Mating Control and Computing

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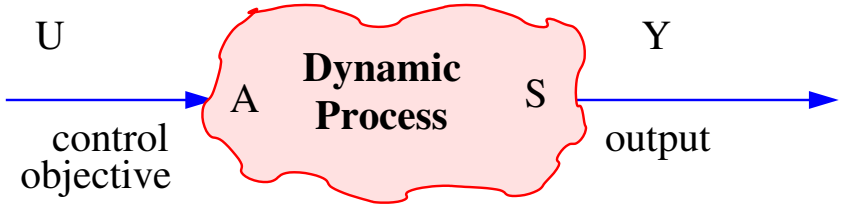
Feedback control paradigm



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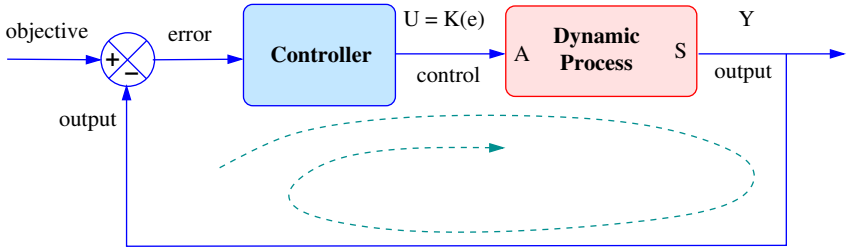

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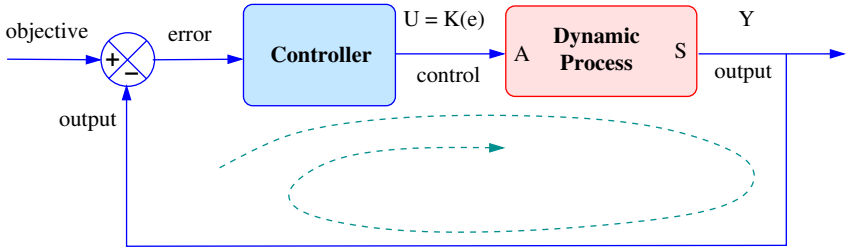

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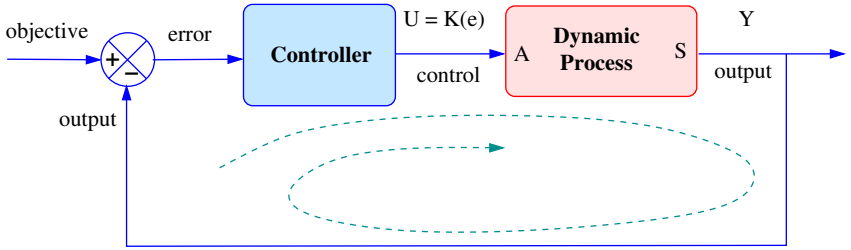

"Make precise systems from uncertain components"

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- **Robustness** w.r.t. modeling uncertainties

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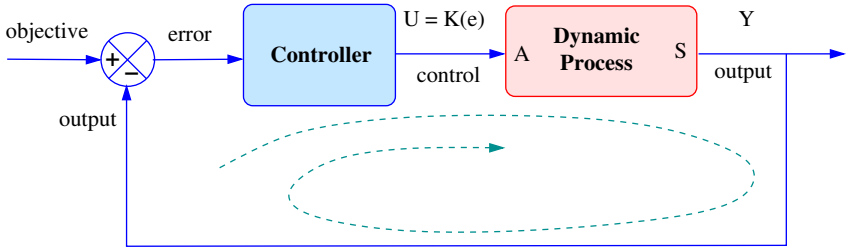

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- Adaptability w.r.t. operating conditions
- Performance profile shaping

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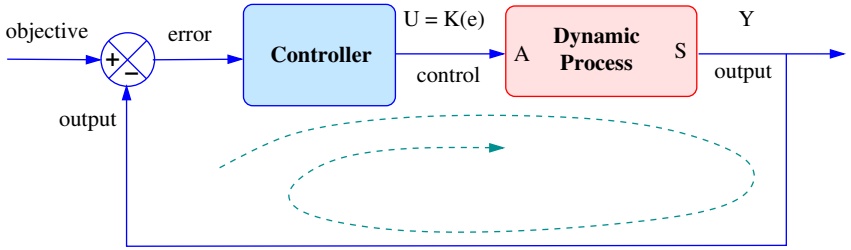

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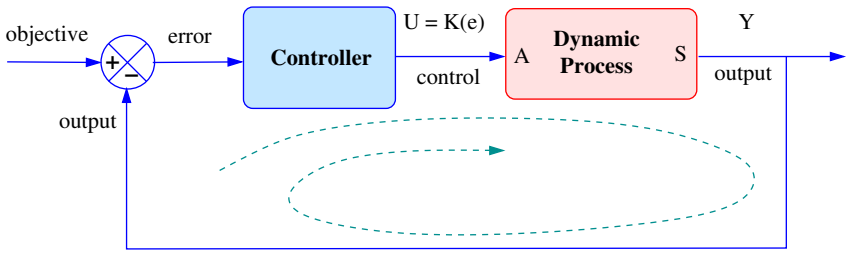
Danger of instability

Control objectives

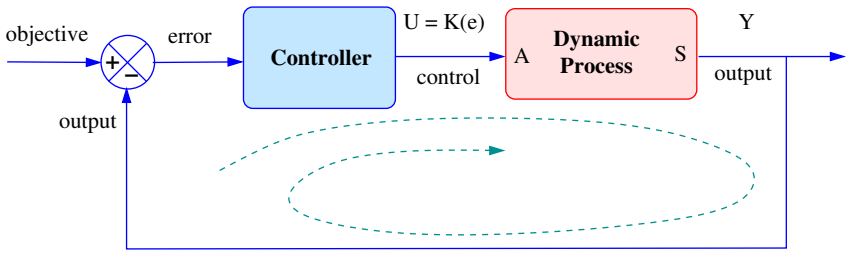


Design and implementation for:

Control oriented goal

Reaching a specified control performance under shared execution resources constraints;

Control objectives



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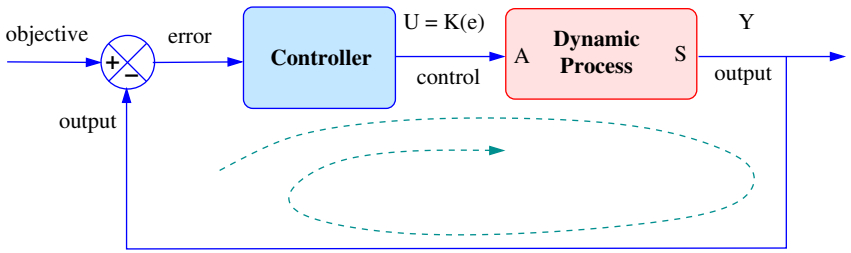

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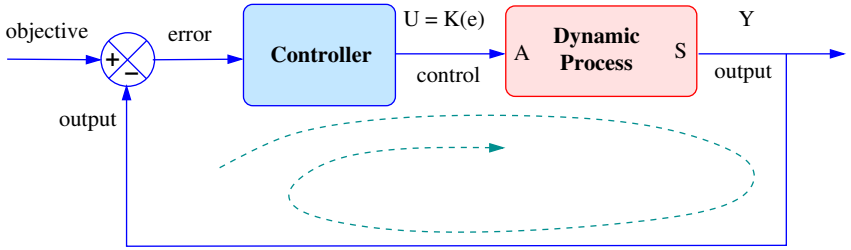
Conflicting constraints!

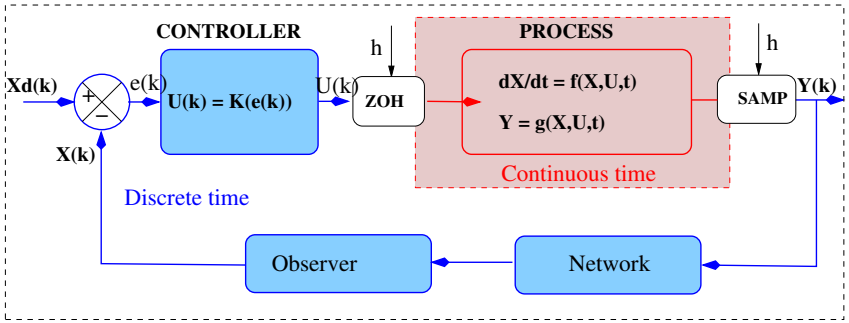
Implementation



Continuous time and analogue control

- Biology
- Fluid level
- Fluid pressure
- Continuous electronics

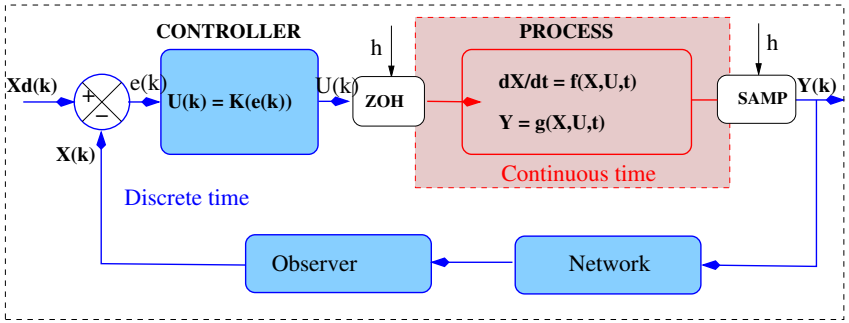
Implementation



Numerical control and sampling

- Sampling and A/D conversion
- Networking
- Computing
- Control update and D/A conversion

Implementation



Numerical control and sampling

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Timing constraints required by the control system's dynamics

$\Longrightarrow$ Real-time system

Current practice

Traditional controller design : separation of concerns between control and computing :

Assumptions

- Perfectly periodic process, No jitter, No data-loss
- Perfect implementation, based on worst case
- Dedicated hardware/software

Consequences

- Over-constrained systems
- Under-using the resources
- Costly components and tools

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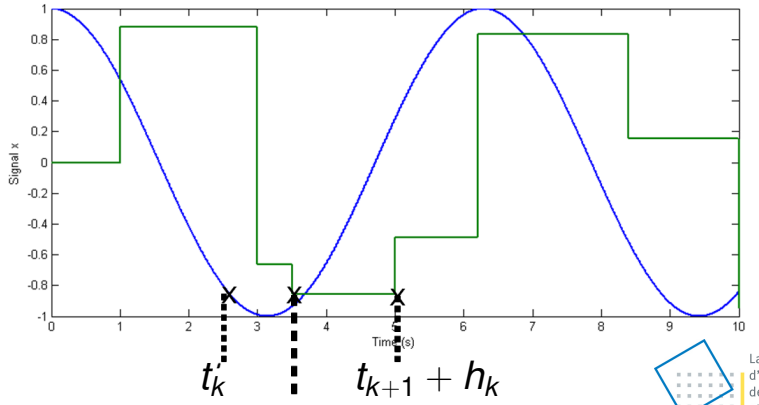
$\Longrightarrow$ formally provable, but costly and inflexible/unrealistic

NCS induced computing constraints

- Limited computing power → computing duration are not negligible
- Variable computing power → they are not constant
- Distributed information sources → delays, data loss or corruption
- Many sources of induced delays: computing, preemption, networking...
- Implementation induced uncertainties (in addition to the usual process uncertainties)

deterioration of a signal transfered through a network.



Needs for co-design

- Large sets of interconnected sensors/controllers/actuators; Networked Control Systems - Cyber Physical Systems
- Dynamic and uncertain environments;
- Heterogeneous components, asynchronous nodes;
- Cheap off-the-shelf hardware/software components.

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$\Rightarrow$ Co-design approach : early integration of constraints from control and computing

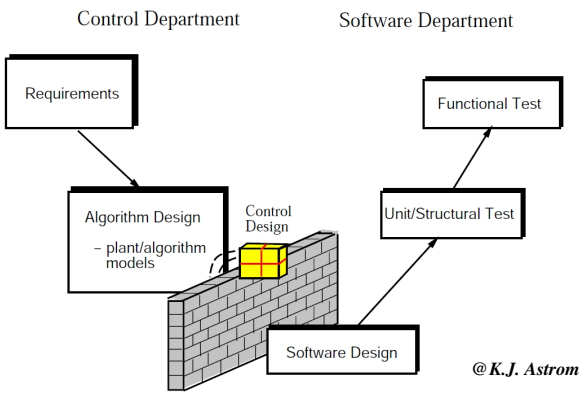
- **Trade off :** performance/robustness/energy/costs. . .
- **Holistic view :** process + algorithm + execution resources

Bridging the gap...

Gathering control & computing

control dpt. computing dpt.

- Continuous time
- Uncertain systems
- Complex dynamics
- ODE



- Discrete events
- Determinism
- Complex data sets
- Automata

Heretical but fruitful!

Pioneering works 1999/2000

Stankovic, Lu, Son and Tao: The Case for Feedback Control Real-Time Scheduling, *ECRTS Euromicro* 1999

Flexible scheduling of web servers

Eker, Hagander and Arzen, A Feedback Scheduler for Realtime Controller Tasks, *Control Engineering Practice*, Dec. 2000

Sharing a computing resource between process controlers

Pioneering works 1999/2000

New class of control problem :

Control of n identical pendulums under CPU power constraint

n LQ controllers, period h_i, exec. time C_i, single CPU

Cost function $J(h) = \frac{1}{h} \int_0^h \begin{pmatrix} x^T(t) & u^T(t) \end{pmatrix} Q \begin{pmatrix} x(t) \\ u(t) \end{pmatrix} dt$

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on-line solving of Riccati and Lyapunov equations
too costly for real-time implementation...

...although quite simple : LTI process, no delay, no jitter, no data loss, no uncertainty

New perspective: Control & Computing Co-Design

- Feedback loops are _not_ hard real-time

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  New degrees of freedom to implement control
  - Asynchronous sampling, anytime control
  - Varying sampling intervals
  - Data loss and (m,k)-firm policies

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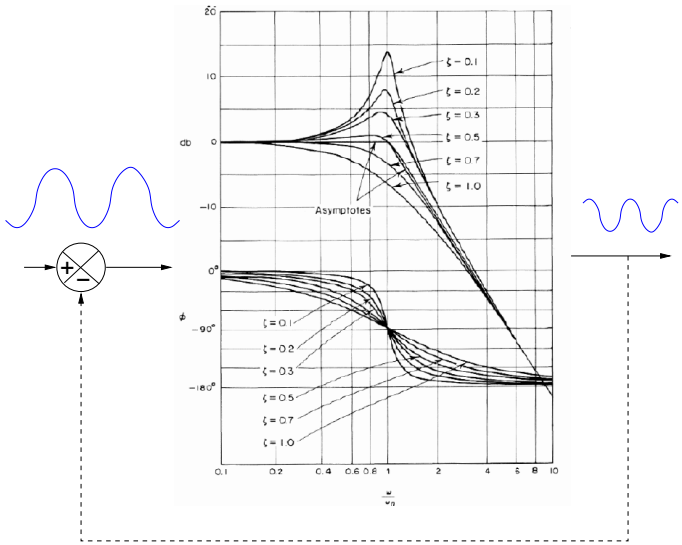
- Computing devices can be object of feedback control
  Benefits of feedback
  - Adaptive w.r.t. operating conditions
  - Robustness w.r.t. process modeling uncertainties

Working directions

- Computing-aware control
- Control-aware computing
- Feedback control of computing devices
- Feedback scheduling
- Control of/over networks
- Integrated control and computing

Stability and robustness



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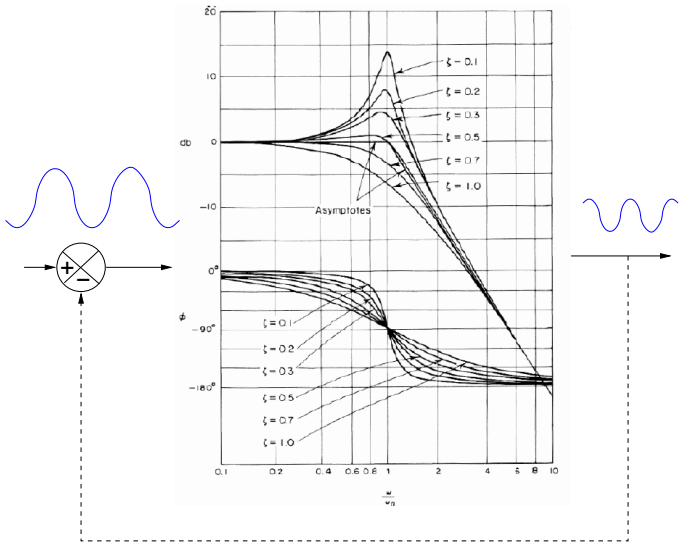

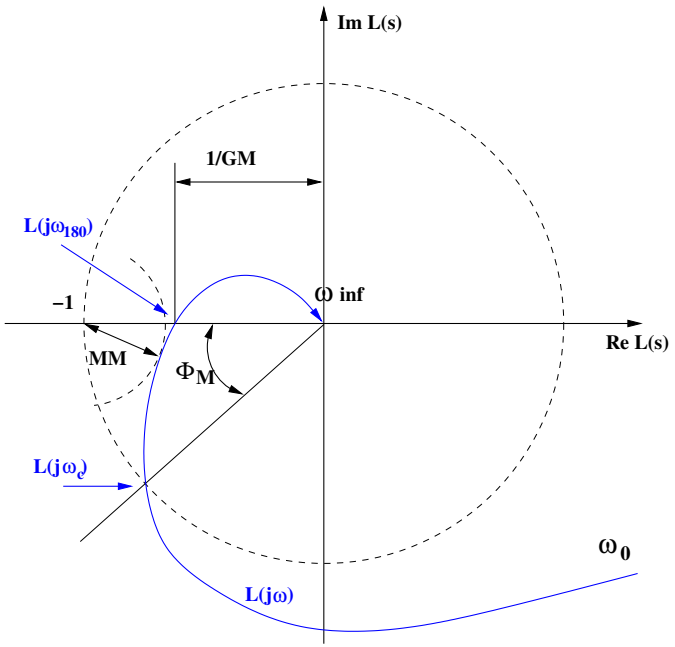

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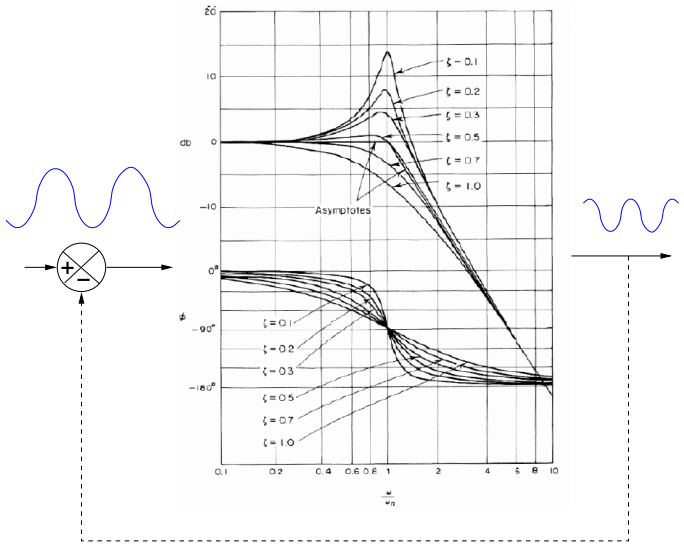

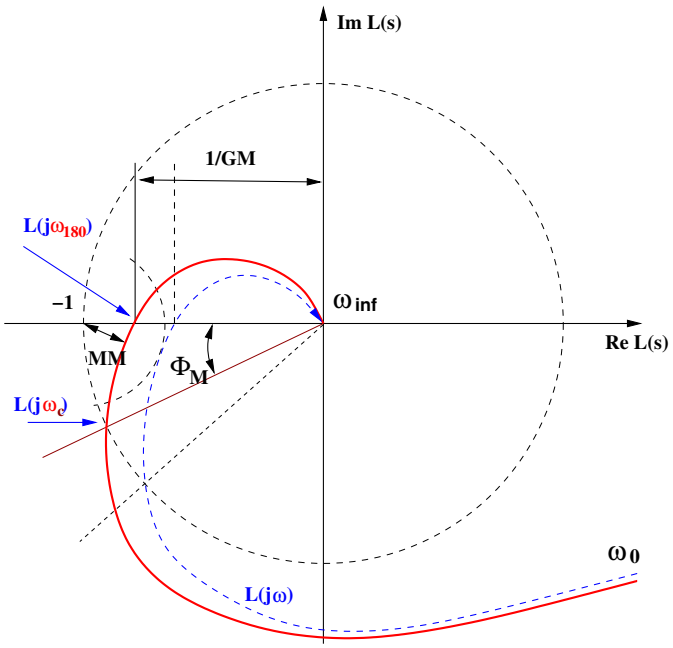

Robustness assessment for Linear SISO systems :

- gain margin, phase margin
- delay margin $\frac{\Phi_M}{\omega_c}$
- module margin
- jitter margin

Jitter and control

Jitter is claimed to be harmful. . .

. . . how to minimize jitter?

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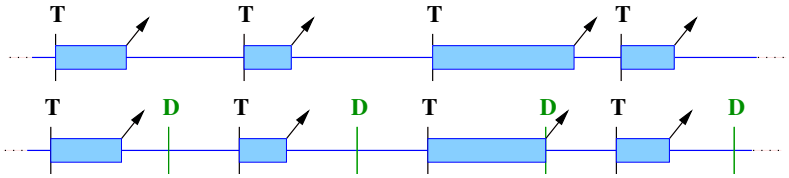
Comparative Assessment and Evaluation of Jitter Control Methods, G. Buttazzo and A.Cervin, RTNS 2007.

Strategies to reduce jitter :

- RM, send control ASAP
- DM, advanced deadlines
- Non-Preemptive scheduling



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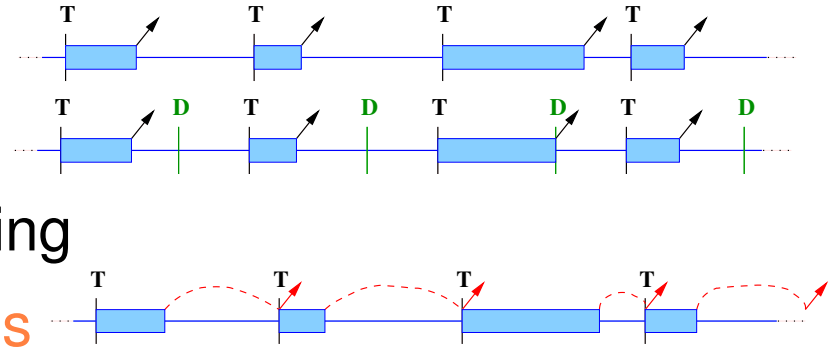

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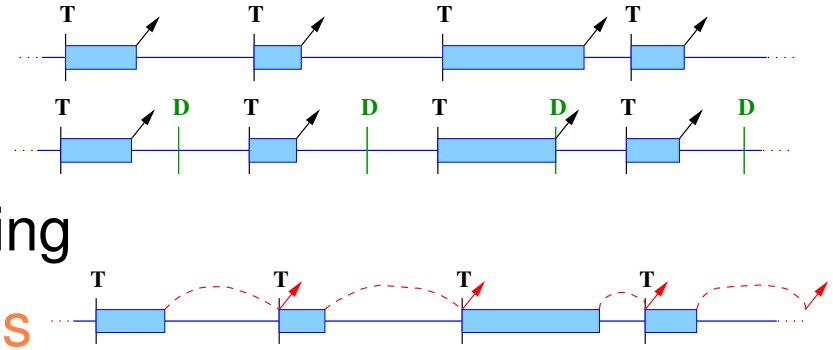


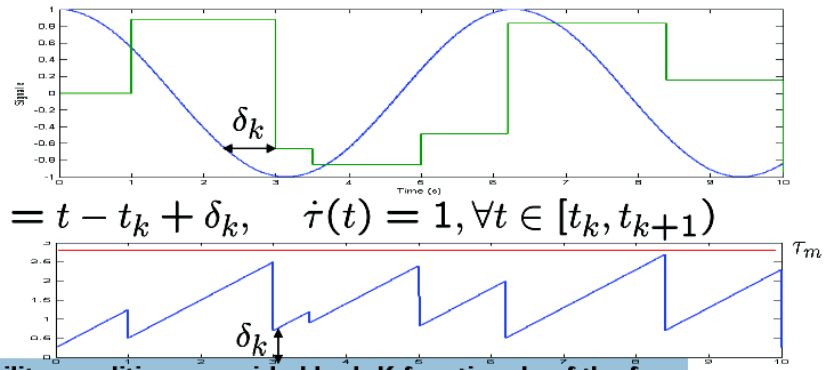
$\Rightarrow$ add a systematic delay

null jitter, but worst control performance!

Control of systems with delays

Generalization to MIMO sampled data systems :

Fridman et al, 2004, Naghshtabrizi et al 2007, Seuret 2009



$$\tau(t) = t - t_k + \delta_k, \quad \dot{\tau}(t) = 1, \forall t \in [t_k, t_{k+1})$$

Stability conditions provided by L-K functionals of the form

$$V(\tau(t), x_t) = x^T(t)Px(t) + (\tau_m - \tau(t)) \int_{t_k}^{t} \dot{x}^T(s)R\dot{x}(s)ds$$
$$+(\tau_m - \tau(t))(x(t) - x(t_k))^T S(x(t) - x(t_k))$$

$\dot{V}(\tau(t), x_t) = \ldots < 0$ **Sufficient conditions (LMI)**

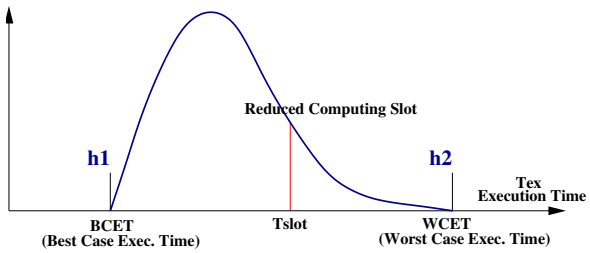
Continuous-time approaches using **Lyapunov Theorem:** takes into account **time-varying delays, data loss, plant uncertainties, actuators saturations,...**

...See for instance, Fridman, Seuret, Richard, Naghstab...

Robust control and scheduling

Slackened real-time scheduling (with A. Seuret - Gipsa&LAAS)

CIFRE Airbus, EU patent 11306103.0-2224



- Saves computing cycles
- Reduced latencies

- Deadline miss
- Sampling disturbances

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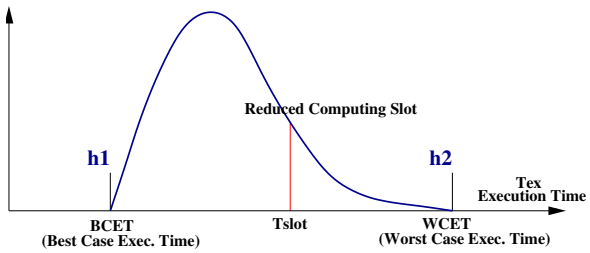

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- N, max. consecutive deadline miss?
- T_{slot} for a given failure rate?

$$\dot{x}(t) = (A+\Delta_\mu A(t))x(t)+(B+\Delta_\mu B(t))u(t)$$

Stability of systems with delays, varying sampling and uncertainties (Lyapunov-Krasovskii functionals)

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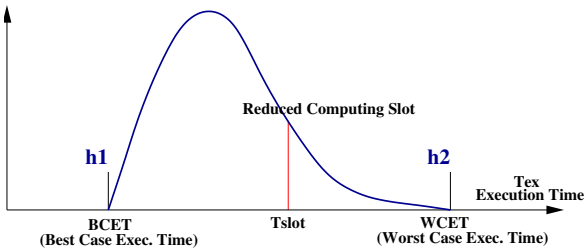

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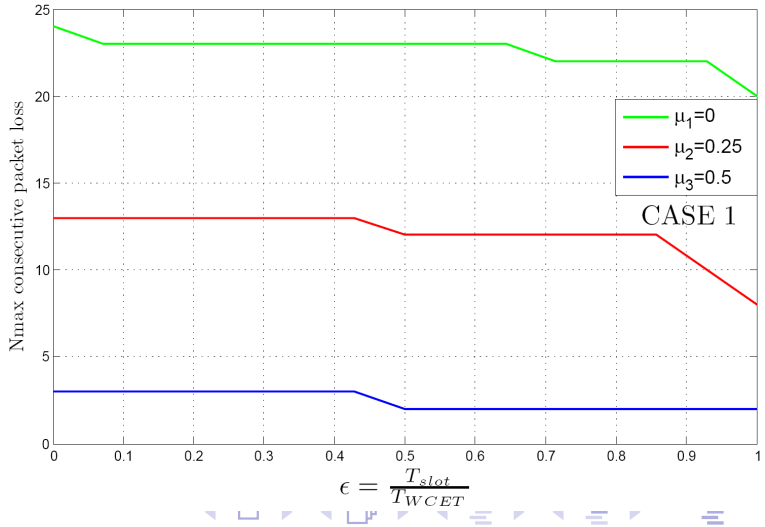
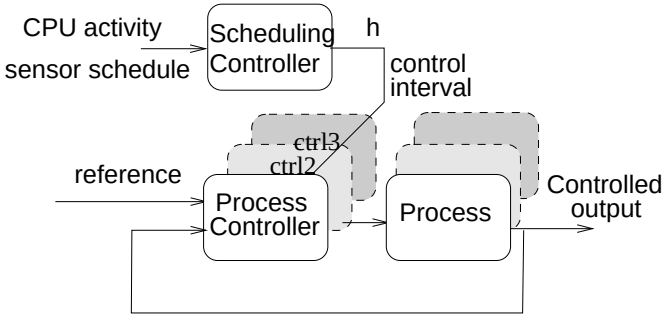


Computing-aware control: Adaptive control rate



- CPU load adaptation using varying control intervals
- frequency scaling capabilities of modern chips
- accommodation with scheduled sensors
- stability whatever h change $h \in [h_{min}, h_{max}]$
- specified performance level

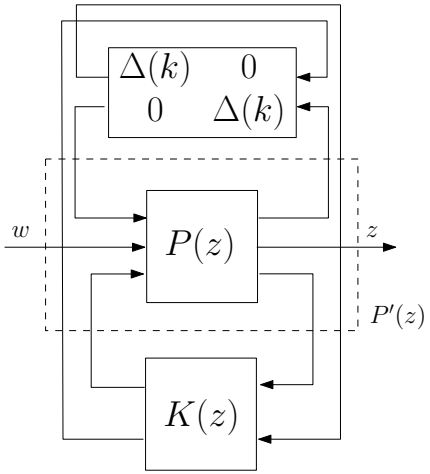
self triggered, event triggered, switched systems,Lyapunov, Lie algebras, . . .

Computing-aware control: Adaptive control rate

Control with varying intervals:

Linear Parameter Varying (with O. Sename - Gipsa-lab)

- LPV model, h is a varying parameter (among others)
- H_∞ synthesis with frequency dependent templates



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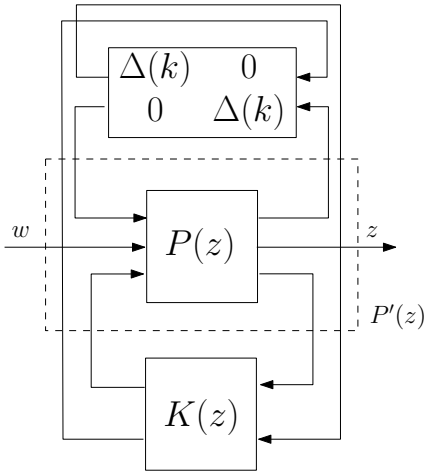
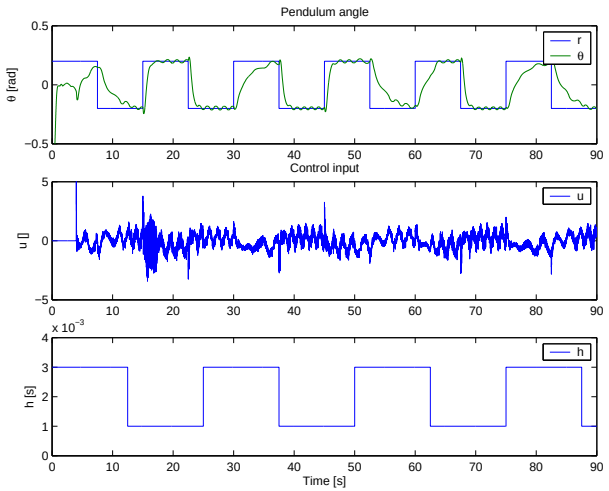
Control with varying intervals:

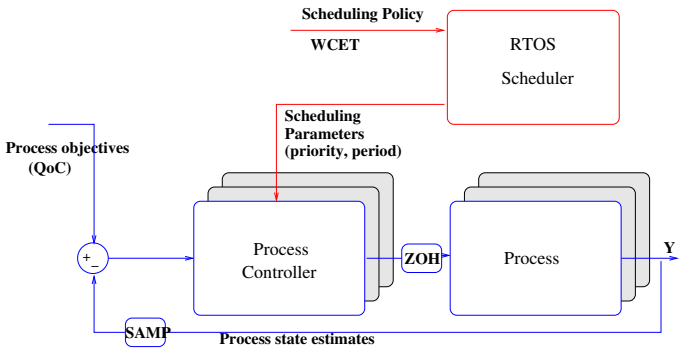
Linear Parameter Varying (with O. Sename - Gipsa-lab)

- LPV model, h is a varying parameter (among others)
- H_∞ synthesis with frequency dependent templates
  - sampling dependent robust controller K(z,h)
  - implementation with standard RT tools
  - easy integration in QoS layer





Control-aware computing



- Software architecture
  - Application analysis -> reducing latencies on critical paths
  - off-line optimization
- Control aware flexible scheduling policies
  - weakly-hard constraints
  - (m, k)-firm dropping policies
  - Control-aware QoS, e.g. elastic tasks
  - Bandwidth allocation: Control Server

Control task structure

- Splitting the control algorithm
- Relative urgency/importance
- Latency reduction on critical paths

while(1){
 Wait-Clock
 A/D-Conversion
 Calculate-Output $u(k) = f(y(k), \hat{x}(k-1), ...)$
 Update-State $\hat{x}(k) = g(y(k), \hat{x}(k-1), ...)$
 D/A-Conversion
}

Control task structure

- Splitting the control algorithm
- Relative urgency/importance
- Latency reduction on critical paths

while(1){
 Wait-Clock
 A/D-Conversion
 Calculate-Output $u(k) = f(y(k), \hat{x}(k-1), ...)$
 D/A-Conversion
 Update-State $\hat{x}(k) = g(y(k), \hat{x}(k-1), ...)$
}

Control task structure

- Splitting the control algorithm
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Control task structure

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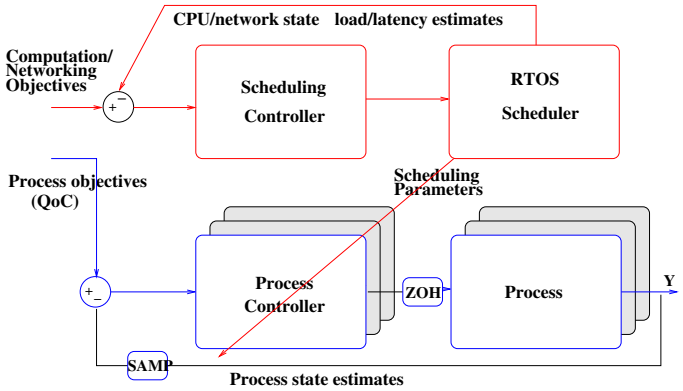
}

- Fast stabilizing loop/ slow navigation loop
- Implementation : multitasking/multi-rate (Orccad features)

Flexible scheduling policies

- Finding scheduling parameters?
  Cost functions period/delay w.r.t. performance
- Off-line non-linear optimization (simplex)
- Bandwidth allocation: Control Server
  each controller reserves a CPU fraction (CBS)
- Minimization of QoS : Elastic Tasks
  QoS sensitivity w.r.t. period (stiffness)

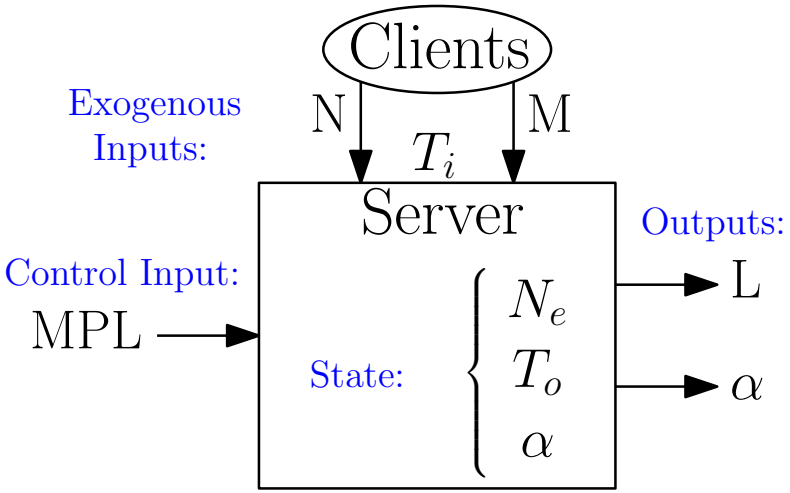
Control aware computing: Feedback scheduling

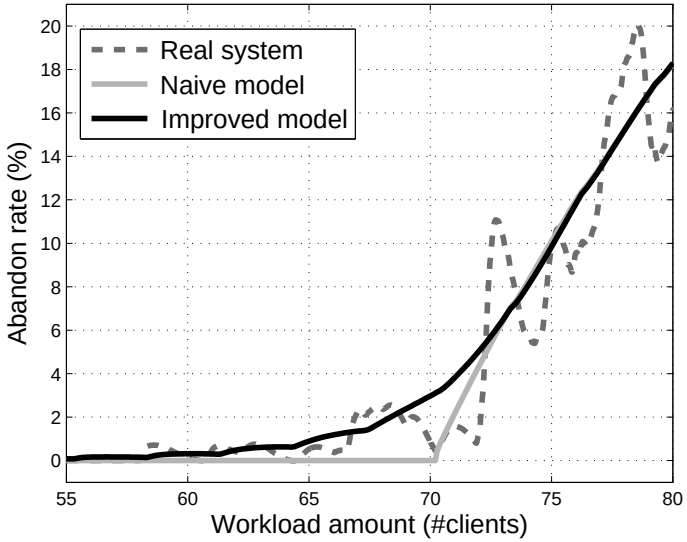


Feedback schedulers :

- Control of the scheduling parameters
- Simple dynamics, complex data sets
- Discrete process, fluid models
- Free sensors and actuators

Web server modeling





input/output latency:

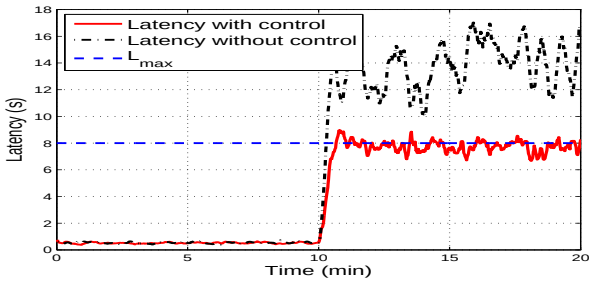
$$L(N_e, M, t) = a(M, t)N_e^2 + b(M, t)N_e + c(M, t)$$

rejection rate: $\dot{\alpha}(t) = -\frac{1}{\Delta}\left(\alpha(t) - \frac{N_e(t)}{AC(t)} \cdot \left(1 - \frac{T_o(t)}{T_i(t)}\right)\right)$

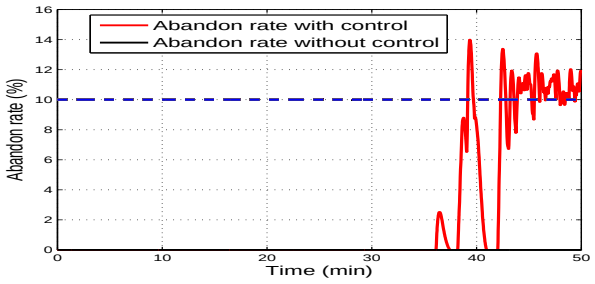
Control objectives

- Maximizing availability $AC = \frac{N_e}{1+\gamma_L(L-L_{\max})}$
- Maximizing performance $AC = \frac{\alpha N_e}{\alpha-\gamma_\alpha(\alpha-\alpha_{\max})}$

γ_L and γ_α : tuning parameters



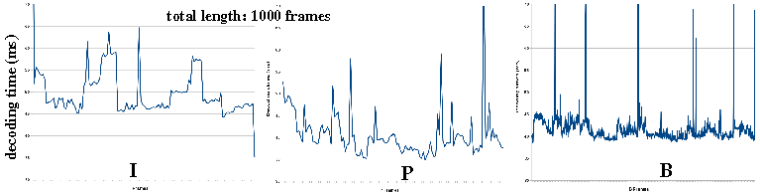
(a) Performance - Latency

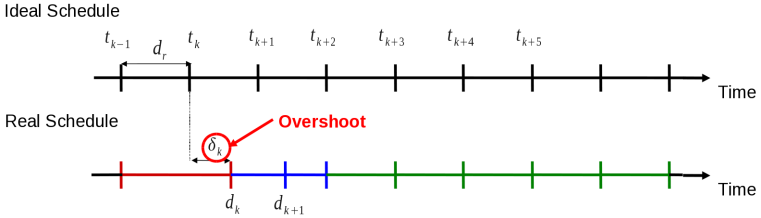


(b) Availability - Rejection rate

Control of a H.264 video decoder

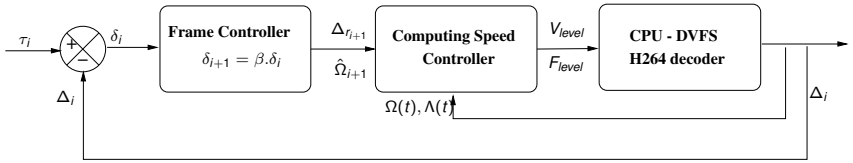
Statement:
Constant display rate (25 fps)
Decoding several frames ahead of display





Model: $\hat{q}_{k+1} = (1-\alpha)\hat{q}_k + \alpha q_{k-1}$

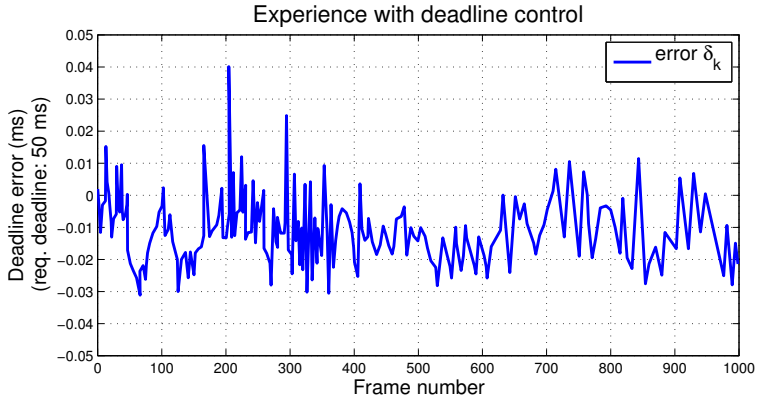
Frame controller : Damping of frames decoding overruns

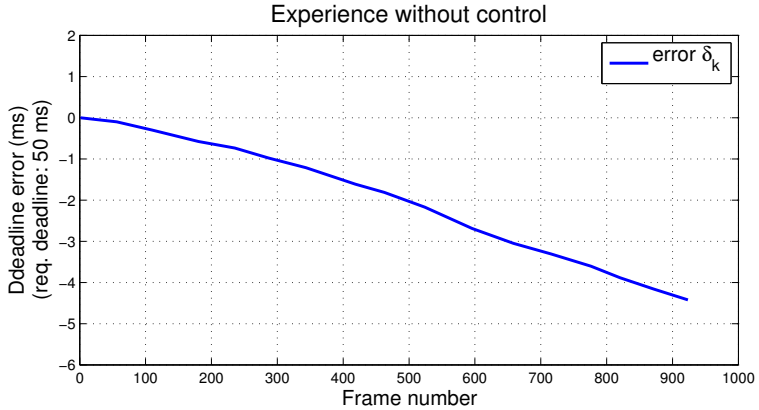


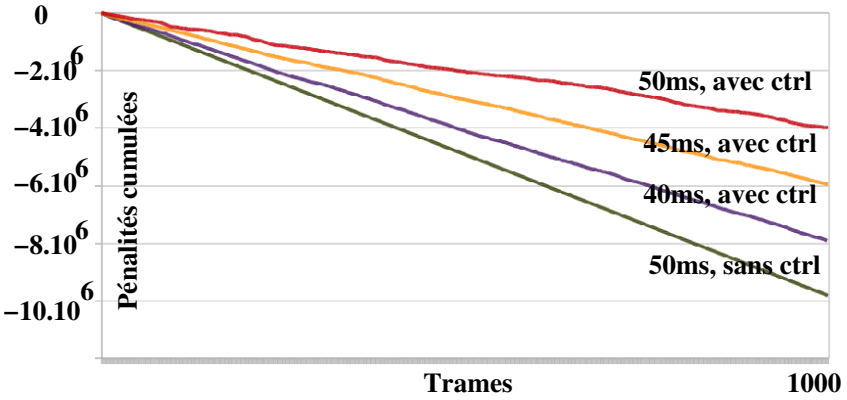
$$d_{r_{k+1}} = t_{k+1} + \beta \times \delta_k, \quad 0 < \beta < 1$$

Control of a H.264 video decoder

Implementation under Linux, Posix Real-time library

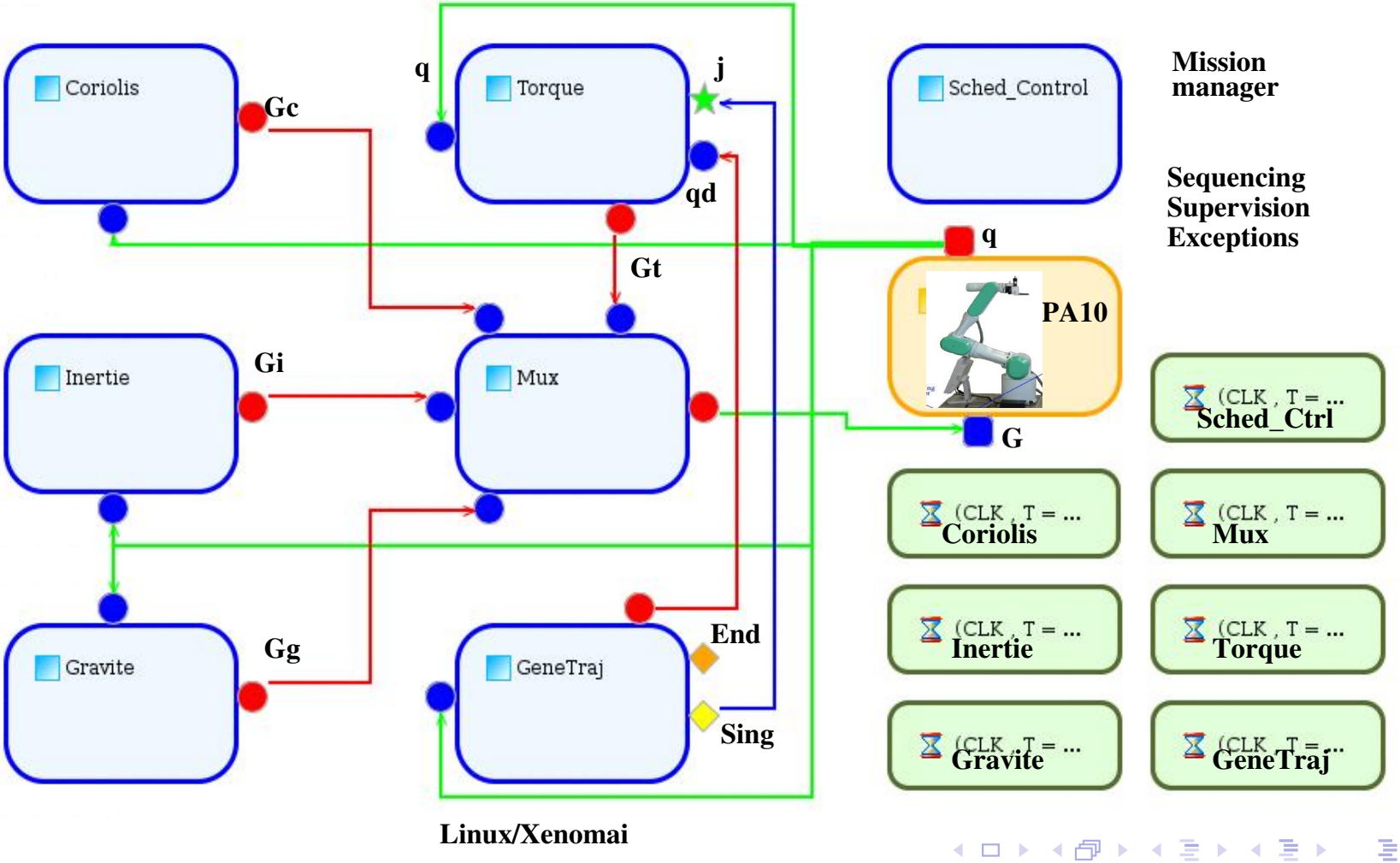




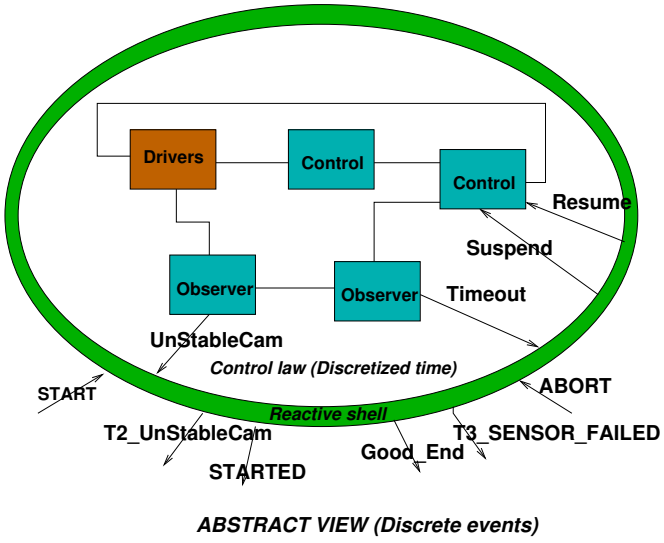


estimated energy saving:
upto 24 %

Feedback scheduling a robot controller



The ORCCAD model



RobotTasks

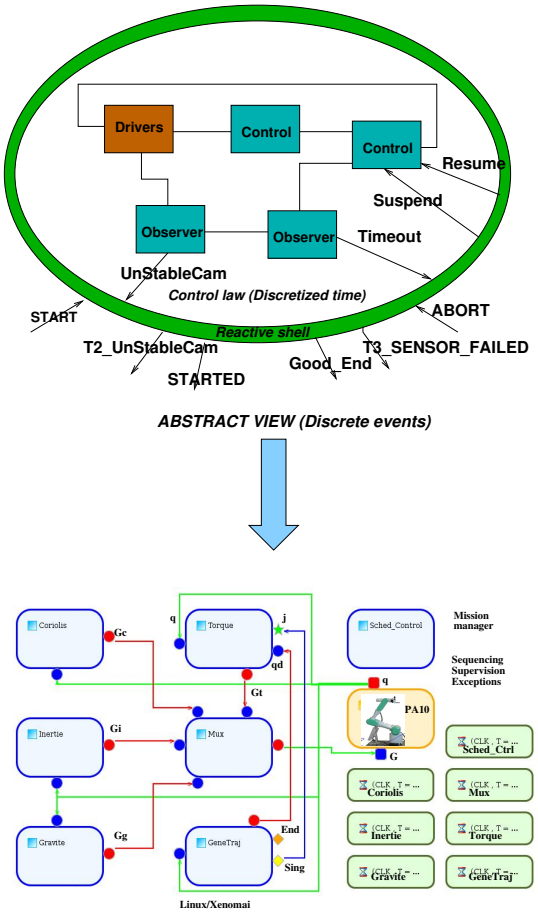
- Feedback Control
- Cyclic real-time data flow
- Event-based view

RobotProcedures

- Discrete Events Control
- Incremental design
- Exception processing
- Mission definition

Bottom up approach, from control to applications

The ORCCAD model



Feedback control action

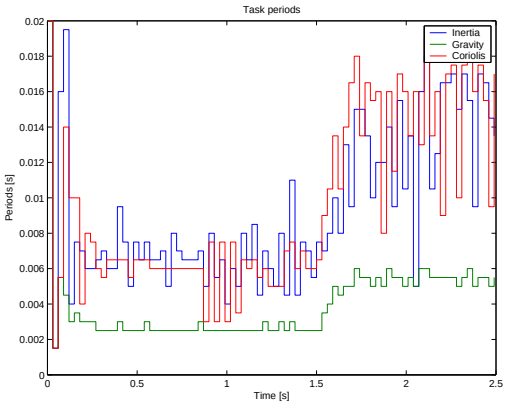
- Control algorithm definition
- Invariant structure for RT life
- Modular design
- Functional parameters
- Timing parameters

Event based behaviour

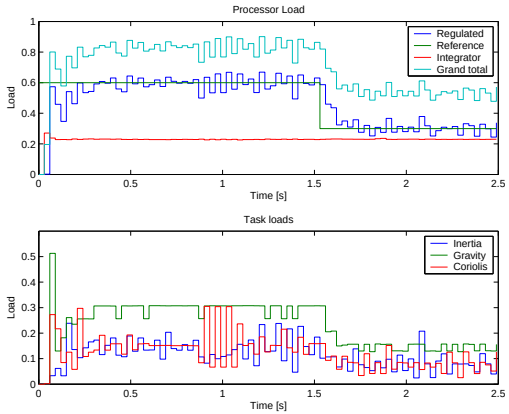
- Precondition (opt. timeout)
- Synchronization
- Exceptions
  - Weak T1
  - Strong T2
  - Fatal T3

Postcondition (opt. timeout)

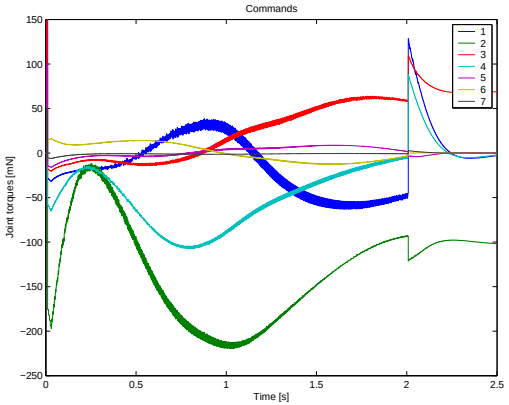
Feedback scheduling a robot controller (Cont'd)



Intervals



CPU load

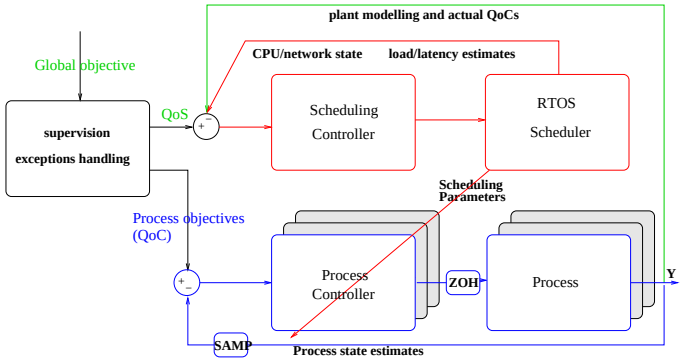


Torques

Cost of the FS < 1%

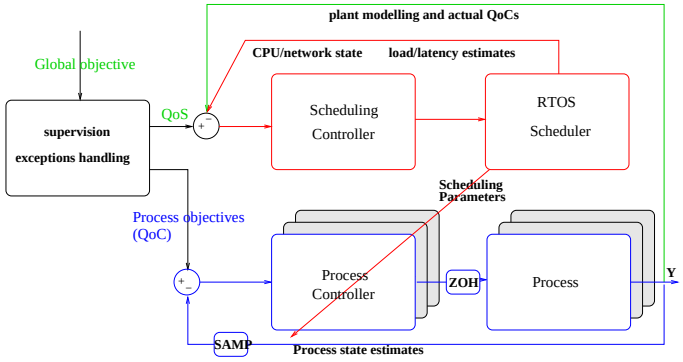
- Negligible or moderate computing cost
- Robust w.r.t. deadlines miss
- No further need for wcet evaluation :=)
- Feasible with off-the-shelf hard/soft

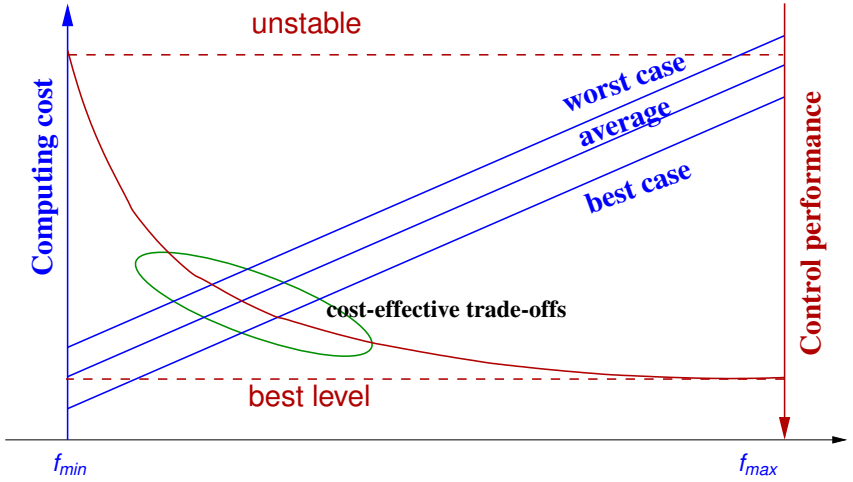
Integrating Control and Scheduling



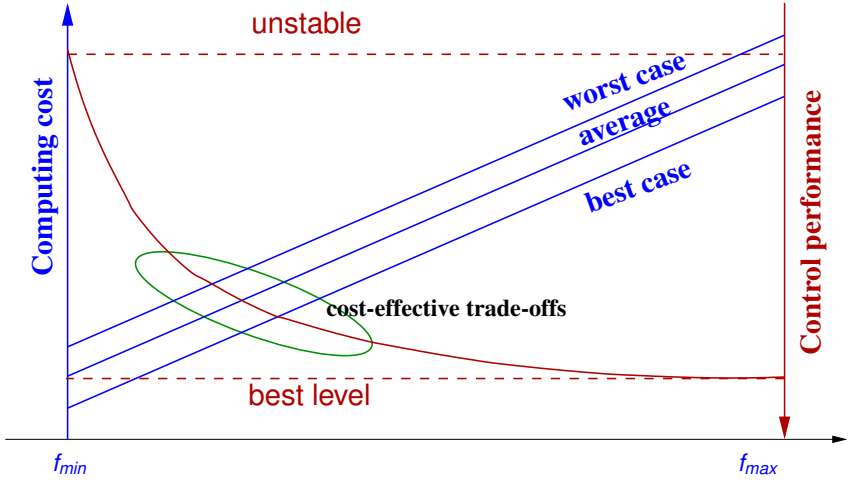
- Hybrid complex dynamics
- Non convex cost functions
- QoS formulation gathering control and computing
- Case studies :
  - LQ control + (m, k)-firm policy
  - Feedback scheduled MPC
  - H_∞ varying sampling + elastic scheduler
  - Convex optimization for LQ period selection
  - Asynchronous (event-based) control

Integrating Control and Scheduling





Integrating Control and Scheduling



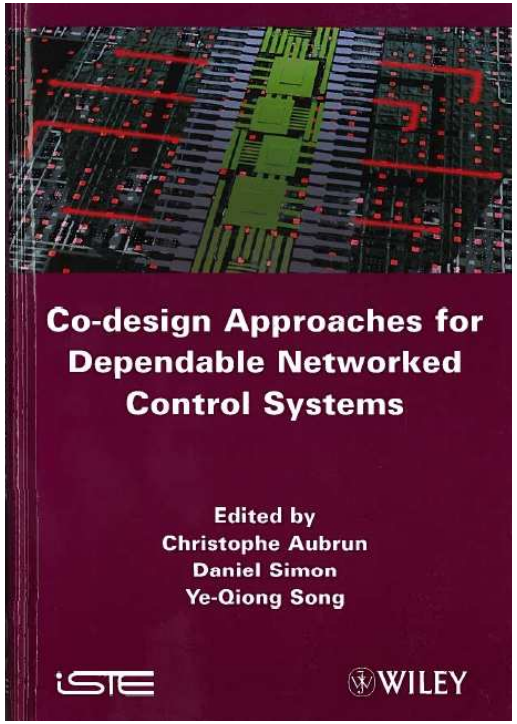
- Cost effective implementation of real-time control
- Average cases rather than worst cases
- Self-management of computing devices
- New viewpoint on control systems safety
- Provability, Certification?

any questions?

Ordonnancement dans les Systèmes Temps Réel
Hermes, Maryline Chetto ed., 2014

Chapitre 11: Conception conjointe
commande-ordonnancement

any questions?



Thank you for your attention