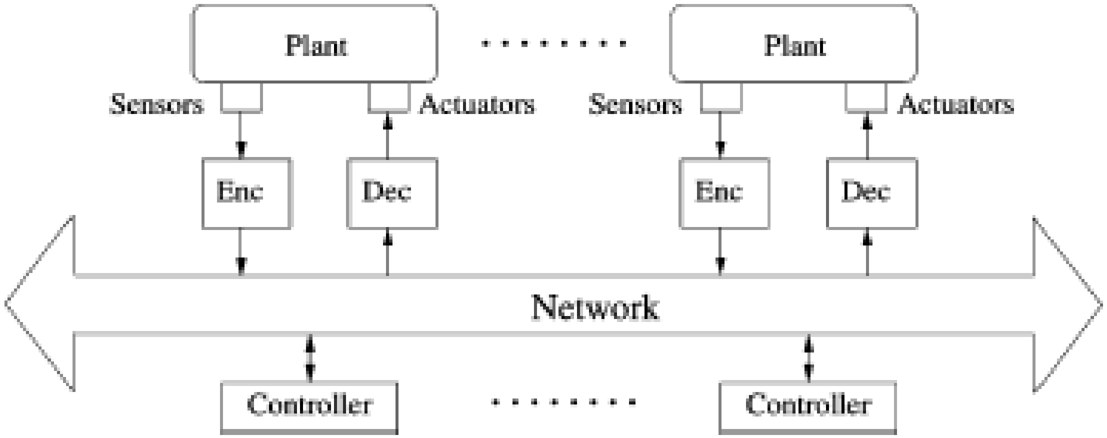


Fig. 1. ***General NCS architecture.*** Hespanha 2007

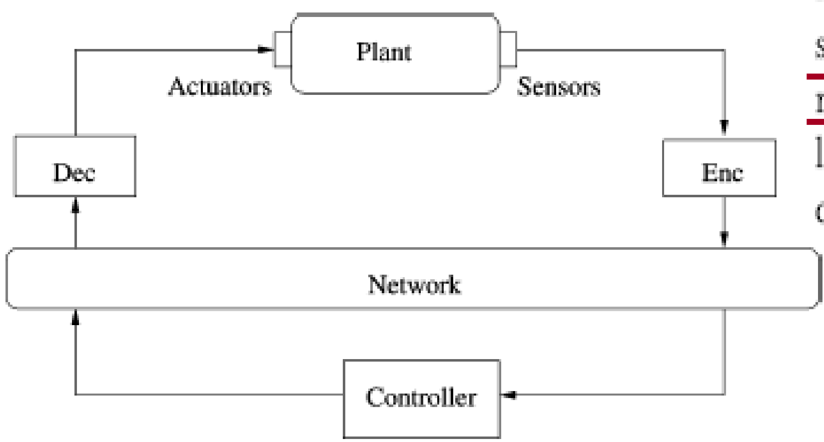


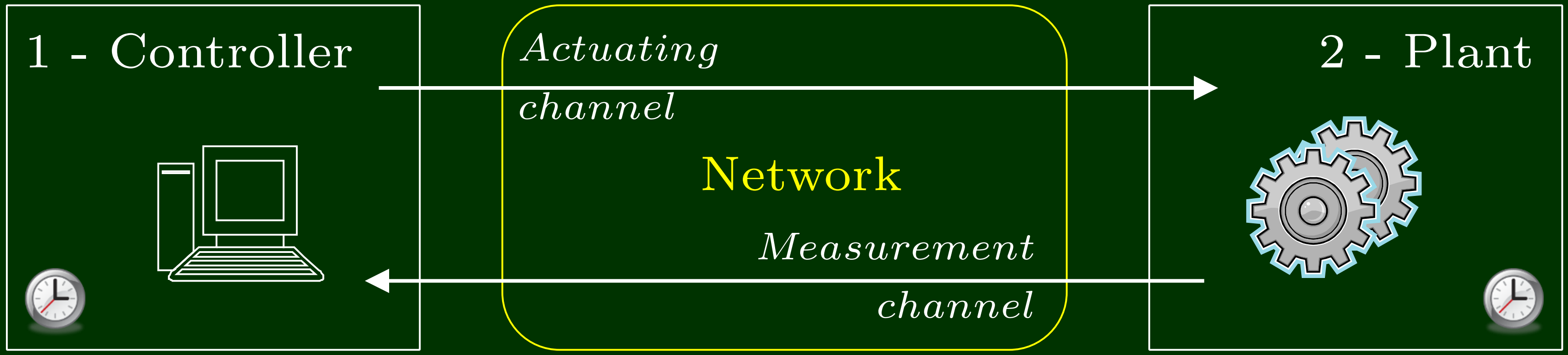
Fig. 2. ***Single-loop NCS.*** Hespanha 2007

It is also often common to consider a single feedback loop as in Fig. 2. Although considerably simpler than the system shown in Fig. 1, this architecture still captures many important characteristics of NCSs such as bandwidth limitations, variable communication delays, and packet dropouts.

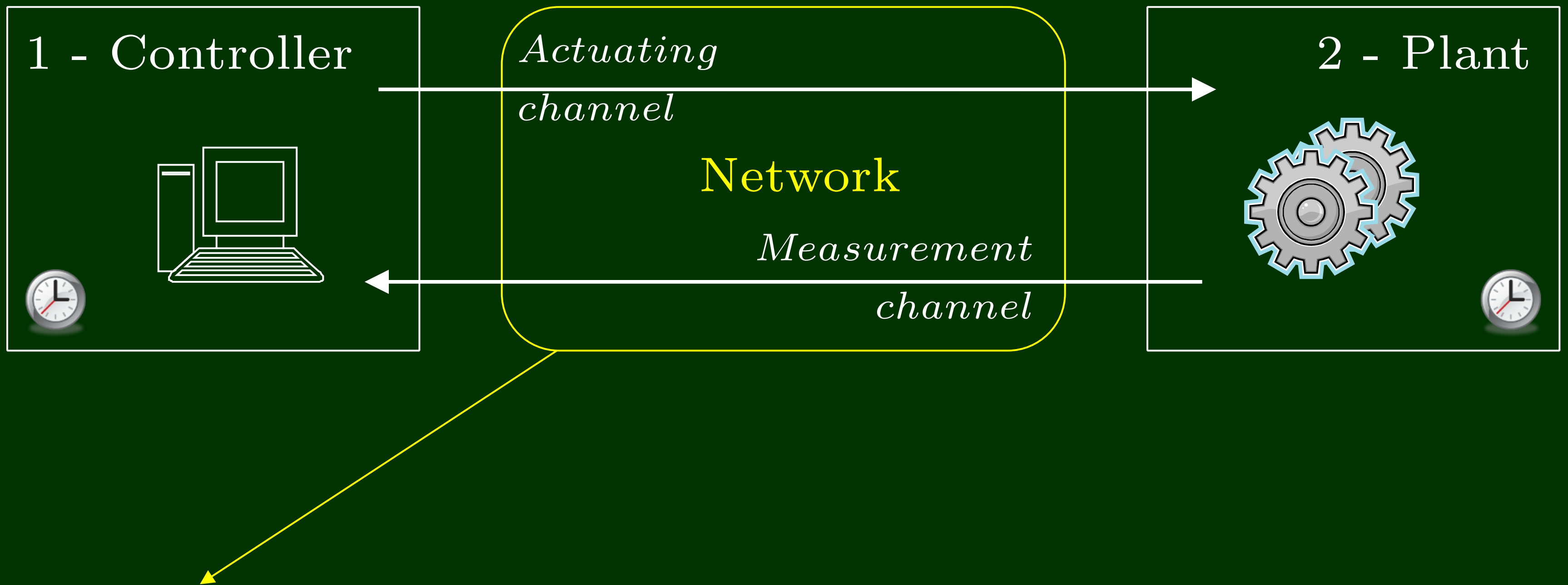
Single-loop NCS.

… the talk will be limited to this case, too.

A good starting point for understanding the issues linked to the presence of networks in the loops



Single-loop NCS



Types of networks:

✓dedicated (ControlNet, DeviceNet) : frequent transmission of small packets → guaranteed time but €

✓Ethernet, wifi : rare transmission of bigger packets → no guarantee for delay but €

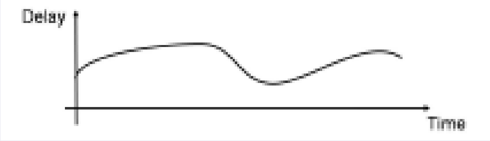
Effects of the network on the closed-loop control

Issue	*Translation in control terms*	*Concerned*	*Not concerned*
limited bandwidth	quantification, limited quantity of info per second (Shannon, *maximum bit rate*)	limited energy resource systems (UAVs, WSN, µ-sensors or µ-actuators, aerosp…)	packet-transmiss. type Inter/Ethernet, Bluetooth… 1 bit or 300 → *idem* ATM=384, Ethernet>368, Bluetooth>499
sampling, coding, scheduling, transmission, asynchronism	variable delays, estimated if there is a model, or time-stamps	packet transmission systems	dedicated and unshared netw. (ControlNet, DeviceNet)
packet losses	asynchronous sampling, variable delay	wireless, UDP-like protocols	TCP-like protocols (but generally useless: time wasting for outdated info)
out-of-sync clocks	delays (at least)	internet	control-dedicated netw. (CAN bus…)

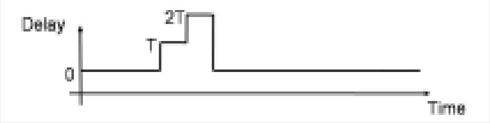
today

In such a framework, we have the equation:

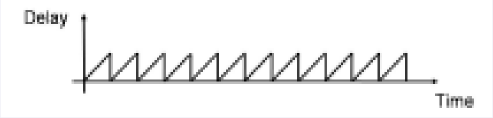
communication + packet loss + sampling = 1 delay



Communication delay : $\tau_i^c(t)$



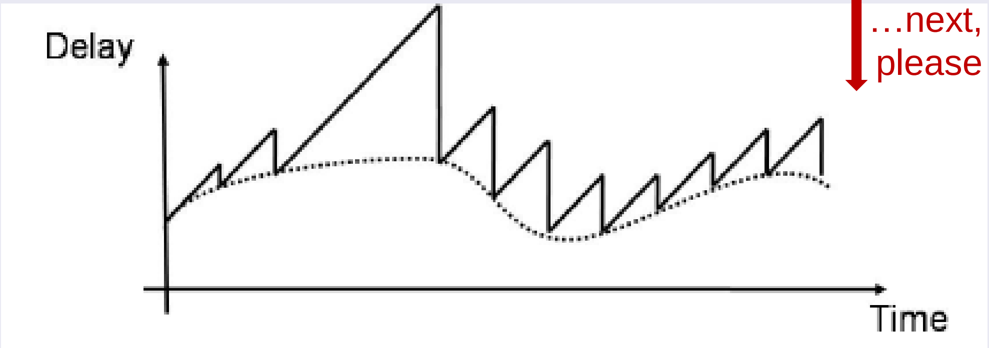
Delay from packet loss : nT



Sampling delay : $\tau_i^s(t)$

…next, please

Total time-delay of NCS :
$\delta_{con}(t)$ and $\delta_{obs}(t)$



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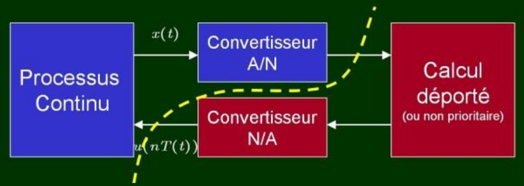
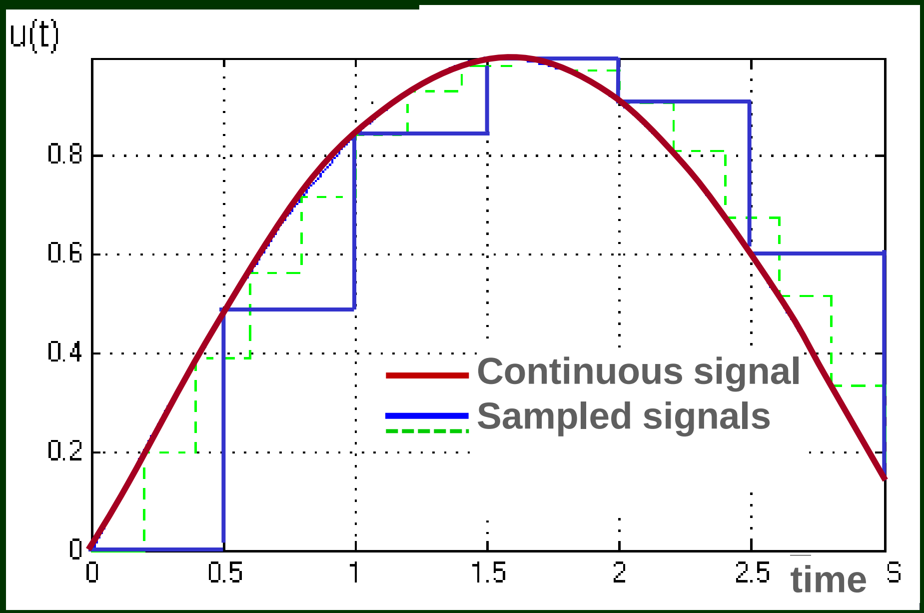
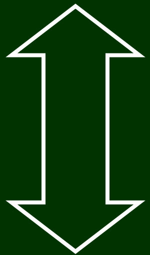


Fridman, Seuret, Richard - *Automatica* 2004

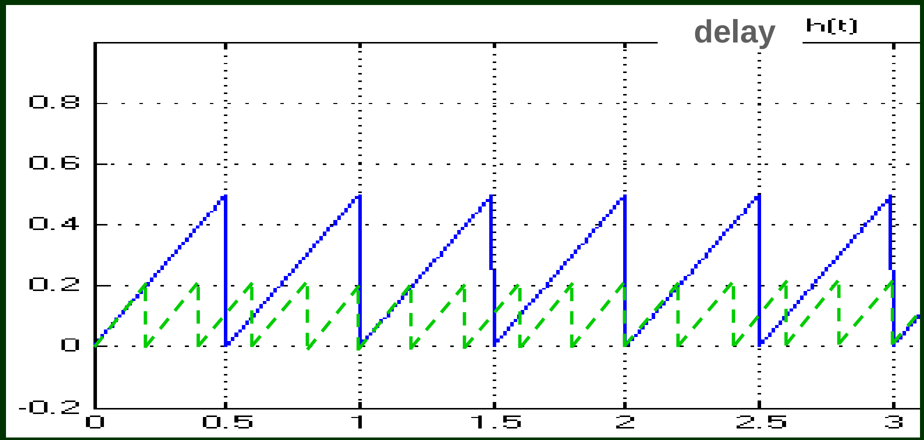


Sampled and hold signal

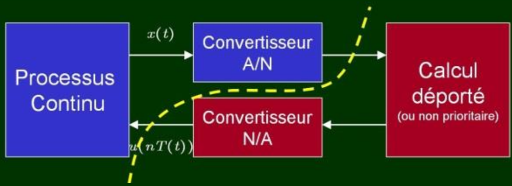
(depicted for a constant period)



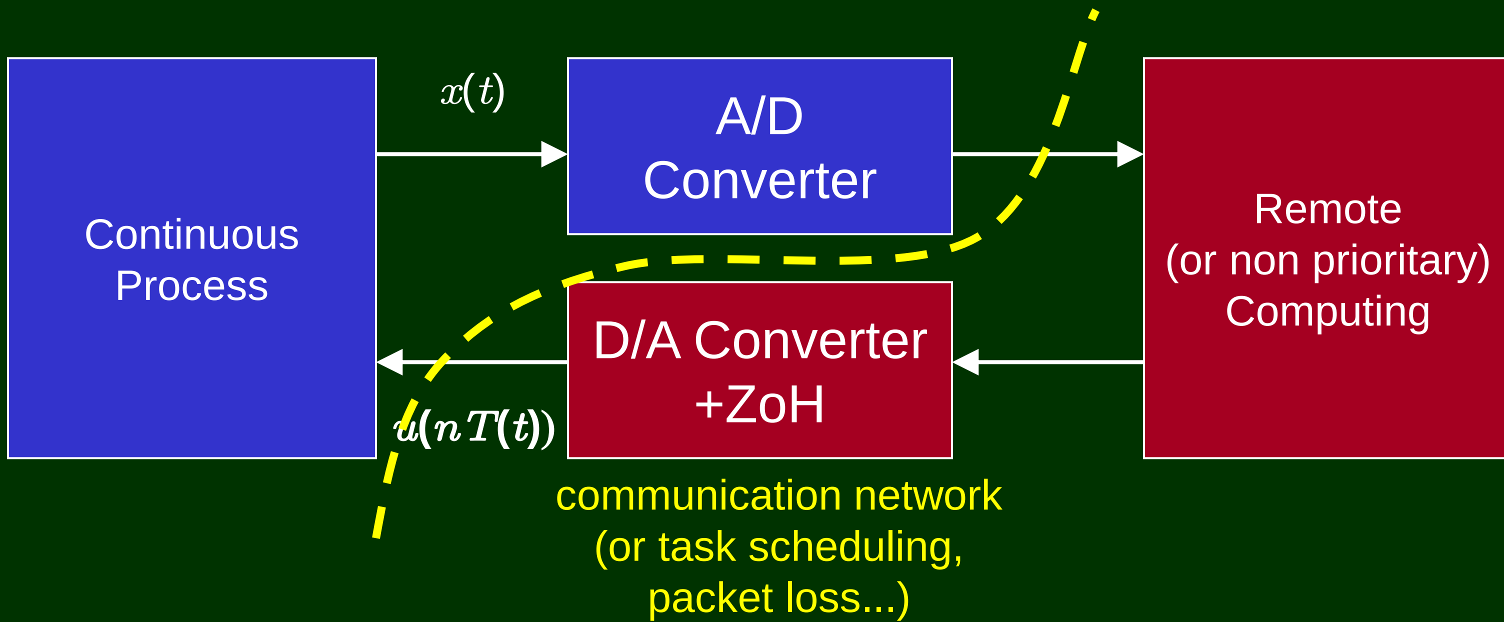
Delayed signal with variable $h(t)$



$$u(t) = u_d(t_k) = u_d(t - [t - t_k]) = u(t - h(t))$$

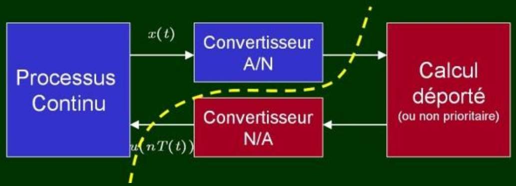


Aperiodic sampling

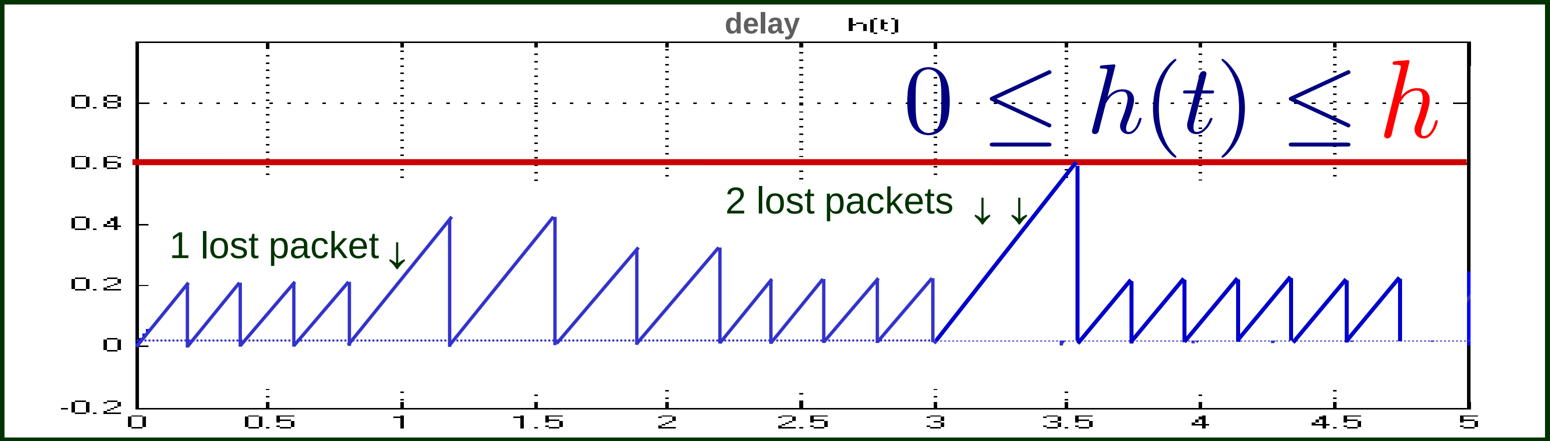


Integration, z-transform, everything's ok, etc.

$$u(t) = u_d(t_k) = g(x(t_k)), \quad \boxed{t_k \neq kT}$$



Another statement of the same problem...



- influence of the *maximum* sampling period h
- application of Fridman's criterion $\dot{h}(t) \leq 1$

See also refined results in:

"A refined input delay approach to sampled-data control". E. FRIDMAN, Automatica 2010

"A novel stability analysis of linear systems under asynchronous sampl". A. SEURET, Automatica 2011

"SOS for sampled-data systems" A. SEURET, M. PEETS, IFAC'11, Milano, Italy, 2011

Note : approaching aperiodic sampling via *switched systems*

PhD L. Hetel 2007 + IEEE TAC 2006 (Daafouz, Iung)

intra-sampling: Taylor trunc. of the exponential terms (cont. delay) → *polytopes, LMI*

nb of packet losses → discrete delay

augmented model → *switched system* (event-based model)

$$x(k+1) = A(k)x(k) + B(k)u(k)$$

$$A(k) = e^{M(t_{k+1}-t_k)},\ B(k) = \int_0^{t_{k+1}-t_k} e^{M(t_{k+1}-t_k-s)} ds N.$$

$$\eta_{i+1} = A(\rho_i)\eta_i + B(\rho_i)u_i.$$

$$A(\rho_i) = e^{M\rho_i},\ B(\rho_i) = \int_0^{\rho_i} e^{Ms} ds N.$$

$$u_c(t_i) = Kx_c(t_j) = Kx_c(t_{i-\theta_i}),$$

$$\theta_i \in \mathcal{T} = \left\{\theta \in \mathbb{Z}^+ :\ \underline{\theta} \le \theta \le \overline{\theta}\right\}$$

$$z_i = \left[\eta_i^T\ \eta_{i-1}^T\ \dots \eta_{i-\overline{\theta}}^T\right]^T$$

$$\rightarrow \bar{A}(\rho_i) = \begin{bmatrix} A(\rho_i) & \mathbf{0} & \dots & \dots & \mathbf{0} \\ \mathbf{I} & \mathbf{0} & \dots & \dots & \mathbf{0} \\ \mathbf{0} & \mathbf{I} & \mathbf{0} & \dots & \mathbf{0} \\ \vdots & & & & \vdots \\ \mathbf{0} & \dots & \mathbf{0} & \mathbf{I} & \mathbf{0} \end{bmatrix},\ \bar{B}(\rho_i) = \begin{bmatrix} B(\rho_i) \\ \mathbf{0} \\ \mathbf{0} \\ \vdots \\ \mathbf{0} \end{bmatrix}$$

$$u_i = \bar{K}_{(\theta_i)} z_i,$$

$$\bar{K}_{(\theta_i)} = [\mathbf{0}\ \dots\ \mathbf{0}\ K\ \mathbf{0}\ \dots\ \mathbf{0}]$$

$$\boxed{z_{i+1} = \left(\bar{A}(\rho_i) + \bar{B}(\rho_i)\bar{K}_{(\theta_i)}\right) z_i}$$

Note : approaching aperiodic sampling via *switched systems*

Unification of both approaches input delay / switched :

"Discrete and intersample analysis of systems with aperiodic sampling"
L. HETEL, A. KRUSZEWSKI, W. PERRUQUETTI, J.P. RICHARD
IEEE TAC 56 (7), p.1696 - 1701, 2011

$$\dot{x}(t) = A_c x(t) + B_c K x(t_k),\ \forall t \in [t_k, t_{k+1}]$$

$$x(t) = \Lambda(t - t_k) x(t_k)$$

$$\Lambda(\theta) := I + \int_0^\theta e^{sA_c} ds\, (A_c + B_c K)$$

$$\mathcal{H}(x) = \{y \ : \ y = \Lambda(\theta) x, \theta \in \mathcal{T}\}$$

$$x(t_{k+1}) \in \mathcal{H}\left(x(t_k)\right)$$

difference inclusion

$x = 0$ *asympt. stable* $\Longleftrightarrow$ $\exists$ *quasi-quadratic Lyapunov function*

$$V(x) = x^T \mathcal{L}_{[x]} x,\ \mathcal{L}_{[\cdot]} : \mathbb{R}^n \to \mathbb{R}^{n \times n},$$

$$\mathcal{L}_{[x]} = \mathcal{L}_{[x]}^T = \mathcal{L}_{[ax]},\ \forall x \neq 0, a \neq 0$$

constructive

Note : State-Dependent Sampling

- ***Next sampling instant depends on state x_k***

"A state-dependent sampling for linear state feedback"
C. FITER, L. HETEL, W. PERRUQUETTI, J.P. RICHARD
Automatica 48 (8), p.1860-1867, 2012

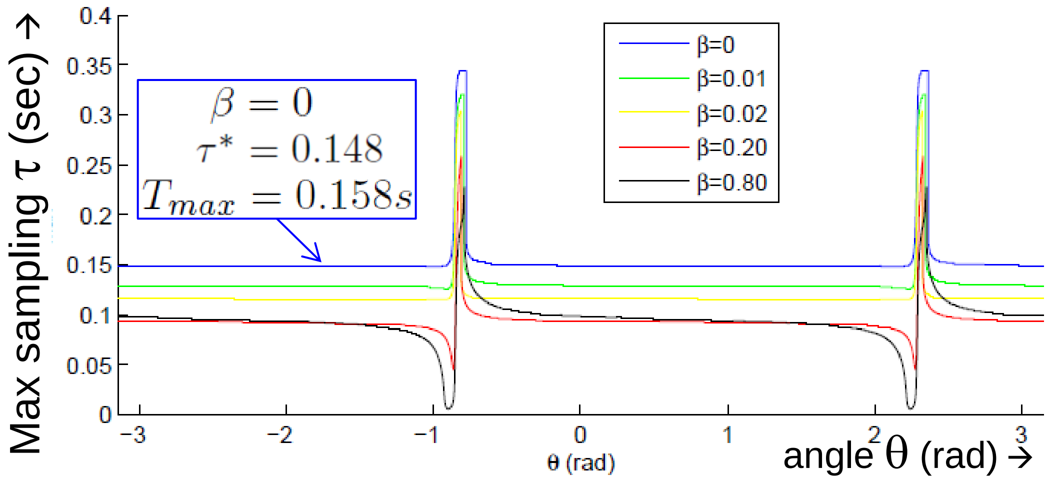
- *Self-triggering*
- *Complexity is off-line*
- *LRF technique*

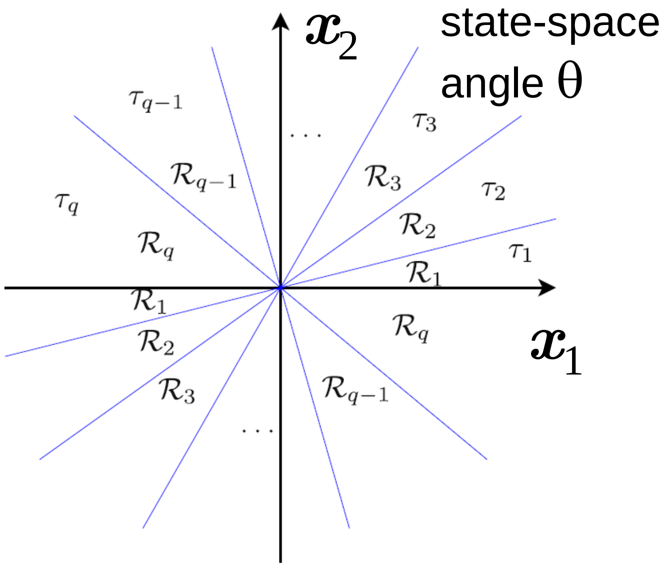
$$\dot{x}(t) = A_c x(t) + B_c K x(t_k),\ \forall t \in [t_k, t_{k+1}]$$

$$\dot{x}(t) = \begin{pmatrix} 1 & 15 \\ -15 & 1 \end{pmatrix} x(t) - \begin{pmatrix} 1 \\ 1 \end{pmatrix} K x(t_k),$$

$$K = \begin{pmatrix} -5.33 & 9.33 \end{pmatrix}.$$

$$t_{k+1} = t_k + \tau(x(t_k))$$





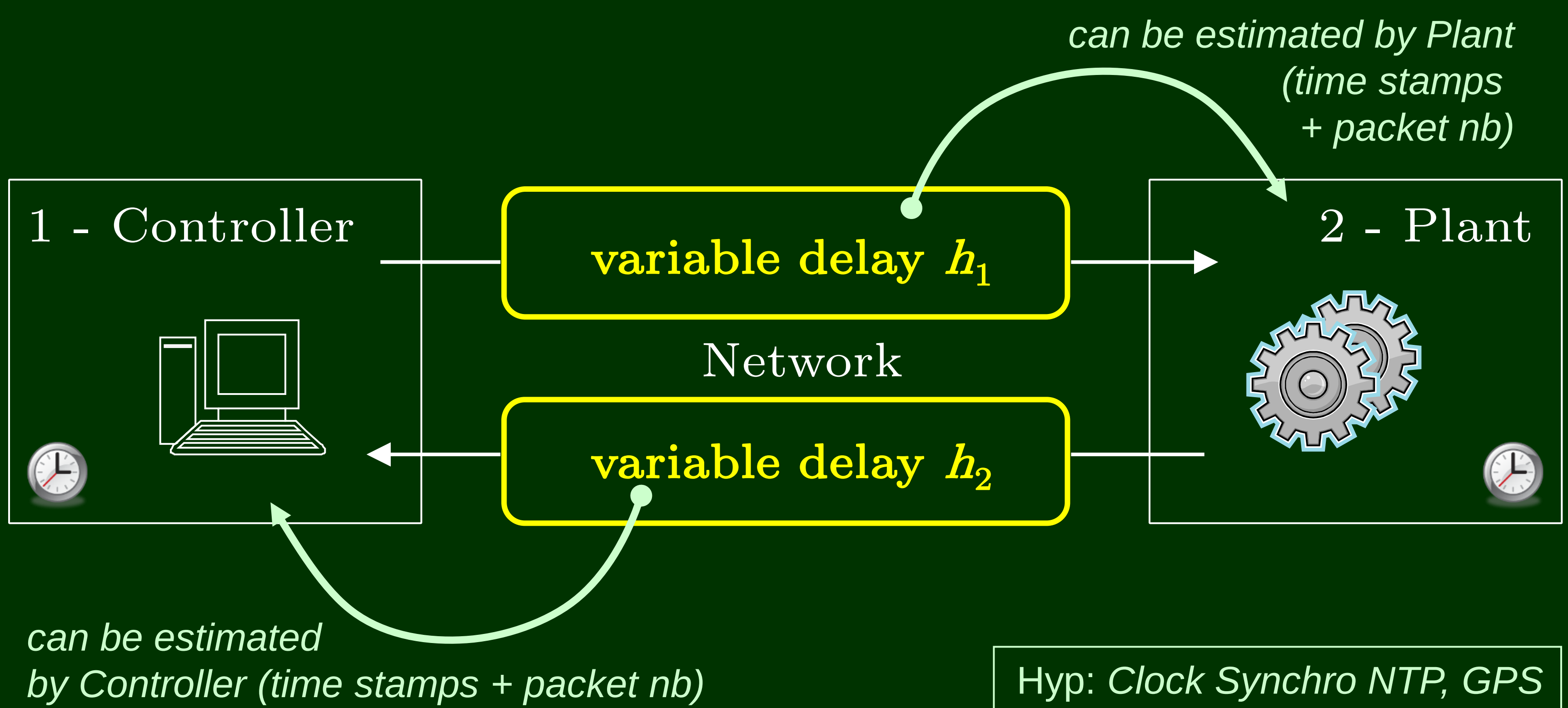
Max next sampling computed off-line (β-stab.) → less often than with periodic sampling

... let's sum up until now:

transmission time + access time + packet loss + sampling…

= 2 variable delays

known / unknown ?



Hyp: *Clock Synchro NTP, GPS*

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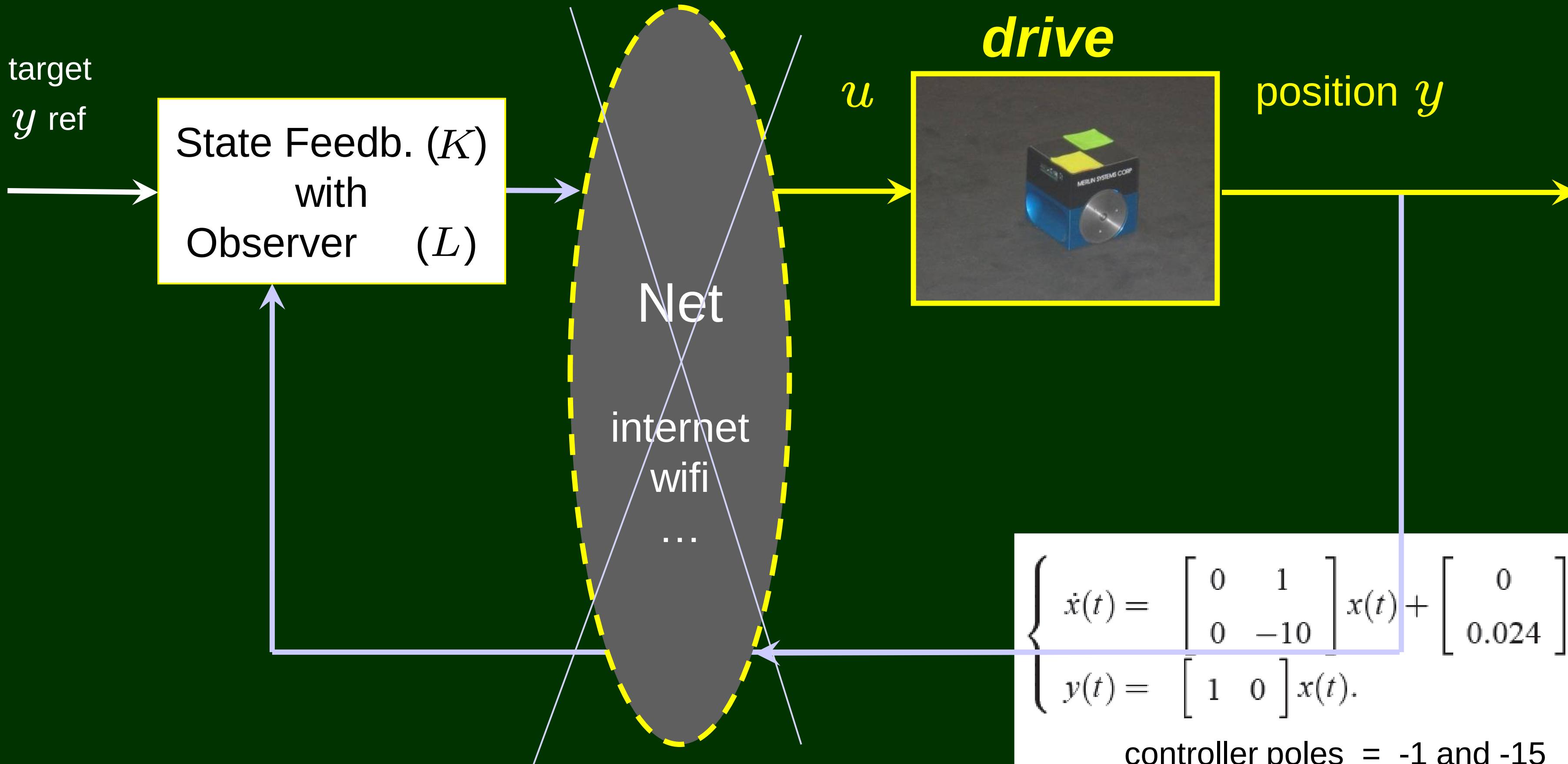
A crude example

Theory (when neglecting the network effetc)



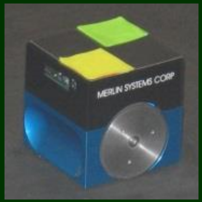
$$\begin{cases} \dot{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & -10 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0.024 \end{bmatrix} u(t), \\ y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} x(t). \end{cases}$$

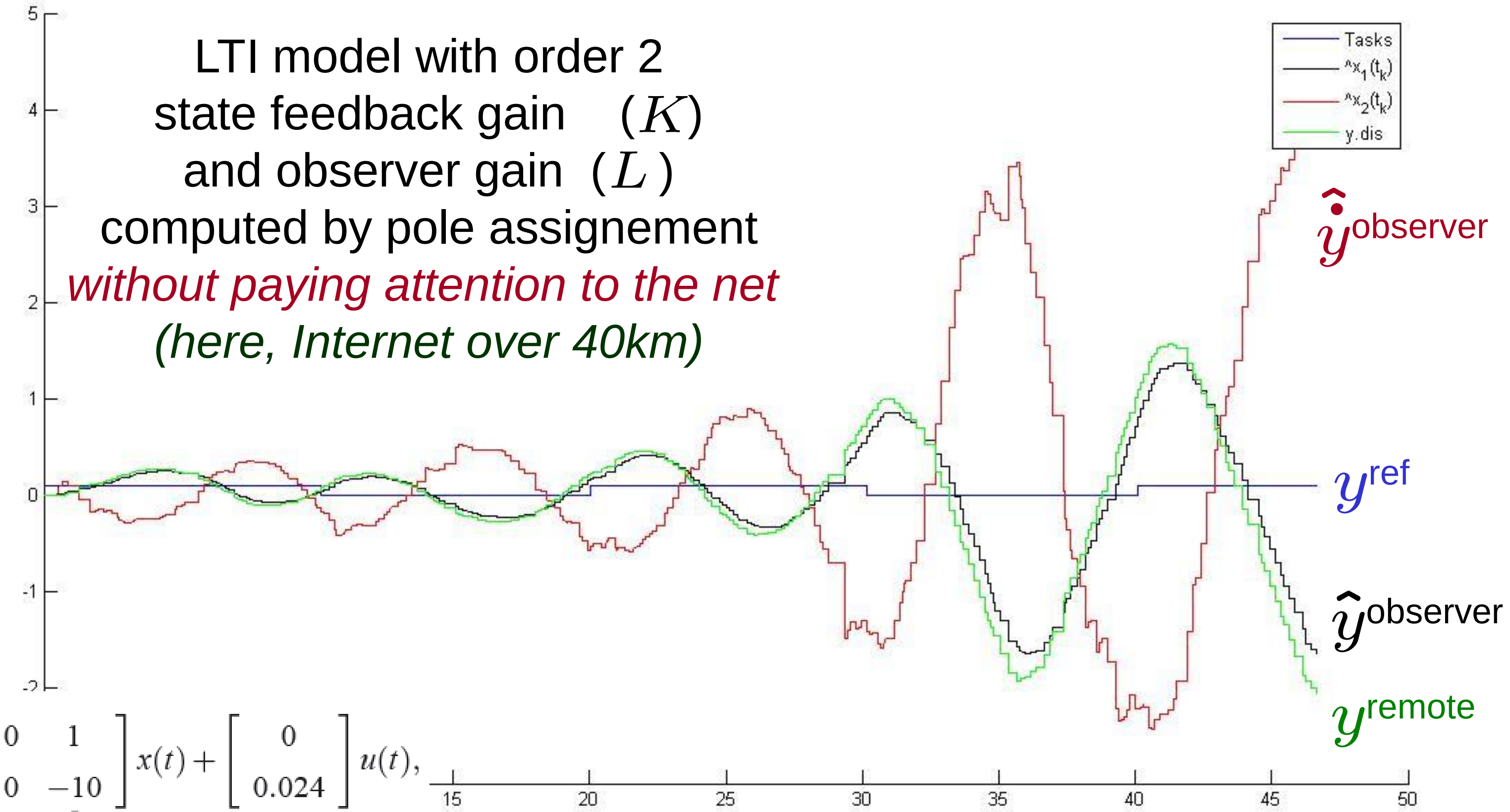
controller poles = -1 and -15

observer poles = -2 and -20

$$\Rightarrow \quad K = \begin{bmatrix} -750 & -300 \end{bmatrix} \quad L = \begin{bmatrix} 12 \\ -80 \end{bmatrix}$$

Experimental results (with network)





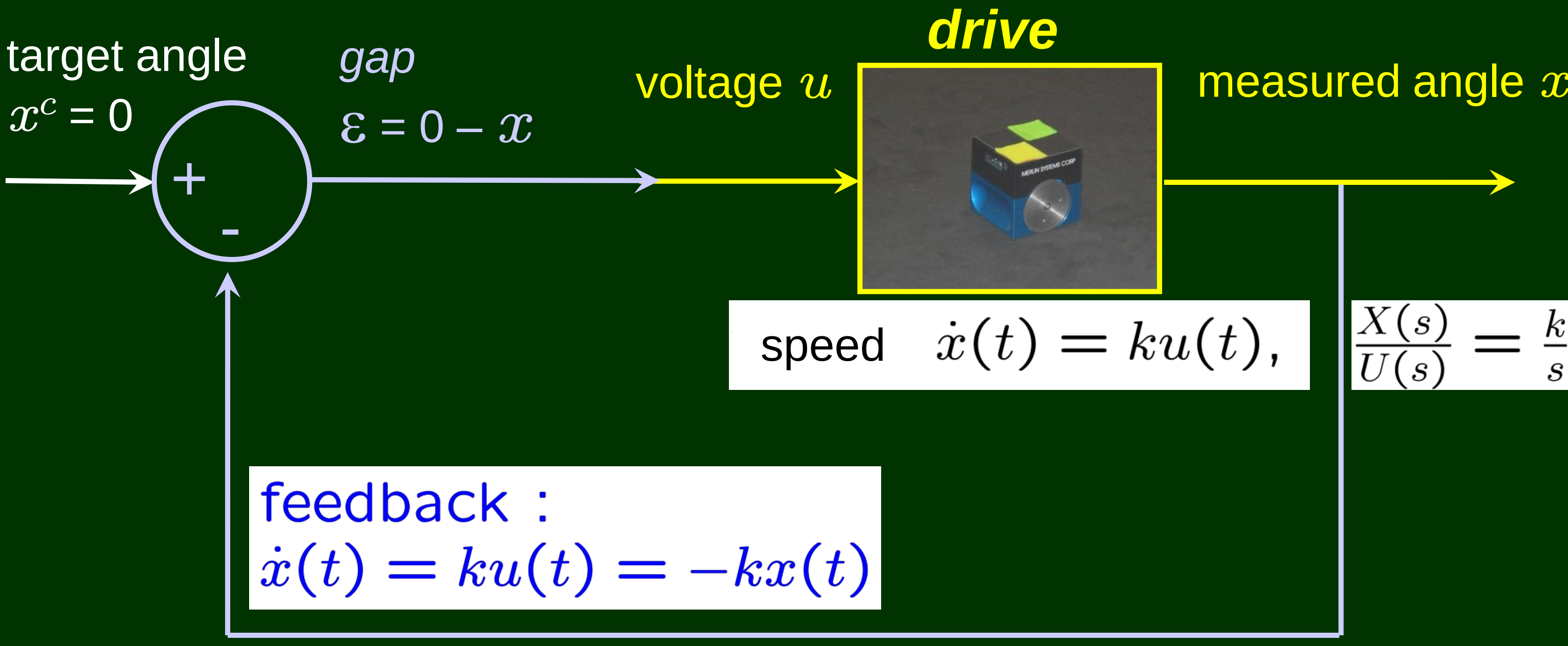
LTI model with order 2
state feedback gain (K)
and observer gain (L)
computed by pole assignement
without paying attention to the net
(here, Internet over 40km)

$$\begin{cases} \dot{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & -10 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0.024 \end{bmatrix} u(t), \\ y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} x(t). \end{cases}$$

Controller poles = -1 and -15
Observer poles = -2 and -20

$$\Rightarrow \quad K = \begin{bmatrix} -750 & -300 \end{bmatrix} \quad L = \begin{bmatrix} 12 \\ -80 \end{bmatrix}$$

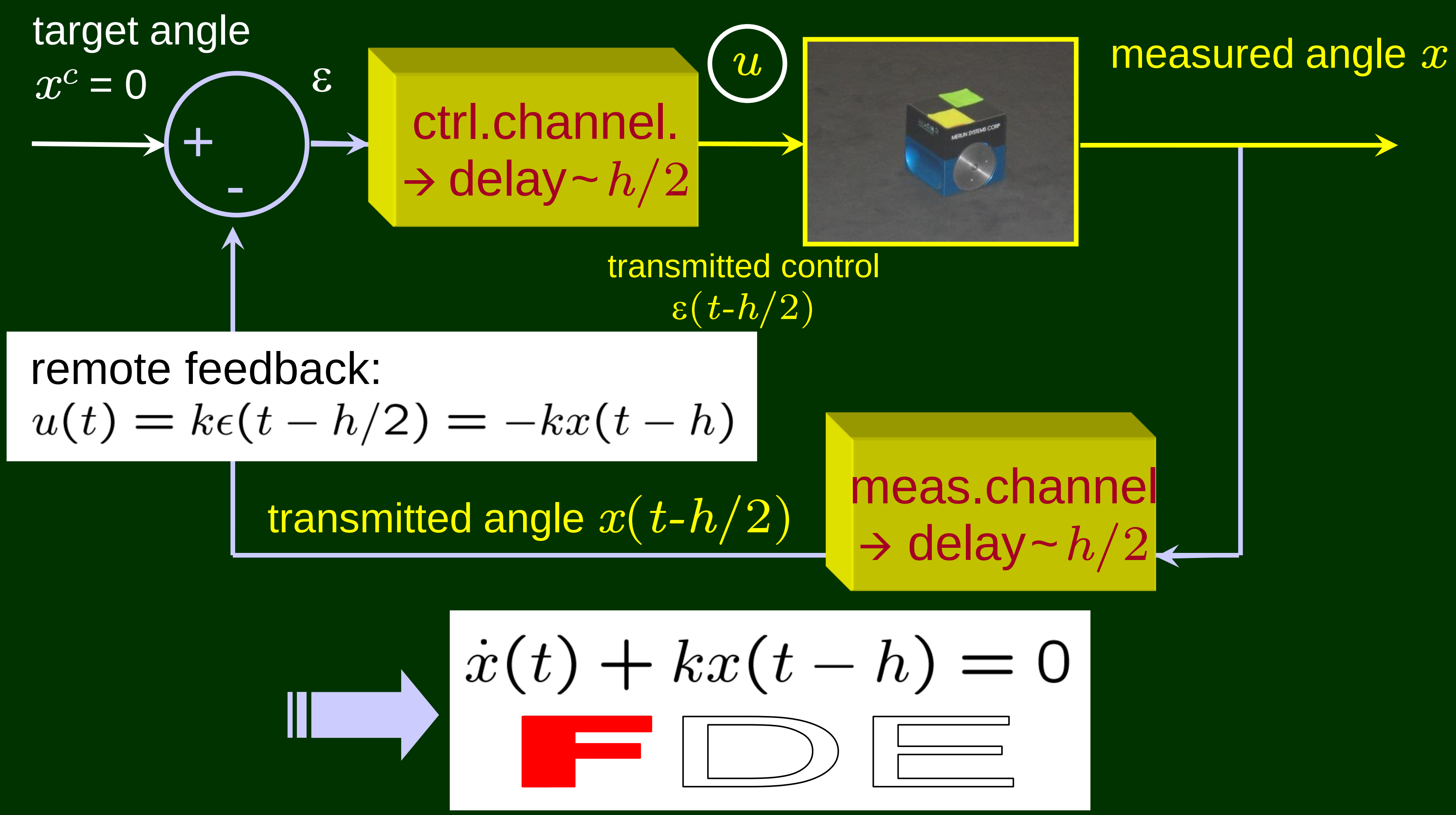
Interpretation on a simplified model



$$\dot{x}(t) + kx(t) = 0$$

ODE

A crude example



Exercise… *for my students, don't worry ;-)*

$$\dot{x}(t) + x(t-h) = 0$$

(cas $h = 1,\ k = 1$)

$$\dot{x}(t) = -x(t-1)$$

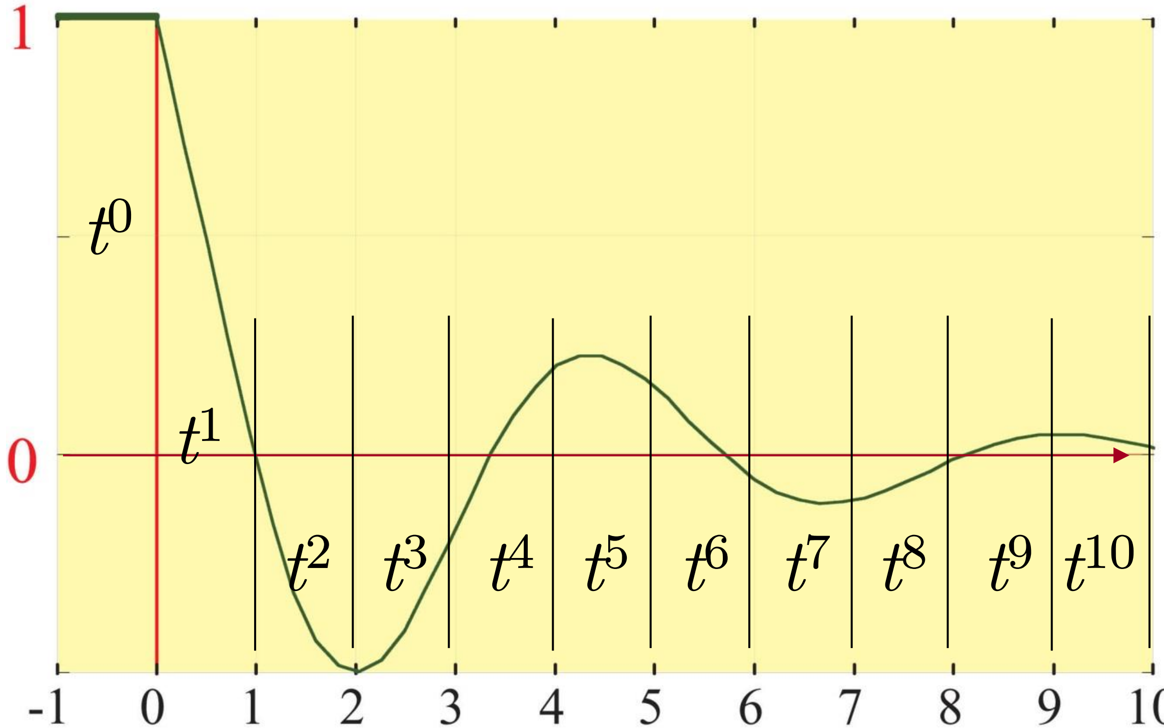
C.I. $t = 0 \ : x(t=0) = 1$??

$t \in [-1, 0]:\ x(t) = 1$ (C.I.)

$t \in [0, 1]:\quad x(t) = 1 - t,$

$t \in [1, 2]:\quad x(t) = \frac{1}{2} - t + \frac{t^2}{2},$

etc.



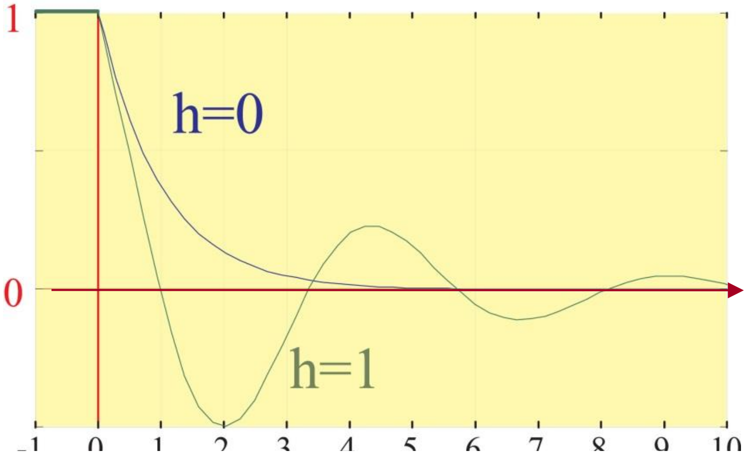
A crude example

$$\dot{x}(t) + x(t-h) = 0$$

w.r.t. h ?

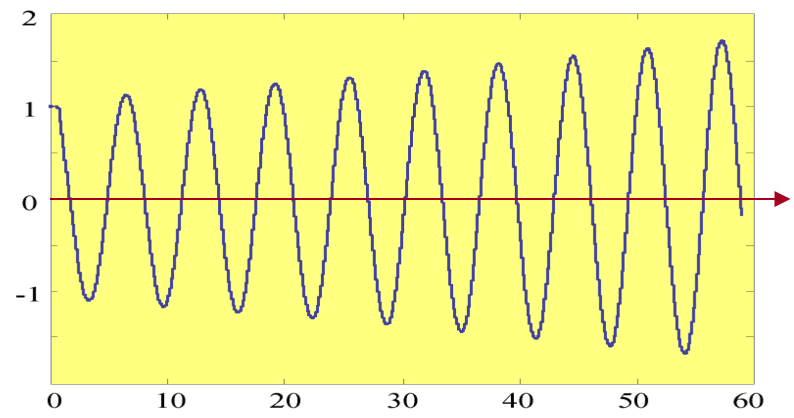
$$\dot{x}(t) + x(t) = 0$$

$$\dot{x}(t) + x(t-1) = 0$$



$$\dot{x}(t) + x(t-\tfrac{\pi}{2}) = 0 \; ?$$

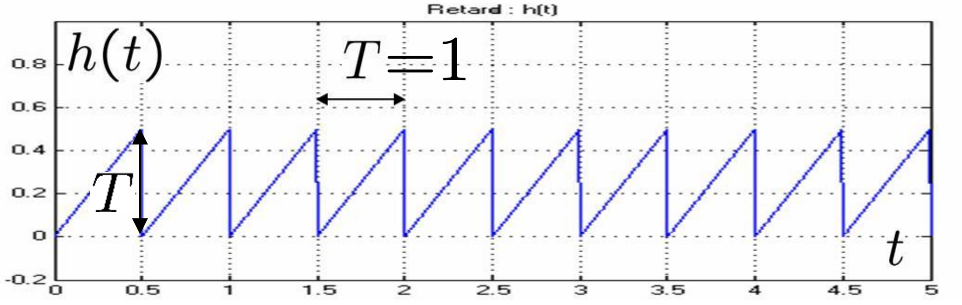
$$\dot{x}(t) + x(t-1.6) = 0$$

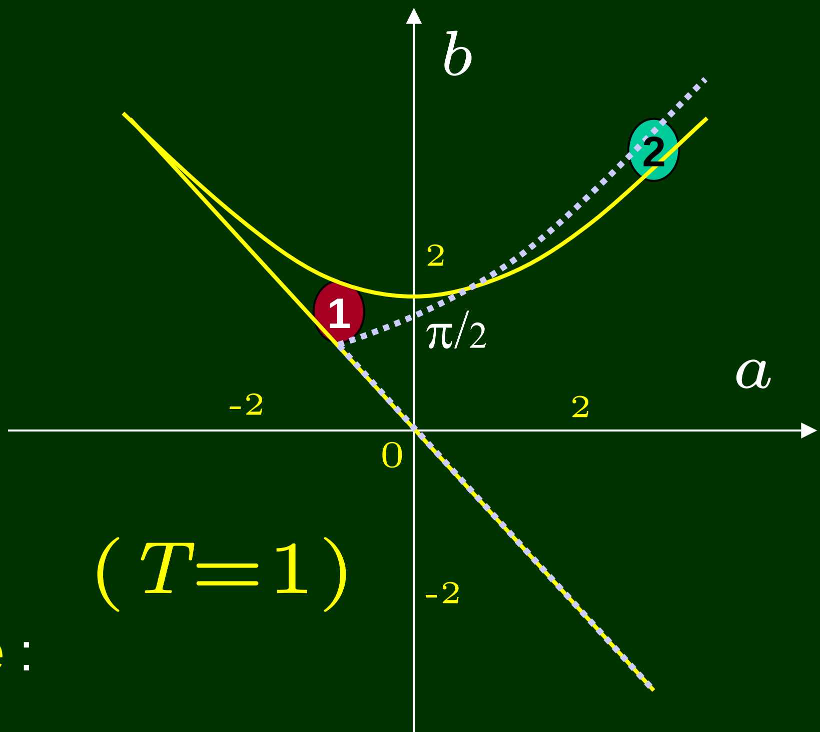


… and mind the variable delays!

$$\dot{x}(t) = -ax(t) - bx(t - h(t)) \qquad (1)$$

$$h(t) = t - kT \quad \text{for} \quad kT < t \le (k+1)T$$





variable : asymptot. stable iff $\in$ yellow zone :

$$\left|(1+\frac{b}{a})e^{-aT} - \frac{b}{a})\right| < 1 \quad \text{if } a \neq 0$$

$$|1 - bT| < 1 \quad \text{if } a = 0$$

constant : $\forall h \in [0,1]$ iff $\in$ grey zone

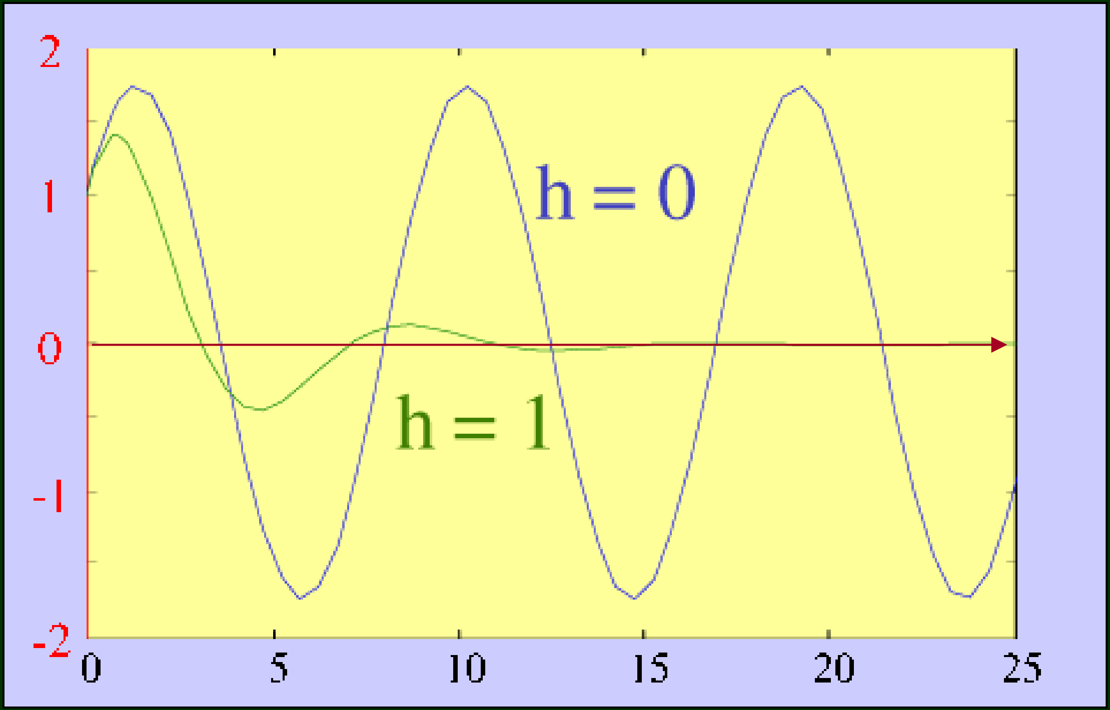
1 stable $h(t)$<1 - unstable h=cte<1

2 unstable $h(t)$<1 - stable h=cte<1

A crude example

(digression...)

$$\ddot{y}(t) + y(t) - \tfrac{1}{2}y(t-h) = 0$$



A known delay may also have a stabilizing effect

Here, derivative effect: $y(t-h) \approx y(t) - h\dot{y}(t)$

Few words about Lyapunov method for TDS

ODE :

$$\dot{x}(t) = -ax(t) \Rightarrow \begin{cases} V(x(t)) = x^2(t) > 0 \\ \dot{V}(x(t)) = -2\, ax^2(t) < 0\ldots \text{ etc.} \end{cases}$$

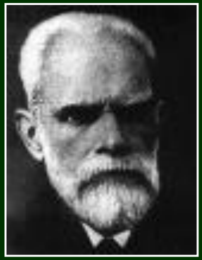
FDE :

$$\dot{x}(t) = -ax(t) - bx(t-h)$$

$$V(x(t)) = x^2(t)$$ (« usual » quadratic)

cross terms

$$\dot{V}(x(t)) = -2\,[ax^2(t) + \boxed{bx(t)x(t-h)}] \leq \ldots ?$$



➔ need of specific adaptations:

1) *functions* of Lyapunov-Razumikhin (not here)

2) *functionals* of <u>Lyapunov-Krasovskii</u>

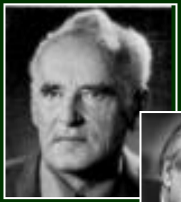


Illustration of the LKF approach

(*Lyapunov-Krasovskii functionals*)

$$\dot{x}(t) = -ax(t) - bx(t-h)$$

$$V(x_t) = x^2(t) + |b| \int_{-h}^{0} x^2(t+s)ds$$ **(quad + integral)**

$$\dot{V}(x_t) = -2x(t)[ax(t) + bx(t-h)] + |b|[x^2(t) - x^2(t-h)]$$

$$\leq -2(a - |b|)x^2(t) \quad \ldots \ \dot{V}(x_t) < 0 \text{ if } |b| < a$$

Remarks on the conservatism:

1) here, a « pessimistic » condition since it is i.o.d. - independent of the delay h …

2) linked with the majoration of the crossed terms, here : $-[x(t) + x(t-h)]^2 \leq 0$

$$\Rightarrow -2bx(t)x(t-h) \leq bx^2(t) + bx(t-h)^2$$

More general…

The system model

$$\dot{x}(t) = Ax(t) + A_1 x(t - \tau(t)), \quad (2)$$

x vector + variable delay

with the initial condition :

$$x(t_0 + \theta) = \phi(\theta),\ \dot{x}(t_0 + \theta) = \dot{\phi}(\theta), \quad \theta \in [-h_2, 0], \quad (3)$$

where $\tau(t) \in [h_1, h_2],\ h_1 \geq 0$.

Lyapunov functionals

$$\begin{aligned} V(t, x_t, \dot{x}_t) &= x^T(t)Px(t) + \int_{t-h_1}^{t} x^T(s)Sx(s)ds \\ &+ h_1 \int_{-h_1}^{0} \int_{t+\theta}^{t} \dot{x}^T(s)R\dot{x}(s)dsd\theta \\ &+ \int_{t-h_2}^{t} x^T(s)S_a x(s)ds + (h_2 - h_1) \int_{-h_2}^{-h_1} \int_{t+\theta}^{t} \dot{x}^T(s)R_a\dot{x}(s)dsd\theta \end{aligned} \quad (4)$$

where $P > 0$ and $R, R_a, S, S_a \geq 0$.

Overview

- Motivations and examples
- Modelling
- Sampling and delay
- A very basic example
- Control *: to buff, or not to buff?* A selection of results
- Conclusions

to buff, or not buff?

1rst solution = act « as if » constant

- ✓ [Niemeyer & Slotine 98][Huang & Lewis 03][Azorin et al. 03][Fattouh & Sename 03] etc.

2nd solution = force the delay to constant

- therefore, maximize it : $0 \leq h_i(t) \leq h_{max} \Rightarrow h_i(t) = h_{max}$
- thanks to a *buffer* → *time-driven*
- then, apply classical techniques:
  - ✓ prediction (Smith) [Lelevé & Fraisse 01]
  - ✓ error eqn. obeying a retarded model [Estrada, Marquez, Moog 07]
  - ✓ etc.

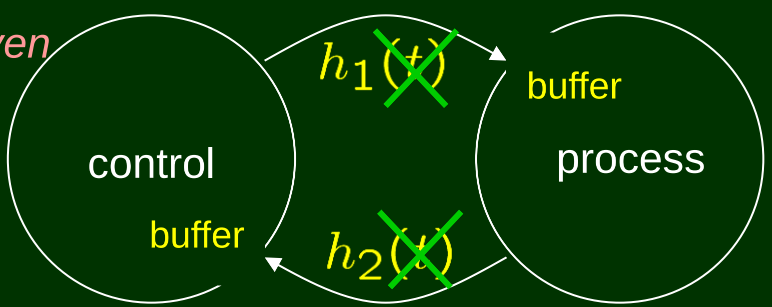
3rd solution (intermed.) only one buffer

[Seuret 06]
[Jiang et.al 08]

4th solution = keep the variable delay…

- ✓ [Witrant et al. 07] [Seuret&Richard 08] → *event-driven*
  [Jiang et al. 09] [Kruszewski et al.11, 12]

Network delay: variable, asymetric →



4.1. Control with predictive model of the network

PhD E. Witrant 2005 + IEEE TAC 2007 (Witrant, Canudas, Georges, Alamir)

with a model of the network and without packet loss (predictible delay)

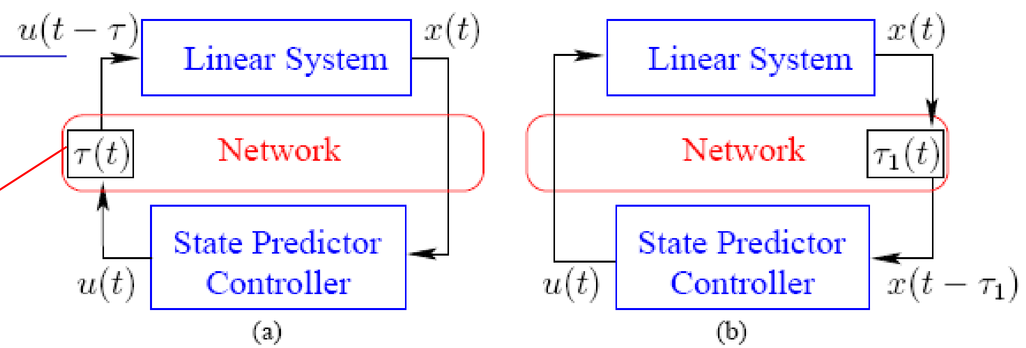
- state predictor with *variable* delays (implicit equation)
- controler of FSA type
- variable prediction horizon
- proven robustness (via *small gain*)
- Application to the T inverted pendulum

$$
\begin{aligned}
\dot{x}(t) &= Ax(t) + Bu(t-\tau(t)) \\
u(t) &= -Ke^{A\hat{\delta}(t)}\left[x(t) + e^{At}\int_t^{t+\hat{\delta}(t)} e^{-A\theta}Bu(\theta-\hat{\tau}(\theta))d\theta\right]
\end{aligned}
$$

where $\hat{\delta}(t) = \hat{\tau}(t+\hat{\delta}(t))$ is the prediction horizon

$$
\begin{aligned}
\dot{x}(t) &= Ax(t) + Bu(t-\tau(t)), \\
y(t) &= Cx(t)
\end{aligned}
$$

$$
\begin{aligned}
\dot{z}(t) &= f(z(t), u_d(t)), \quad z(0) = z_0 \\
\tau(t) &= h(z(t), u_d(t))
\end{aligned}
$$



Time-delay on the actuator (a) and measurement (b) signals.

$$\dot{x}(t) = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -18.785 & 0 & 14.820 & 0 \\ 0 & 0 & 0 & 1 \\ 56.924 & 0 & -15.181 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ 7.520 \\ 0 \\ -8.824 \end{bmatrix} u$$

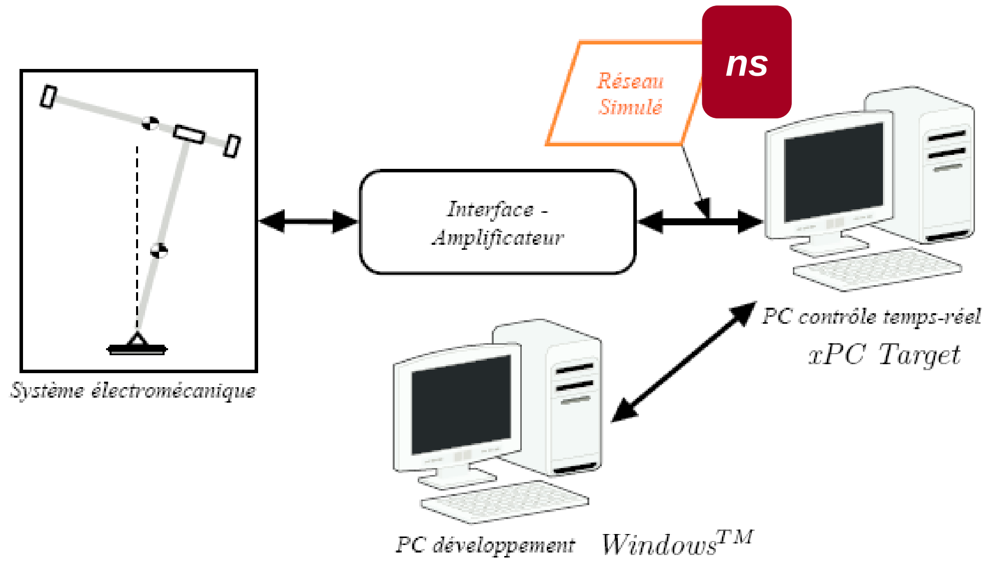
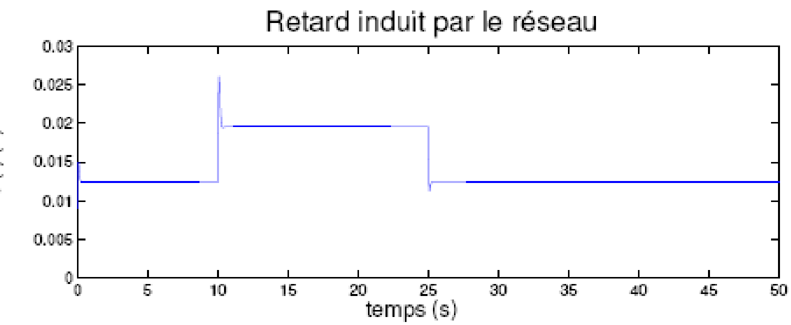
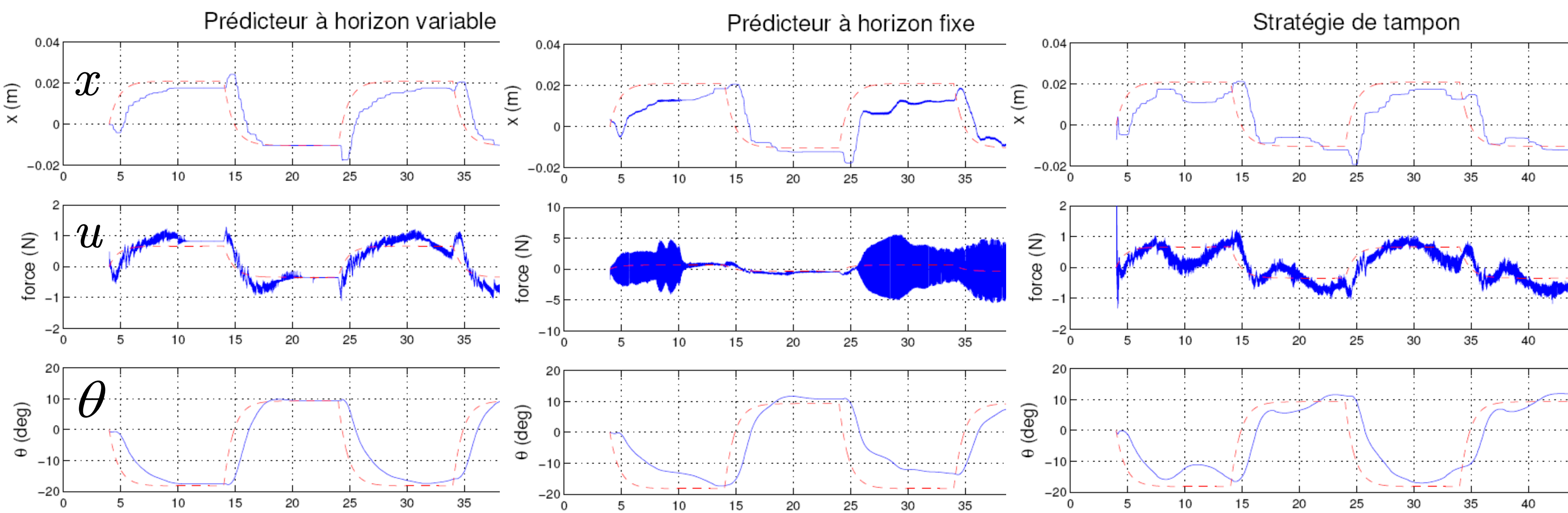


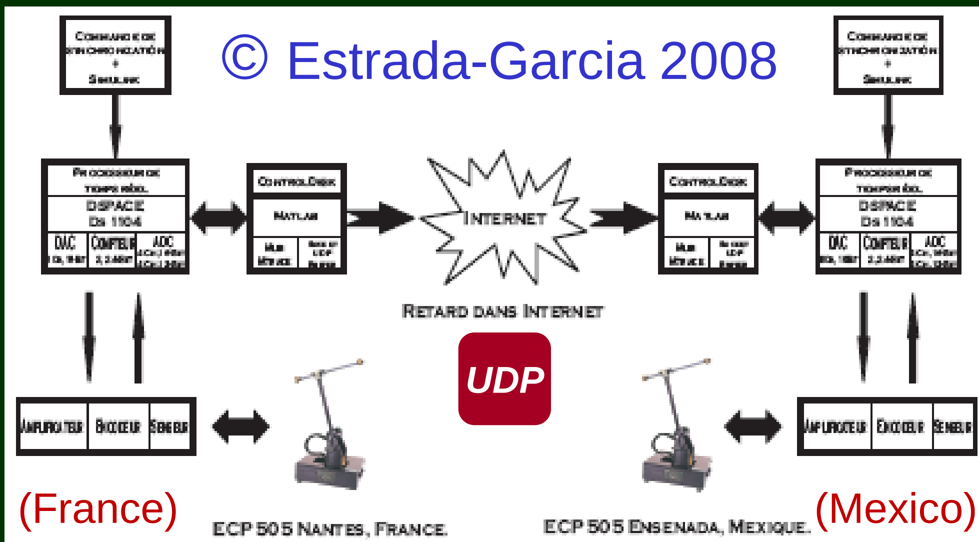
FIG. 5.6 – Banc d'essai expérimental.





4.2. Control with buffers (two-way)

PhD H.J. Estrada-Garcia 2008 (+Moog, Marquez-Martinez)



Aim: synchronization of a Slave pendulum (Nantes) on a Master one (Ensenada).

y^{ref} supposed t.b. known from both sides.

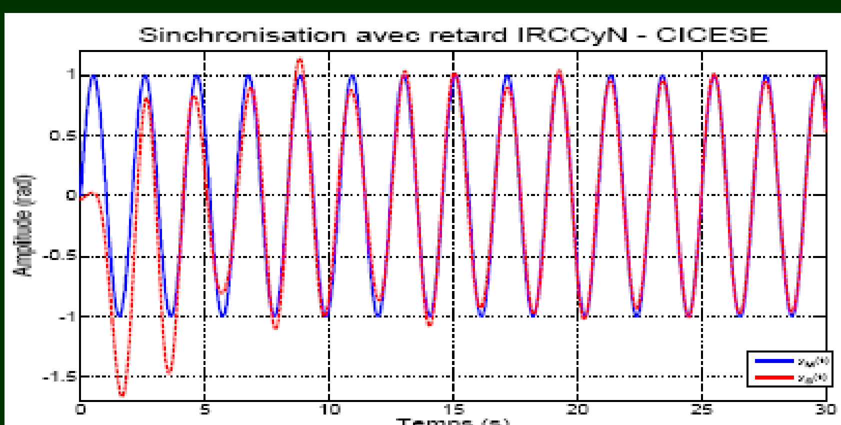
Strategy:

1) *buffers* at 300ms = τ

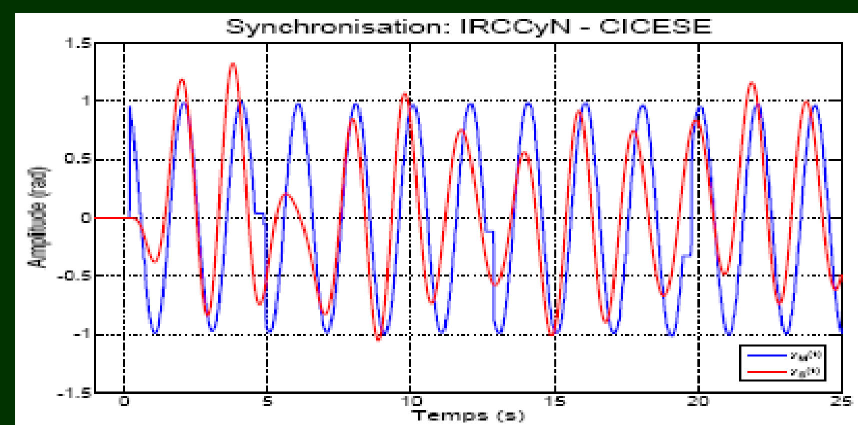
2) control s.t. M/S error obeys:

$$e^{(3)}(t) + a_2\ddot{e}(t-\tau) + b_2\dot{e}(t-\tau) + c_2 e(t-\tau) = 0.$$

→ causal control



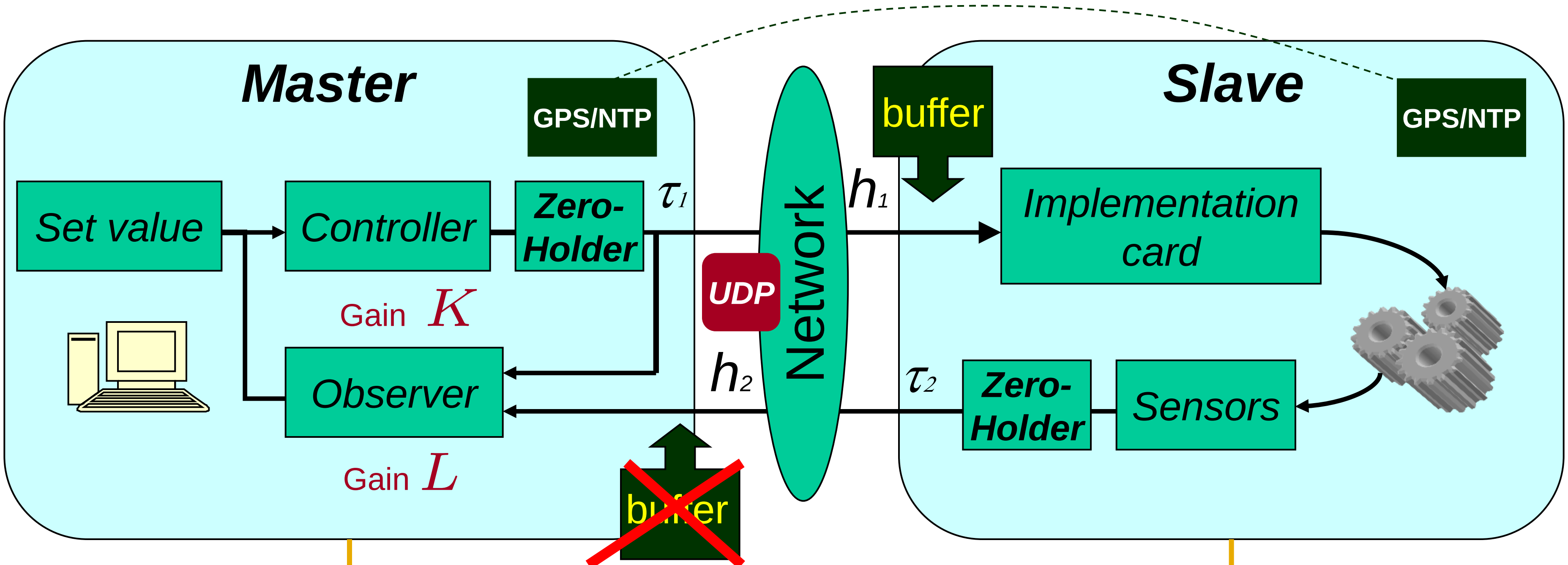
simulated pendulum, real network



real pendulum, real network

4.3. Commande avec tampon aller seul

PhD A. Seuret 2006 (+Dambrine, Richard)



$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t-\delta_1)) \\ \qquad -L(y(t-\delta_2(t)) - \hat{y}(t-\delta_2(t))), \\ \hat{y}(t) = C\hat{x}(t), \end{cases}$$

known thx to buffer

known thx to time-stamps

- defines the target
- receives Slave's output
- observes Slave's state
- computes & sends control

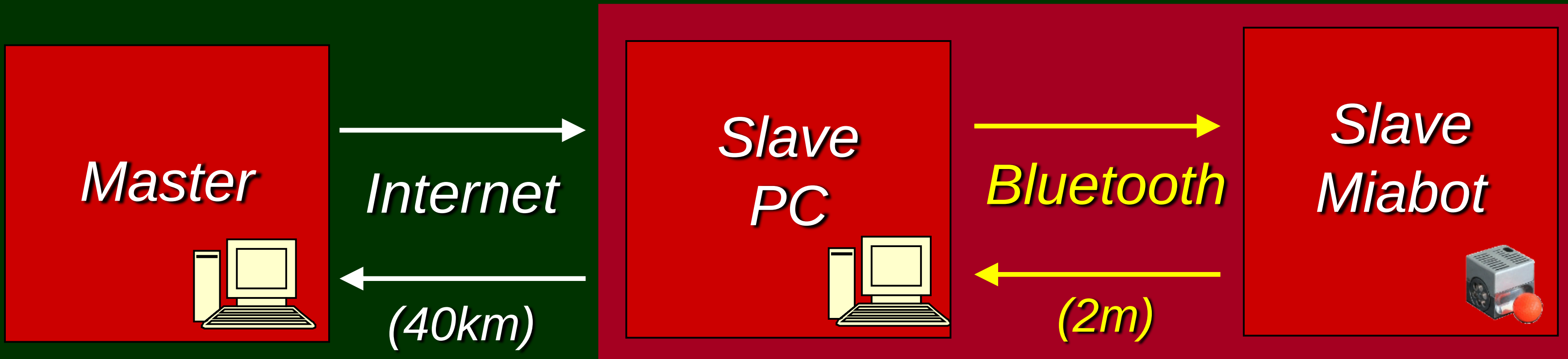
- Limited computation power

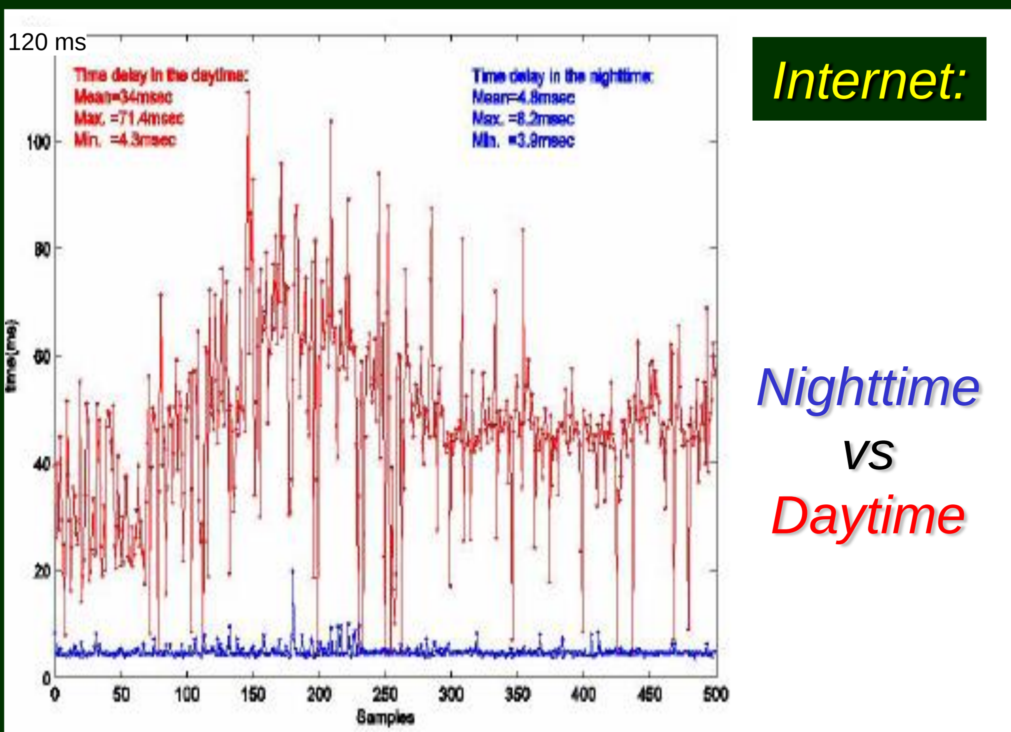
$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t-\delta_1(t)), \\ y(t) = Cx(t). \end{cases}$$

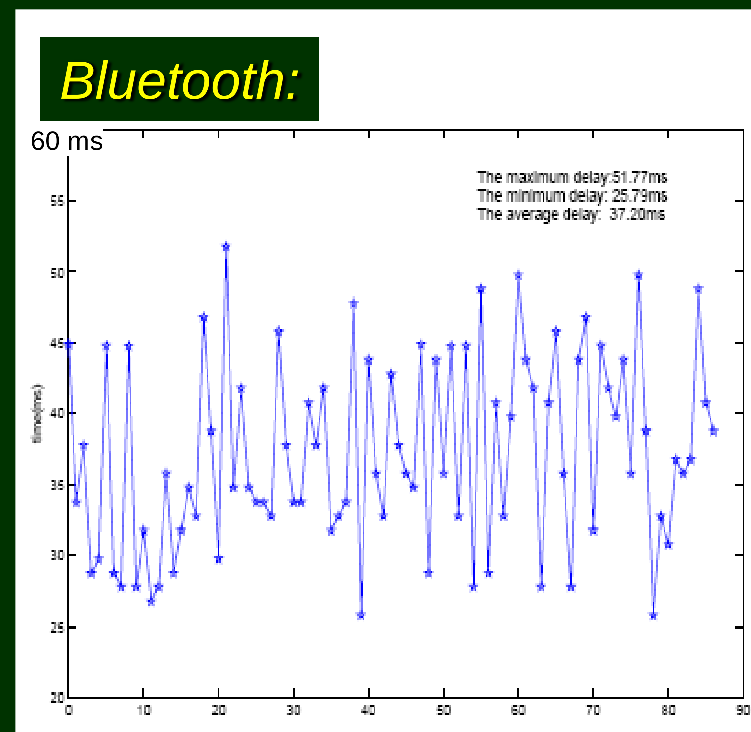
- receives & applies control
- sends measured output

Thèse W. Jiang 09 + Springer 08 **(+Kruszewski, Toguyeni, Richard)**

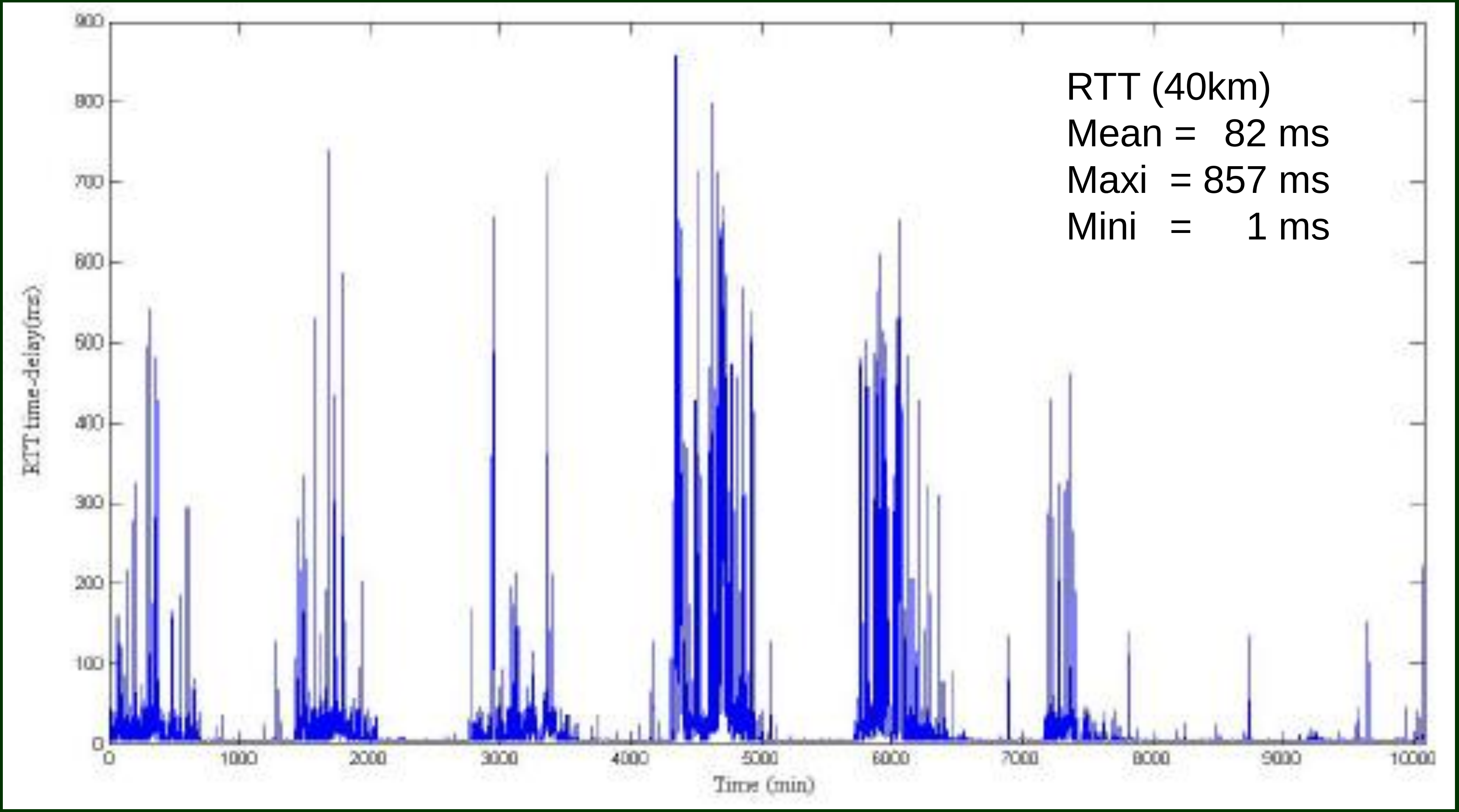
Passage à l'expérimental + adaptation à la QdS disponible



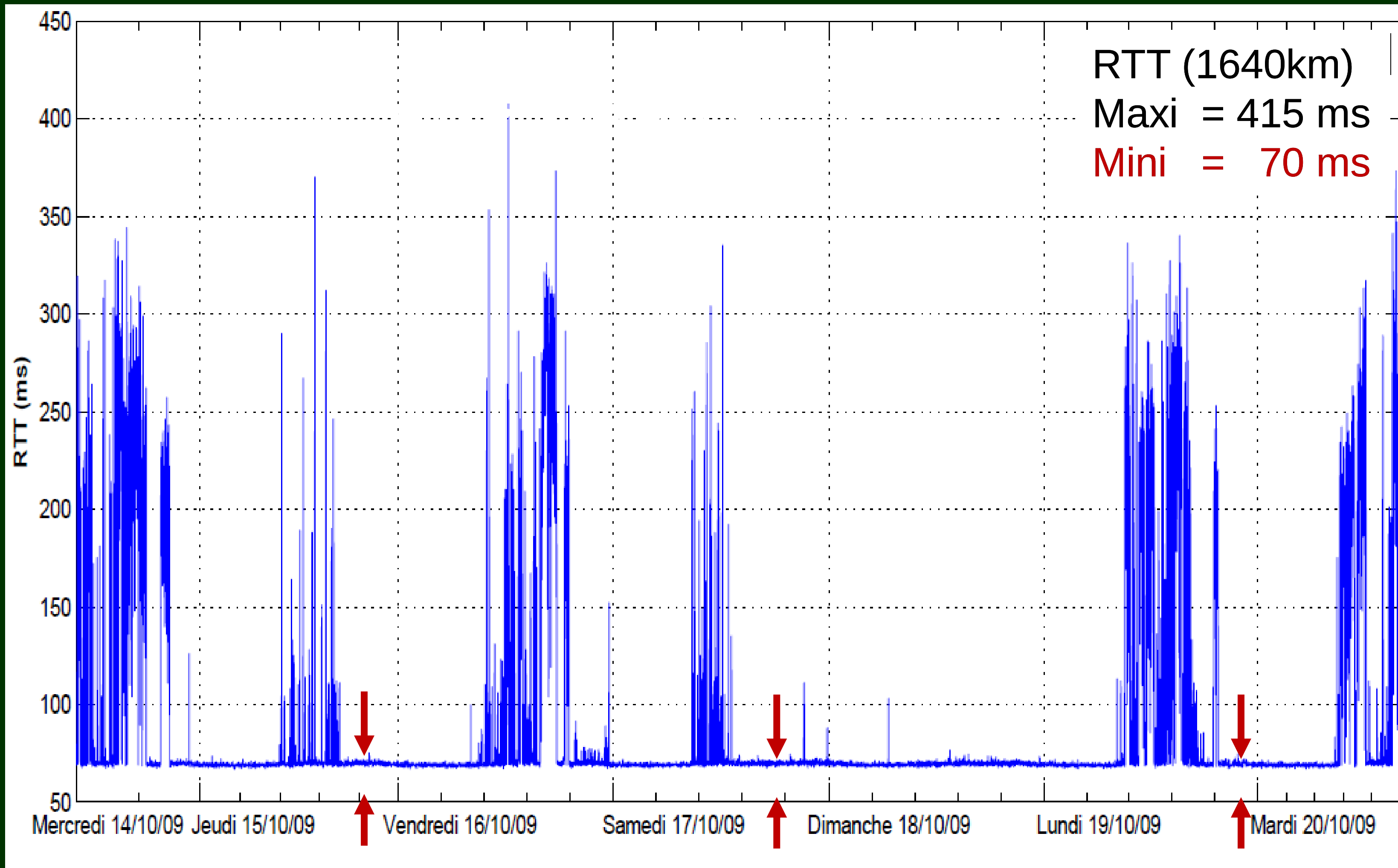




One week of RTT…



Lille-Lens (40 km) – Source: WJ. Jiang 2008



Tunis-Lille (1640 km) – Source: S. Belhaj, ENSIT 2009

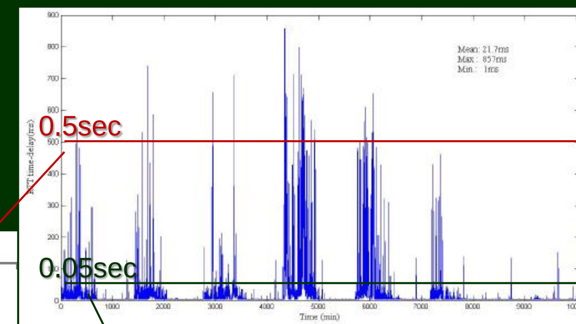
Other RTT (approx. values): *unshared CAN 2m: 200µsec* *bluetooth 2m: 40ms*

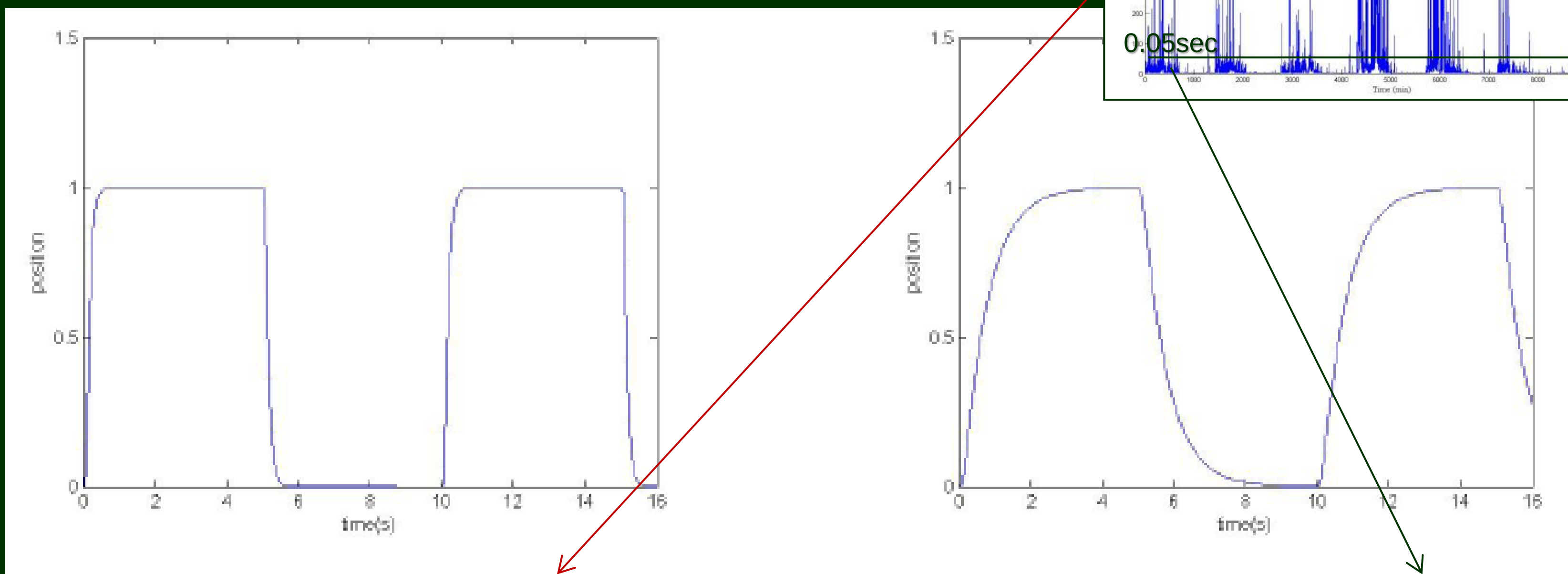
internet 40km: 300ms *internet 1640km: 300ms*

orbital stations: 0.4-7s *underwater 1.7km: >2sec*

One week of RTT…

The achievable exponential rate depends on h_m , which motivates some adaptation w.r.t. QoS...





$h_m = 0.05s, \alpha = 8.74$ $\qquad$ $h_m = 0.5s, \alpha = 0.96$

Link max delay ↔ provable performance

Model of the switching system

Two switching modes are considered : the big time-delay and the small time-delay.

$$1)\quad \dot{x}(t) = Ax(t) + \chi_{[h_1,h_2]}(\delta_{con}(t))BK_1x(t-\delta_{con}(t)) + (1-\chi_{[h_1,h_2]}(\delta_{con}(t)))BK_2x(t-\delta_{con}(t)), \tag{8}$$

$$2)\quad \dot{e}(t) = Ae(t) - \chi_{[h_1,h_2]}(\delta_{obs}(t))L_1Ce(t-\delta_{obs}(t)) - (1-\chi_{[h_1,h_2]}(\delta_{obs}(t)))L_2Ce(t-\delta_{obs}(t)). \tag{9}$$

$\chi : \mathbb{R} \longrightarrow \{0,1\}$ is defined by :

$$\chi_{[h_1,h_2]}(s) = \begin{cases} 1, & \text{if } s \in [h_1, h_2] \\ 0, & \text{otherwise.} \end{cases} \tag{10}$$

Note : we assume $\chi(\delta_{con}(t)) = \chi(\delta_{c}$

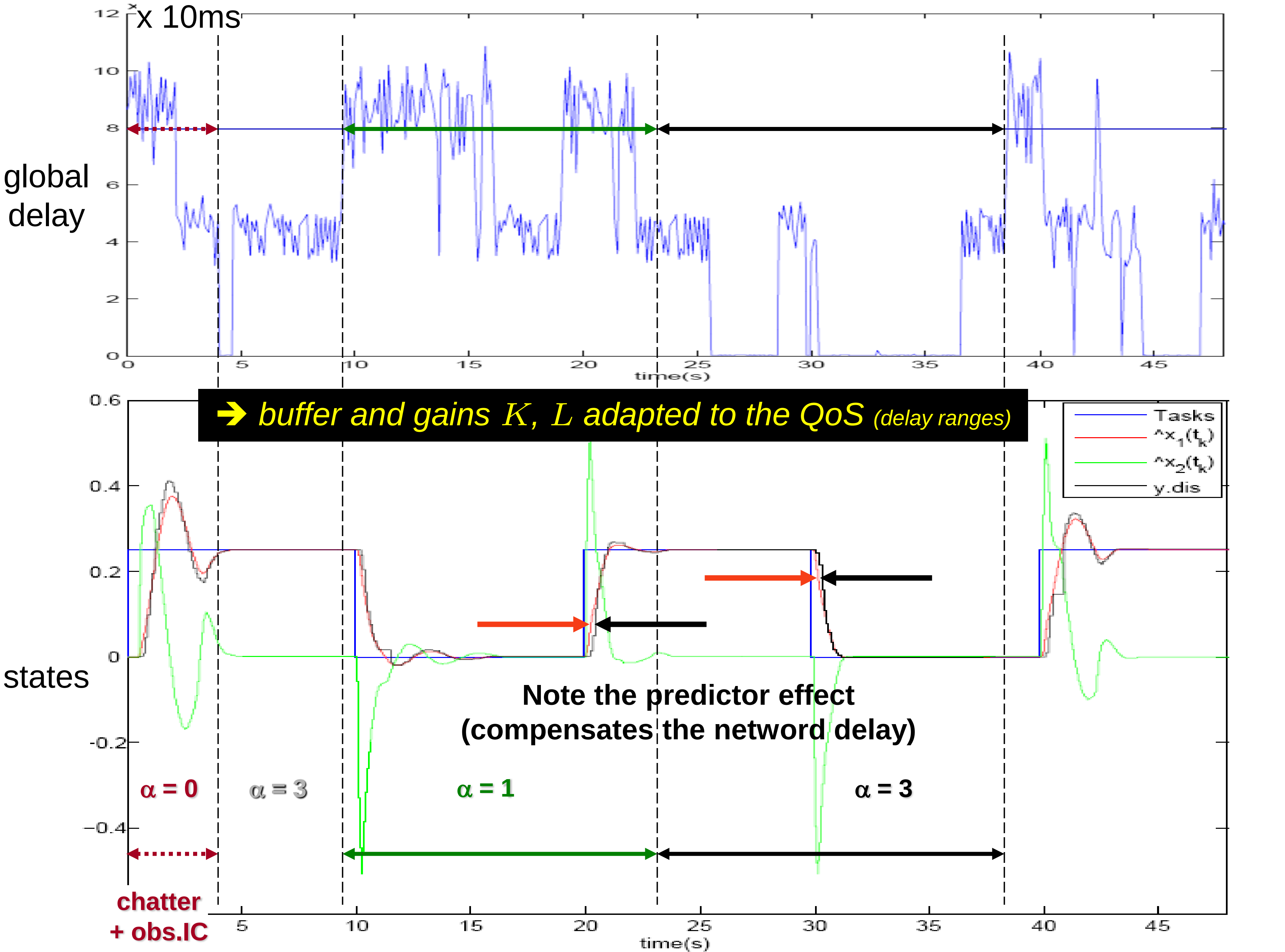
General switched system

$$\dot{x}(t) = Ax(t) + \chi_{[h_1,h_2]}(\tau)A_1x(t-\tau(t)) + (1-\chi_{[h_1,h_2]}(\tau))A_2x(t-\tau(t)), \tag{11}$$

The LKF :

$$V(t,x_t,\dot{x}_t) = x^T(t)Px(t) + \sum_{i=0}^{2}\int_{t-h_{i+1}}^{t} x^T(s)S_ix(s)ds + \sum_{i=0}^{2}(h_{i+1}-h_i)\int_{-h_{i+1}}^{-h_i}\int_{t+\theta}^{t}\dot{x}^T(s)R_i\dot{x}(s)dsd\theta, \tag{12}$$

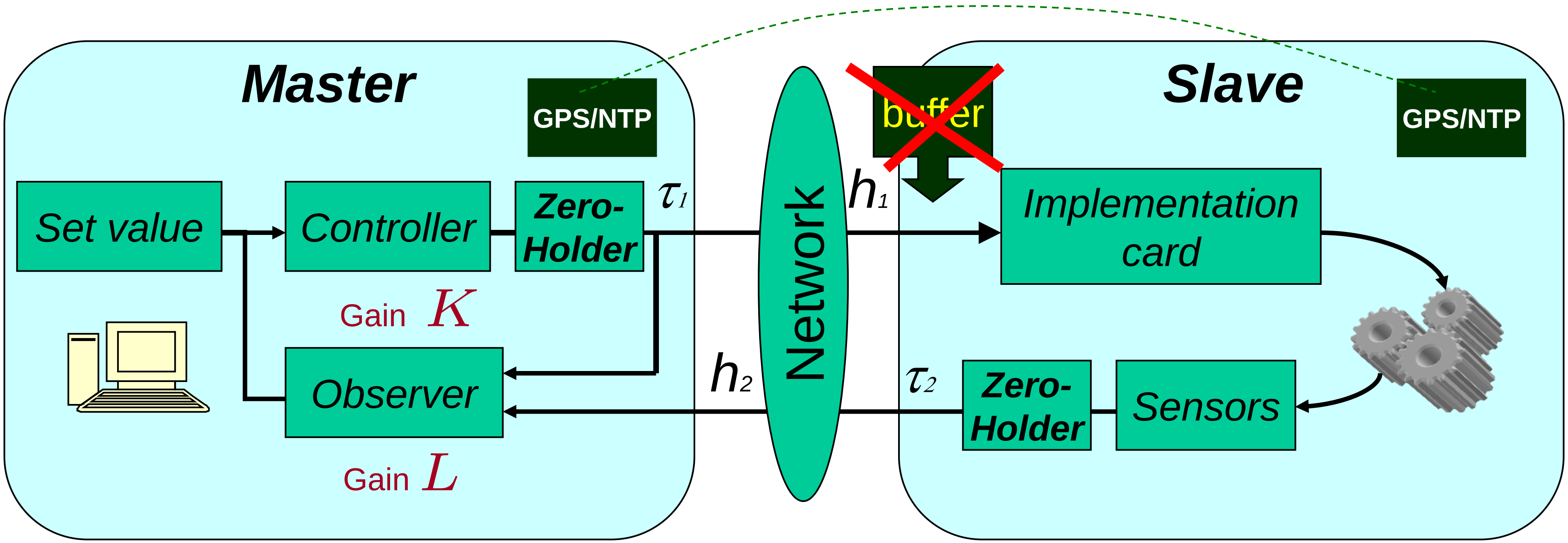
where $h_0 = 0$, $P > 0$ and $R_i, S_i \geq 0$.



x 10ms
global delay
time(s)
→ buffer and gains K, L adapted to the QoS (delay ranges)
Tasks
^x_1(t_k)
^x_2(t_k)
y.dis
states
Note the predictor effect
(compensates the netword delay)
α = 0
α = 3
α = 1
α = 3
chatter
+ obs.IC
time(s)

4.3. Buffer-free control (*event-driven*)

A. Seuret - JPR 2008 (theory) + W. Jiang, A. Kruszewski *et al.* (experim.+switches)
cf. IEEE T. CST 2011

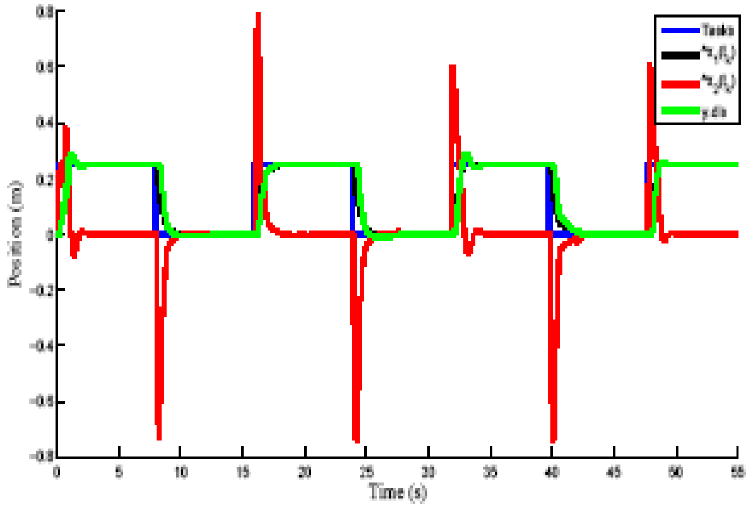


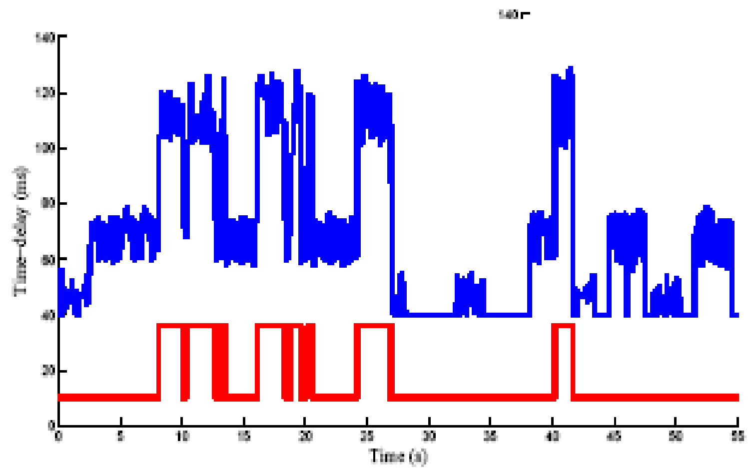
$$\hat{\delta} \neq \delta$$

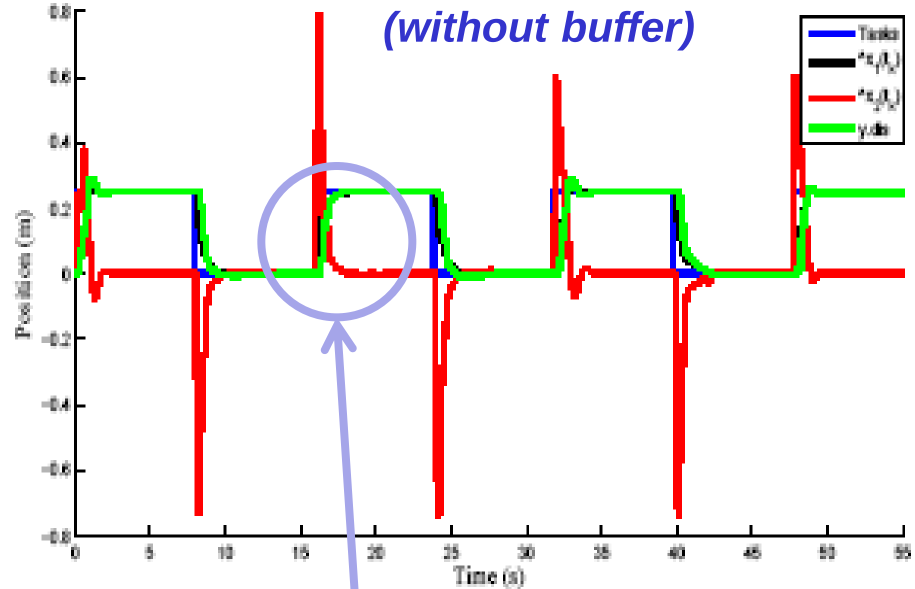
$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t - \hat{\delta}_1(t)) \\ \qquad\quad -L(y(t - \delta_2(t)) - \hat{y}(t - \delta_2(t))), \\ \hat{y}(t) = C\hat{x}(t), \end{cases}$$

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t - \delta_1(t)), \\ y(t) = Cx(t). \end{cases}$$

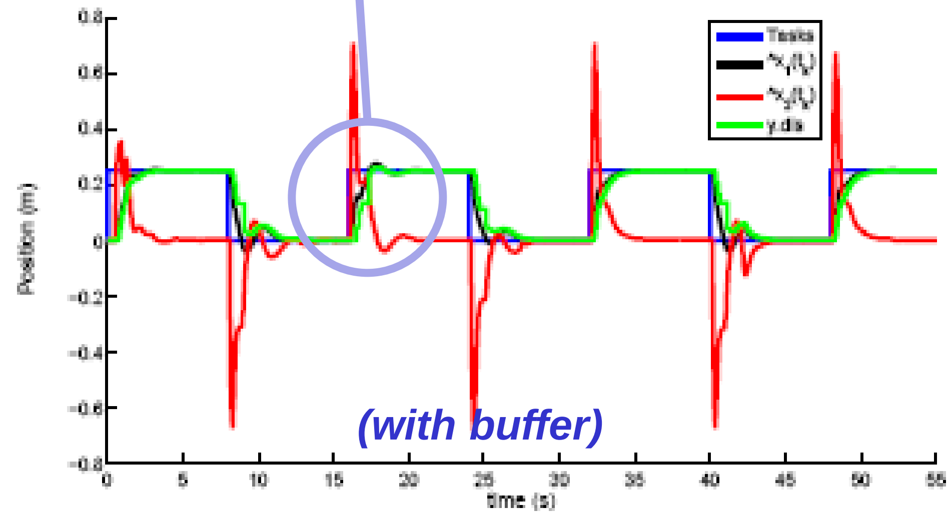
Results from the event-driven mode





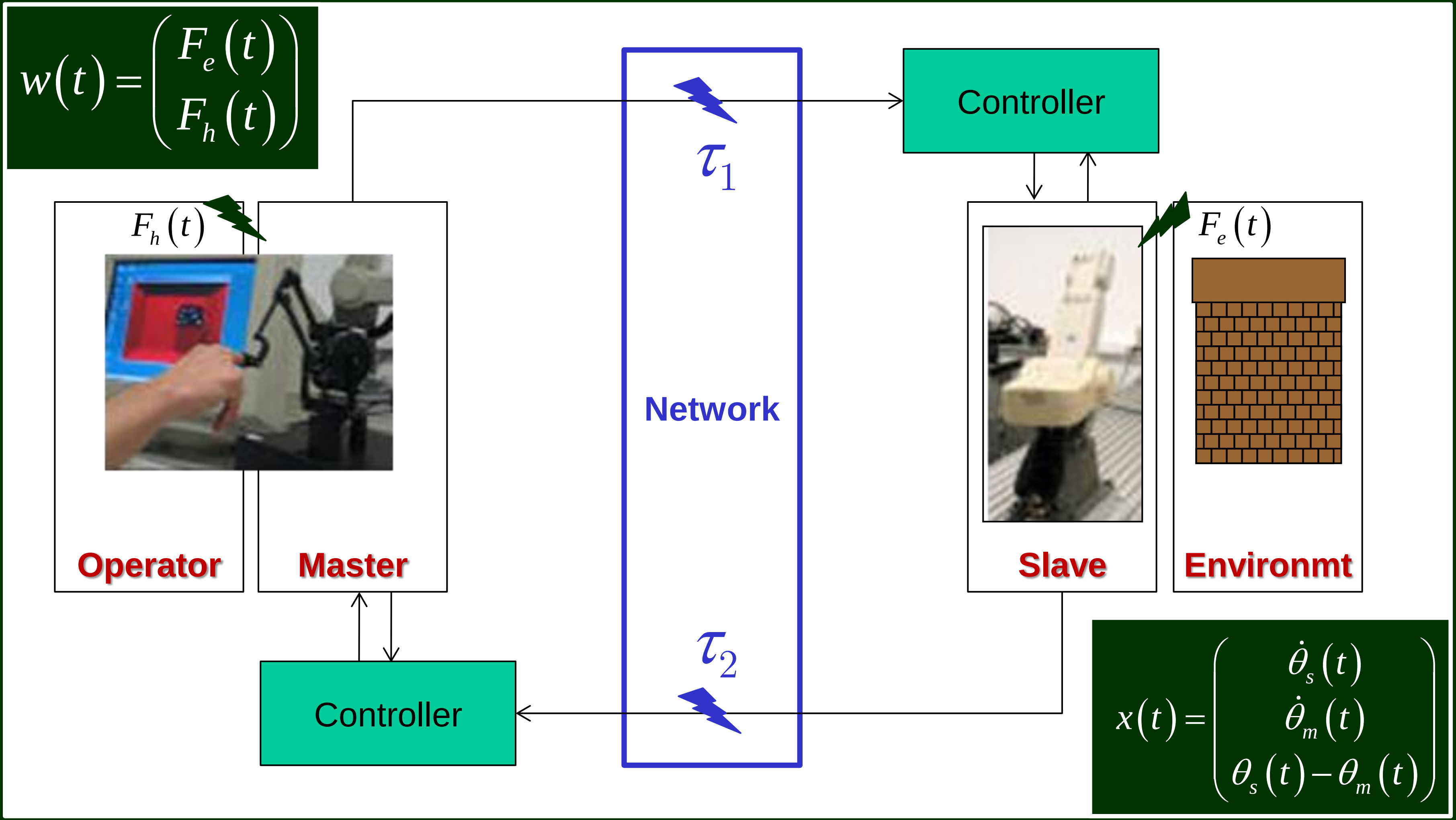


Event-driven vs. time-driven mode.



Natural continuation: teleoperation (LKF + H_∞)

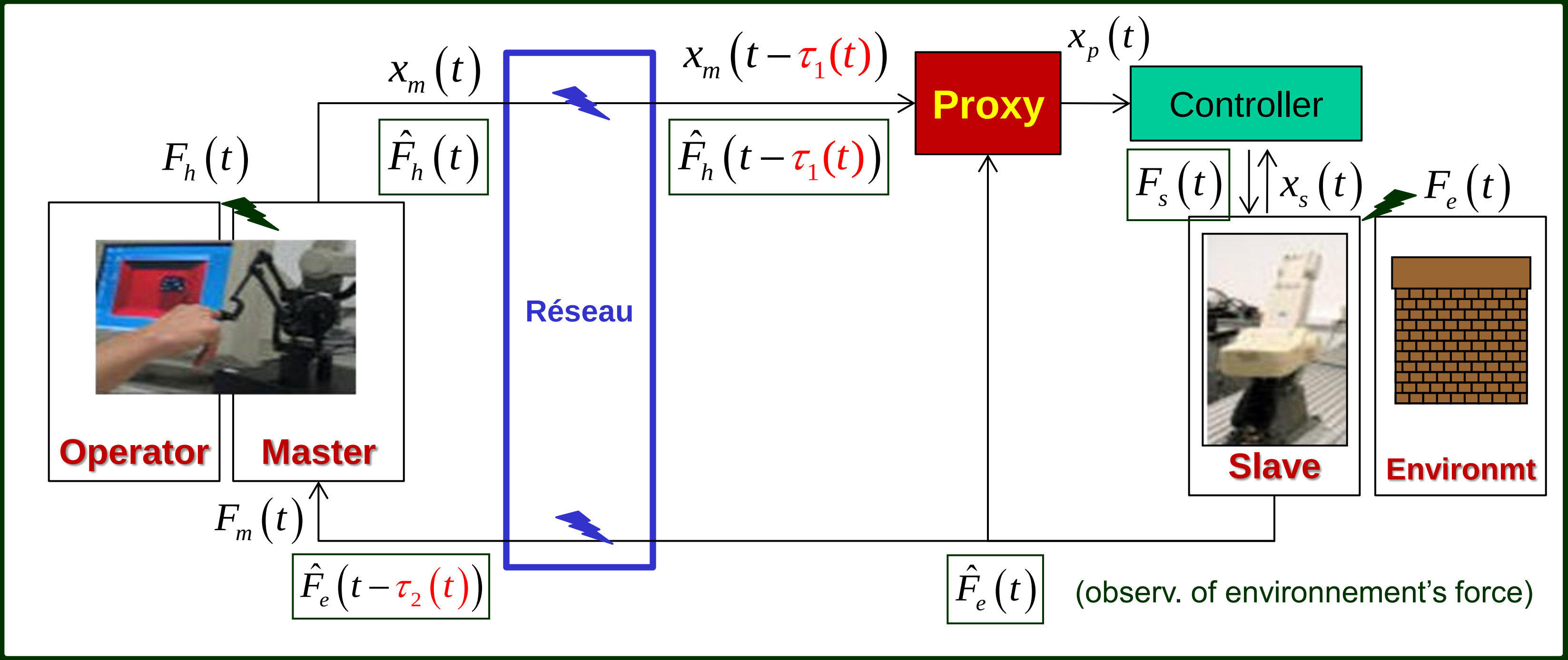
1) Basic scheme: position tracking - θ (no force target)



PhD Bo Zhang (2012) **(+ Kruszewski, Richard)**

2) Improved scheme: force and position tracking (haptic rendering)

(ETFA 2011)



- Proxy synchronized on Master
- Slave synchronized on Proxy

Proxy « emulates » Master without delay

- Reduction of the delay effect
- Accurate haptic rendering

2) Improved scheme: force and position tracking (haptic rendering)

(ETFA 2011)

- Reduction of the delay effect
- Accurate haptic rendering

Combining LKF with H_∞

$$J(w) = \int_0^\infty (z(t)^T z(t) - \gamma^2 w(t)^T w(t))dt < 0$$

To ensure $J(w) < 0$, we consider the condition,

$$\dot{V}(t, x(t), \dot{x}(t)) + z(t)^T z(t) - \gamma^2 w(t)^T w(t) < 0$$

We choose a Lyapunov-Krasovskii Functional candidate,

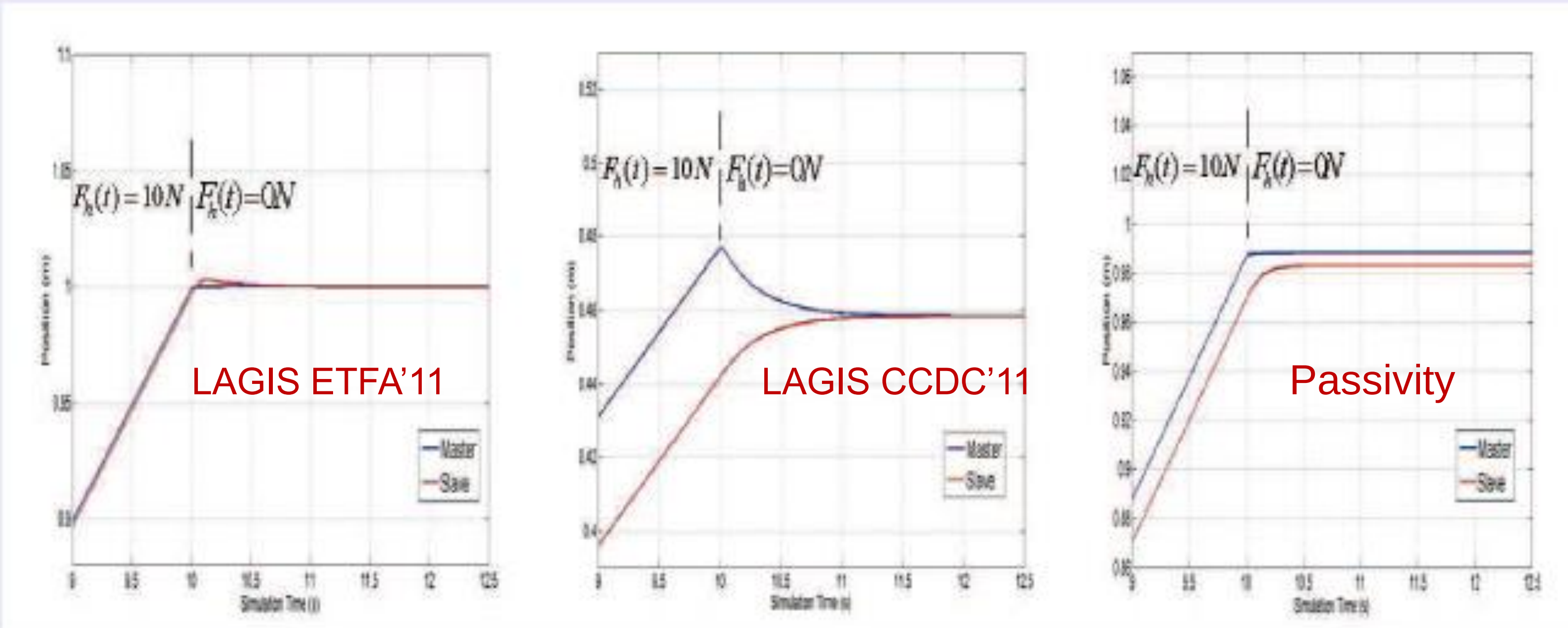
$$V(t, x(t), \dot{x}(t)) = x(t)^T P x(t)$$
$$+ \int_{t-h_2}^{t} x(s)^T S_a x(s) ds + \int_{t-h_1}^{t} x(s)^T S x(s) ds$$
$$+ h_1 \int_{-h_1}^{0} \int_{t+\theta}^{t} \dot{x}(s)^T R \dot{x}(s) ds d\theta$$
$$+ \sum_{i=1}^{n} (h_2 - h_1) \int_{-h_2}^{-h_1} \int_{t+\theta}^{t} \dot{x}(s)^T R_{ai} \dot{x}(s) ds d\theta$$

$$w(t) = \begin{pmatrix} F_e(t) \\ F_h(t) \end{pmatrix}$$

$$x(t) = \begin{pmatrix} \dot{\theta}_s(t) \\ \dot{\theta}_m(t) \\ \theta_s(t) - \theta_m(t) \end{pmatrix}$$

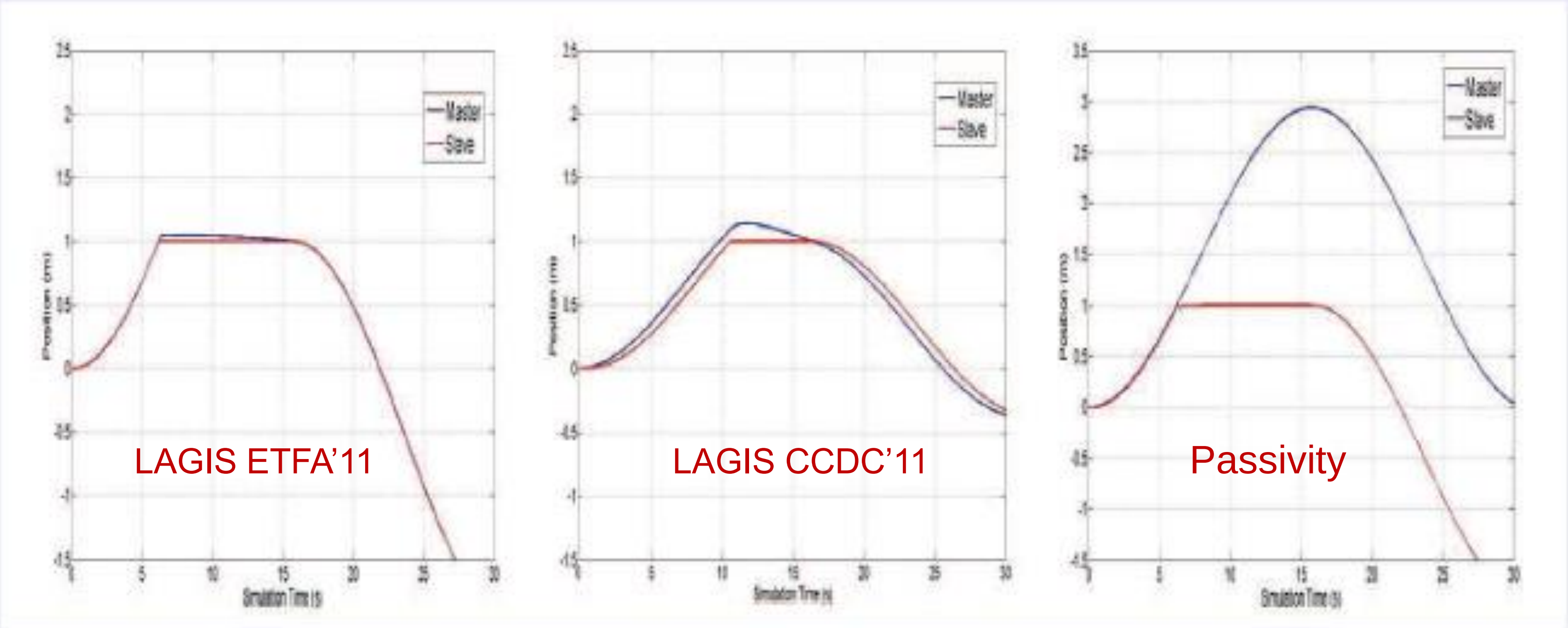
$$\theta_s(t) - \theta_m(t) = z(t)$$

Tracking in abrupt changing motion :



- Left Figure : new proxy control scheme.
- Middle Figure : new control scheme (B. Zhang, A. Kruszewski, J.-P. Richard, CCDC, 2011).
- Right Figure : passivity theorem (Y. Ye, Y.-J. Pan and Y. Gupta, CDC, 2009).

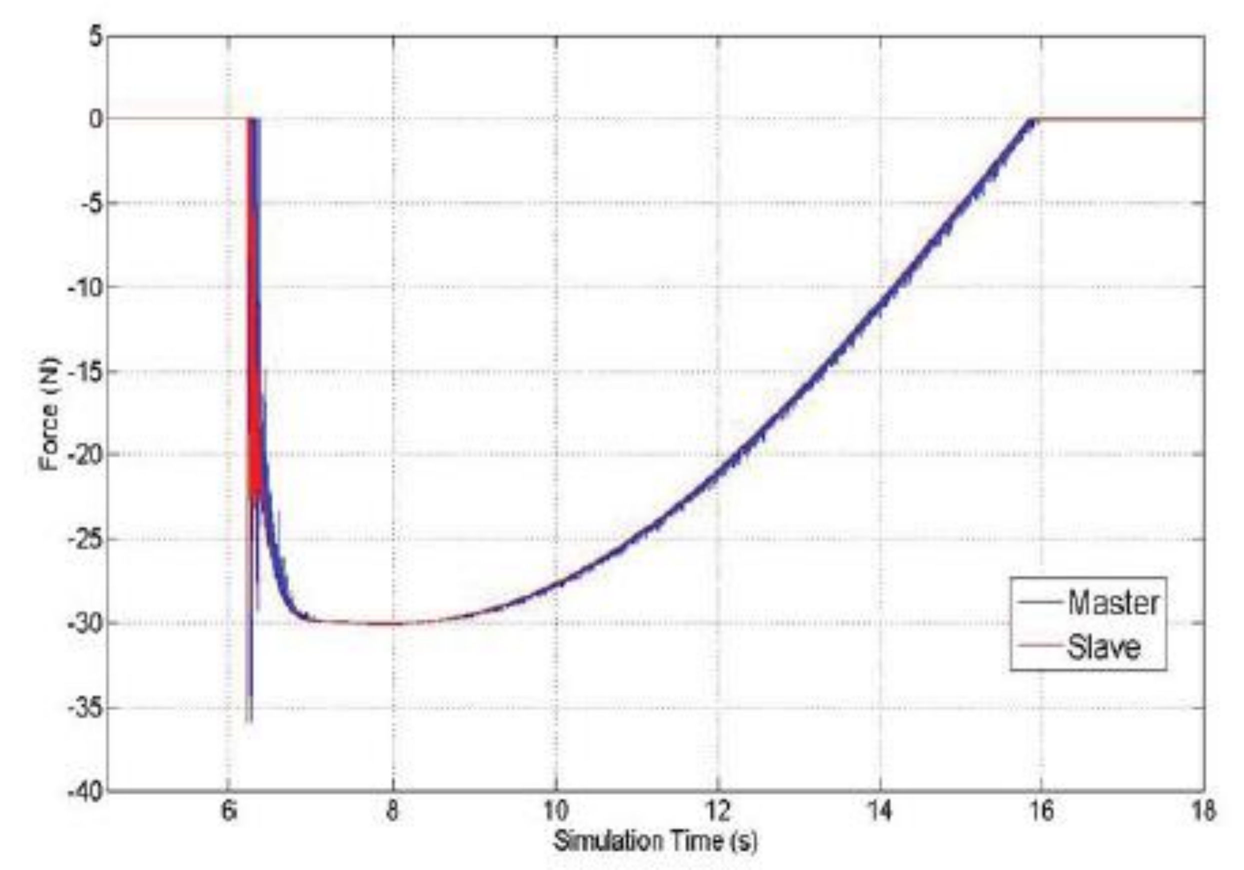
Tracking in wall contact motion :



- The hard wall : the stiffness $K_e = 30kN/m$, the position $x = 1.0m$.
- Left Figure : new proxy control scheme.
- Middle Figure : new control scheme (B. Zhang, A. Kruszewski, J.-P. Richard, CCDC, 2011).
- Right Figure : passivity theorem (Y. Ye, Y.-J. Pan and Y. Gupta, CDC, 2009).

➡ the proxy structure allows for reducing the lag

and gives a good force rendering…



Intermediate conclusion on bilateral teleoperation

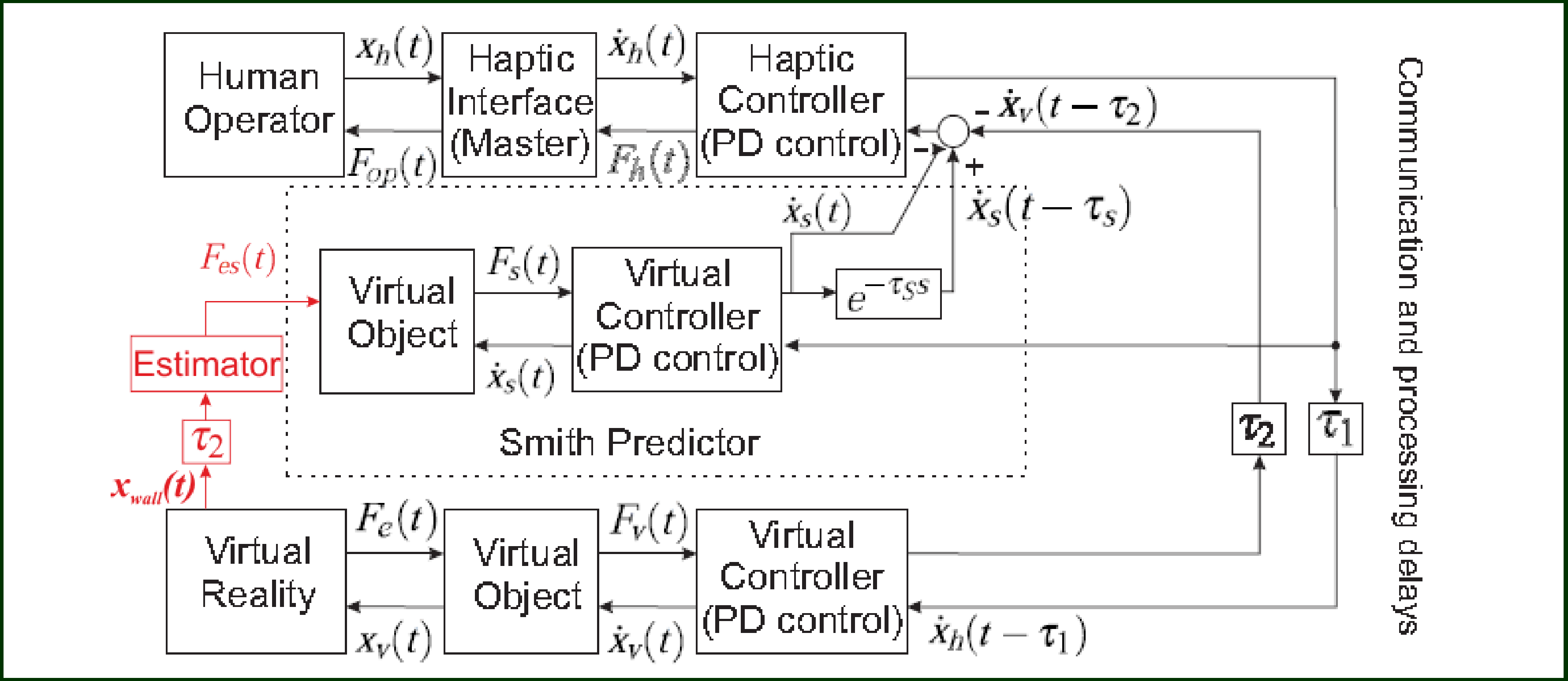
- Classical solution = passivity, without performance
- Alternative LFK + Hinf, various possible structures:
  - position/Position (CCDC 2011) $\Rightarrow$ position tracking OK
  - force/Position (ETFA 2011) $\Rightarrow$ position +haptic rendering
  - LMI conditions $\Rightarrow$ stability + performance γ
  - under variable delays (estimated by means of time stamps+NTP)
  - and still *buffer-free*…

An other work on bilateral teleoperation

"Network-based haptic systems with time-delay"

B. LIACU 2012 (NICULESCU, ANDRIOT, COLLEDANI, BOUCHER, DUMUR)

- Aim: improve the end user *perception*.
- *Smith predictor with distance feedback*, uses the information from the virtual environment so to have a better predictor model in wall contact.
- Experiments with simulated constant delays 50-80ms.



Overview

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- Conclusions

Conclusion-Summary

- Quite general problems formulated thx to delay/switch models

  $\Rightarrow$ *design in the presence of variable delays*

- Control with a network model [Witrant 05] — predictor with variable delay
- General case (without network model) :
  - ✓ with 2 buffers [Estrada 08] — retarded error equation
  - ✓ with 1 buffer [Seuret 06] — state feedback + observ./predict.
  - ✓ + adapt. to QoS [Jiang-Kruszewski-R-T 08] — ‘ ‘
  - ✓ with 0 buffer [S-R 08, Jiang-K-R-T 09] — ‘ ‘
- Bilateral teleoperation with performance (alternative to passivity)
  - ✓ with 0 buffer [Zhang-K-R 11] — state feedback + obs + H_∞

Other healthy readings:

"A switched system approach to exponential stabilization through communication network"

A. KRUSZEWSKI, W.J. JIANG, E. FRIDMAN, J.P. RICHARD, A.TOGUYENI

IEEE TCST, 20 (4), pp. 887–900, 2012

"A novel control design for delayed teleoperation based on delay-scheduled Lyapunov-Krasovskii functionals“

A. KRUSZEWSKI, B. ZHANG, J.P. RICHARD

Int. J. Control, accepted May 2013, to appear.

"Control design for teleoperation over unreliable networks: A predictor-based approach"

A. KRUSZEWSKI, B. ZHANG, J.P. RICHARD

Springer, in *Delay Systems: From Theory to Numerics and Appl.*, Edt. Vyhlidal, Lafay, Sipahi,, 2013

"Remote Stabilization via Communication Networks with a Distributed Control Law"

E. WITRANT, C. CANUDAS DE WIT, D. GEORGES, M. ALAMIR

IEEE TAC, vol. 52, pp. 1480-1485, 2007

"Master-Slave synchronization for two inverted pendulums with communication time-delay“

H J. ESTRADA-GARCIA, L.A. MARQUEZ-MARTINEZ, C.H. MOOG

Springer LNCIS vol.388, 2009, Chap. Part V, pp. 403-414.

"Control of a remote system over network including delays and packet dropout"

A. SEURET, J.P. RICHARD

IFAC'08, 17th IFAC World Congress, Seoul, South Korea, July 2008

“A refined input delay approach to sampled-data control”

E. FRIDMAN, **Automatica**, 48 (2), 2010

“SOS for sampled-data systems“

A. SEURET, M. PEETS, **IFAC’11,** Milano, Italy, 2011

“A novel stability analysis of linear systems under asynchronous samplings”.

A. SEURET, **Automatica** 48 (1), pp. 177-182, 2011

… ongoing at LAGIS on in this area

- Scheduling issues: aperiodic sampling for *nonlinear* systems
  (PhD Hassan Omran Feb. 2014 → hybrid/dissipativity) → **talk in the workshop**

  "Stability of bilinear sampled-data systems with an emulation of static state feedback"
  H. OMRAN, L. HETEL, J.P. RICHARD, F. LAMNABHI-LAGARRIGUE
  CDC'12, 51st Conf. on Decision & Control, Hawaii, USA, 2012

  "On the stability of input-affine nonlinear systems with sampled-data control"
  H. OMRAN, L. HETEL, J.P. RICHARD, F. LAMNABHI-LAGARRIGUE
  ECC'13, 12th European Control Conf., Zurich, Switzerland, 2013

- Keep on developping experimental platforms
  - NCS@LAGIS (various benchtests with Wifi – Zigbee – LAN – CAN – wired)
  - EquipEx FUN Future Internet of Things (WSRN)