Nonlinear hybrid control: from theoretical foundations toward leading edge applied solutions

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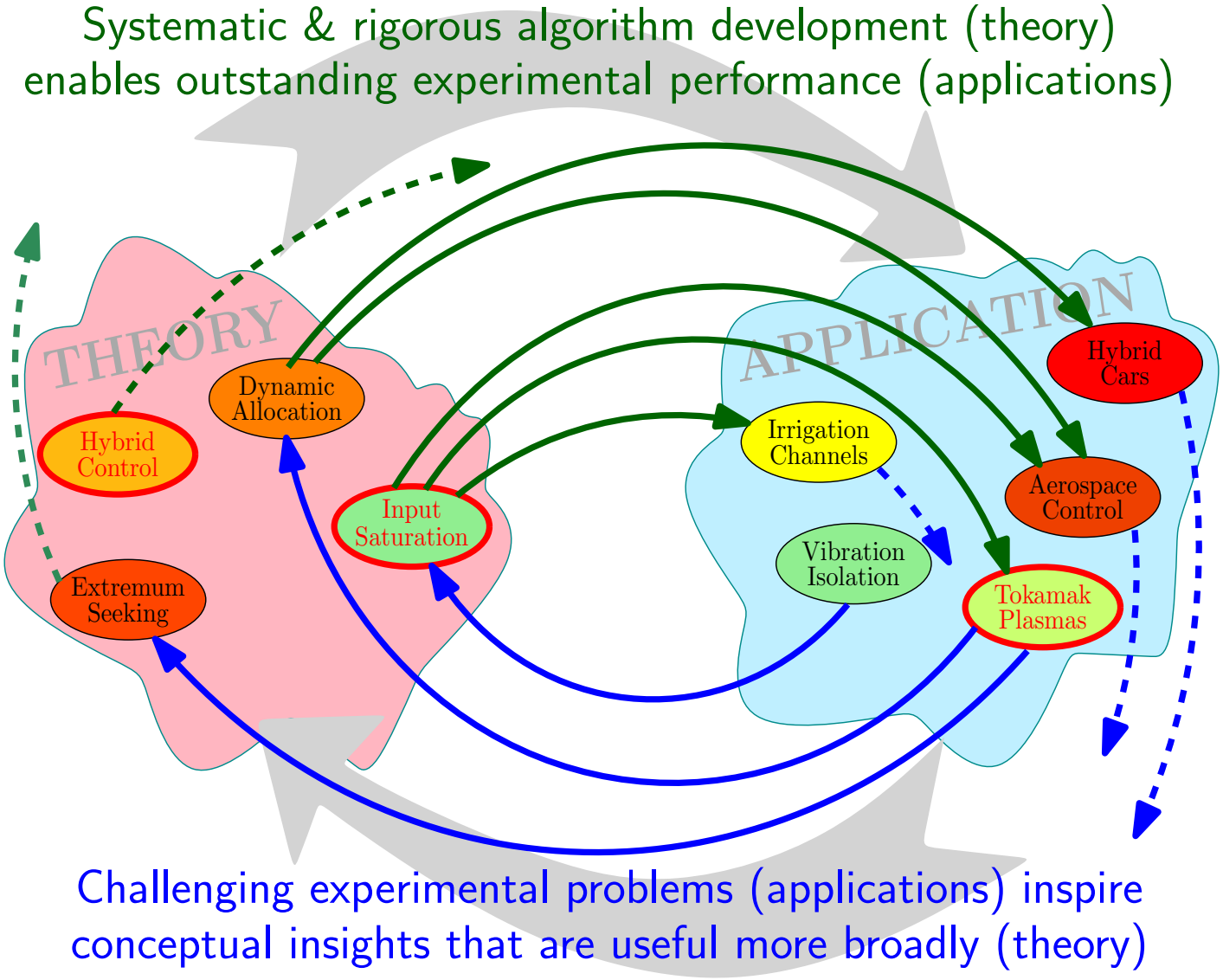
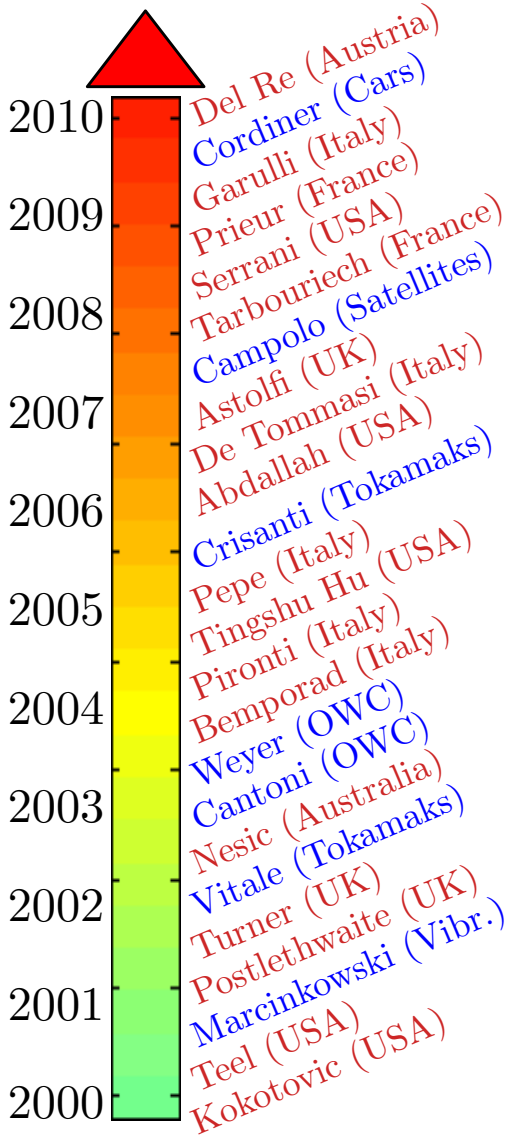
Candidature au poste de Directeur de Recherche CNRS
Paris, April 12, 2011

Interplay between applications/theory sustains my research

Systematic & rigorous algorithm development (theory)
enables outstanding experimental performance (applications)



Challenging experimental problems (applications) inspire
conceptual insights that are useful more broadly (theory)

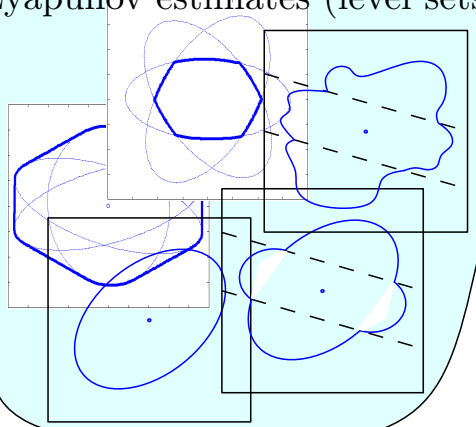


Input saturation interplay provided fertile research ground

[Glattfelder, Jabbari, Megretski, Lin, Sontag, Stoorvogel, Tarbouriech, Turner, ...]

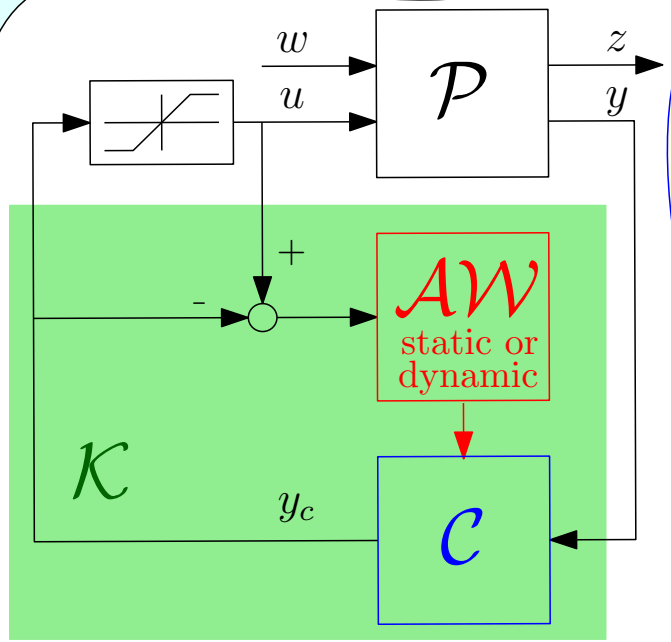
CONVEX OPTIMIZATION – LINEAR MATRIX INEQUALITIES

Performance Assessment
[IEEE-TAC '06, IFAC-WC '11]
H_∞ norm $\Rightarrow$ Nonlinear $\mathcal{L}_2$ gain
$\|z\|_2 \le \gamma_{dz}(s)\|w\|_2,\ \forall \|w\|_2 \le s$
Lyapunov estimates (level sets)



Optimal design of $\mathcal{K}$
[Automatica 2009]
Given $\mathcal{P}$ linear, design
$\mathcal{C}, \mathcal{AW}$ linear solving
$\min_{\mathcal{C},\mathcal{AW}} \gamma_{dz}(s^*)$ *s.t.*
$\|z\|_2 \le \gamma_{dz}(s^*)\|w\|_2,\ \forall \|w\|_2 \le s^*$
Gemeralizes H_∞ control

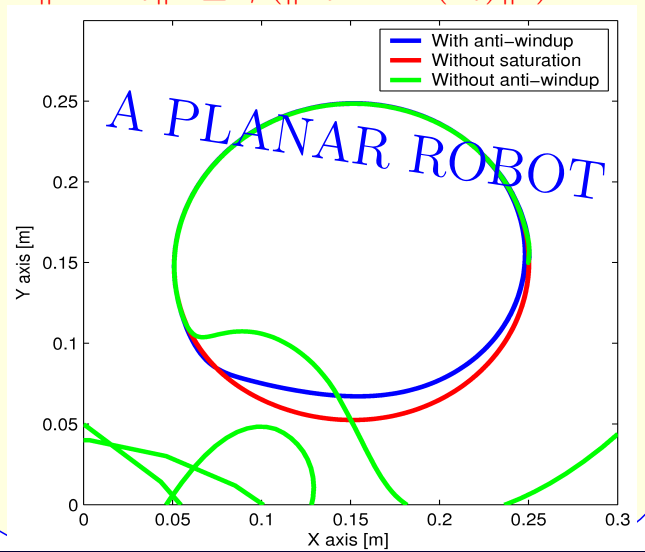
Linear Anti-Windup design
[IEEE-TAC '03, Automatica '05, '08]
Given $\mathcal{P}, \mathcal{C}$ linear, design
$\mathcal{AW}$ linear solving
$\min_{\mathcal{AW}} \gamma_{dz}(s^*)$ *s.t.*
$\|z\|_2 \le \gamma_{dz}(s^*)\|w\|_2,\ \forall \|w\|_2 \le s^*$



[Zaccarian, Teel,
Modern Anti-Windup Synthesis,
Princeton University Press, 2011]

CONSTRUCTIVE NONLINEAR CONTROL

Nonlinear Anti-Windup design
[Automatica '02, '04, IEEE-TAC '04,
SCL '07, '08, IEEE-TRA '04]
Given $\mathcal{P}, \mathcal{C}$ nonlinear, design
$\mathcal{AW}$ nonlinear solving
$\|z - z_\ell\|_2 \le \gamma\left(\|u_\ell - \mathrm{sat}(u_\ell)\|_2\right)$



Bumpless Transfer
[Automatica '05]
Plants $\mathcal{P}$ with input delay
[SCL '05]
Rate Saturation
[SCL '08]
Time-Optimal control
[IEEE-TAC '10]

EXTENSIONS

From continuous + discrete to hybrid dynamical systems

[Branicky, Collins, Henzinger, Liberzon, Lygeros, Sastry, Tavernini, Teel, Van der Schaft ...]

Continuous dynamical system $\frac{dx(t)}{dt} = f(x(t)),\ \forall t \in \mathbb{R}_{\geq 0}$

Discrete dynamical system $x(k+1) = g(x(k)),\ \forall k \in \mathbb{Z}_{\geq 0}$

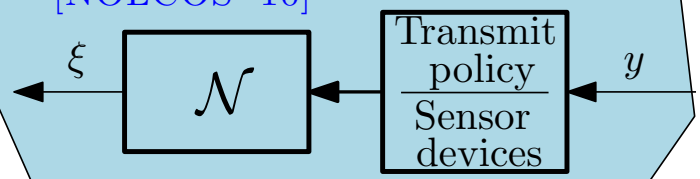
Hybrid dynamical system $\Downarrow$

$$\begin{cases} \frac{dx(t,k)}{dt} = f(x(t,k)), & \text{if } x(t,k) \in F \subset \mathbb{R}^n \text{ (a.e.)} \\ x(t,k+1) = g(x(t,k)), & \text{if } x(t,k) \in G \subset \mathbb{R}^n \end{cases}$$

Continuous t and Discrete k merged into Hybrid time $(t,k) \in \mathbb{R} \times \mathbb{Z}$

Event-triggered transmission on control networks

[NOLCOS '10]



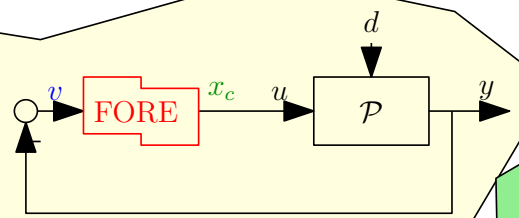
$\xi^+ = y$ if $f(x,y) \leq 0$

Reset Control Systems

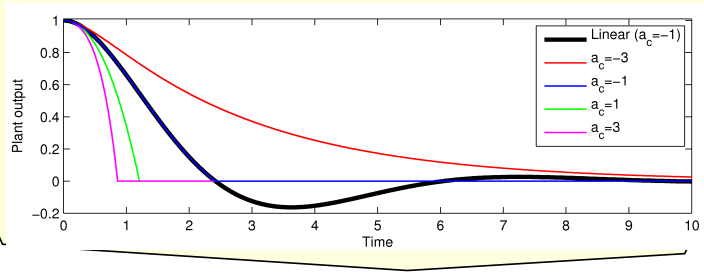
[Automatica '08, IEEE-TAC '11]

Revisited Clegg integrators (1958)

$\lim_{\lambda_{FORE} \to +\infty} \gamma_{dy} = 0$



Improve performance (e.g., remove overshoot)

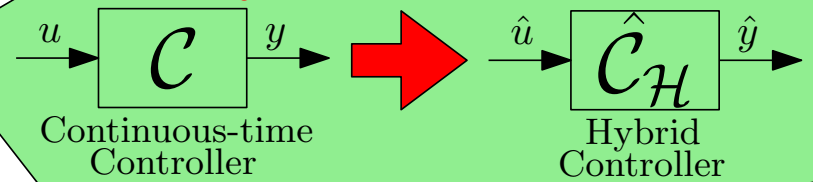


Reset passivation of controllers

[Automatica '11]

Given $\mathcal{C}$ embed resets to passivate it

$$\int_0^\infty \hat{y}(t)^T \hat{u}(t) dt \geq \varepsilon_2 \|\hat{y}(\cdot)\|_2^2$$



Continuous-time Controller

Hybrid Controller

Sampled-data control systems

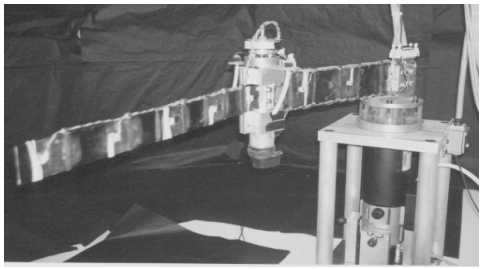
[ACC '10]

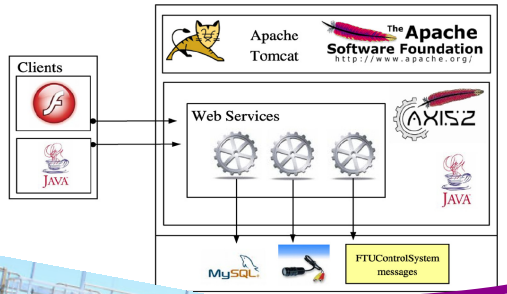
Hybrid loops design for performance improvement

[NOLCOS '10, IFAC '11]

Experimental challenges inspired and benefited from theory

Control of flexible robots
[IEEPROC '98, KYBERNETICA '99]
Addressing lightweight structures





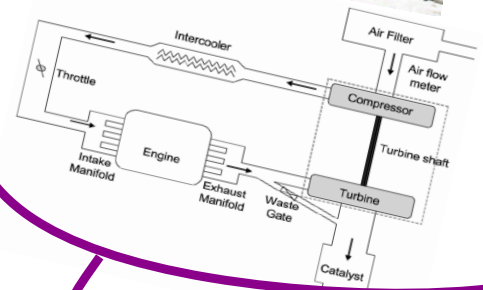
Real-time software architectures
[IEEE-TNS '04, FED '04, '05, '07, '08]
Necessary insight to propose
Innovative control solutions

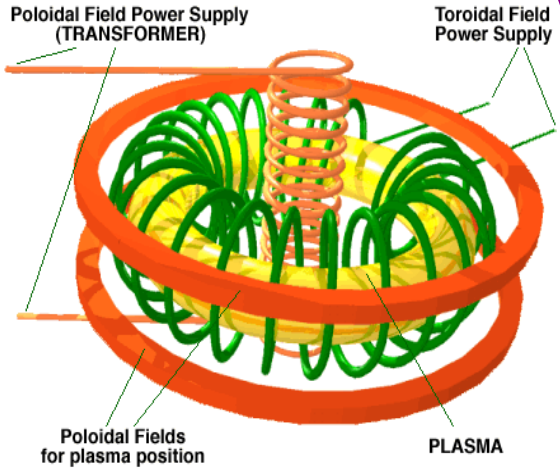
Vibration isolation and suppression
[EJC '00, CEP '06]

Control of irrigation channels
[CEP '07]

Control of hybrid cars
[CDC '10]

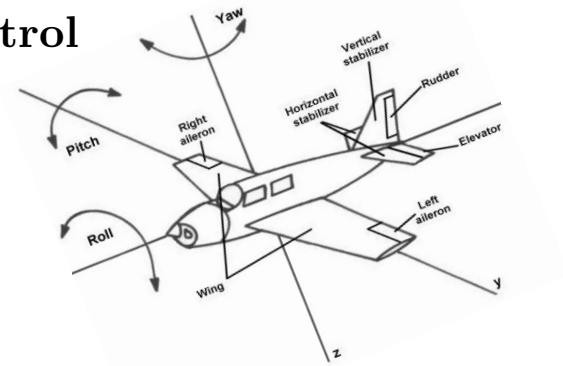
Internal Combustion Engine control
[IN PROGRESS]





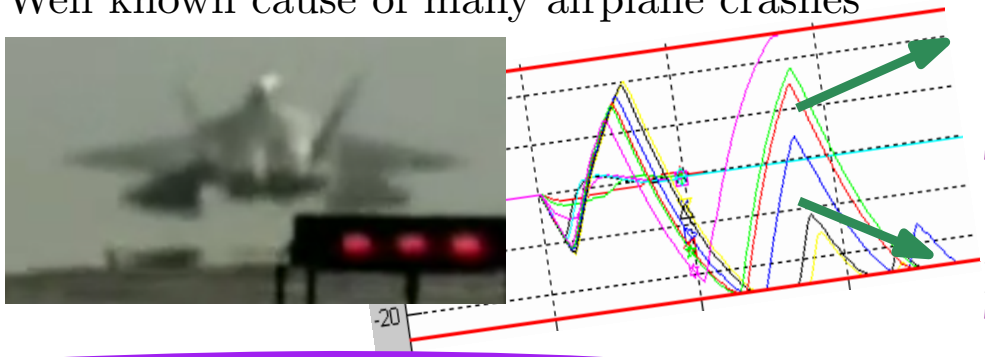
Control of Tokamak Plasmas
[CEP 08, IEEE-TPS '10,
AUTOMATICA '11, IEEE-TCST '11]
Regulation and estimation problems

Satellite and aircraft control
[IJC '05, AIAA GNCC '11]

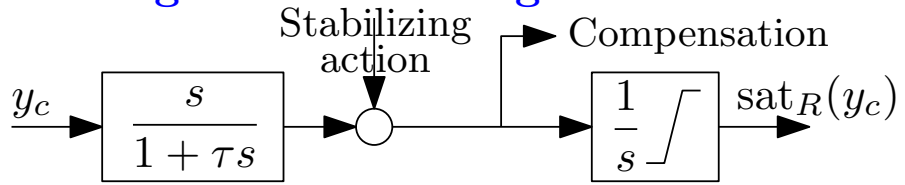


Nonlinear hybrid solutions for aerospace systems @ LAAS

Input Rate Saturation handling
Well known cause of many airplane crashes



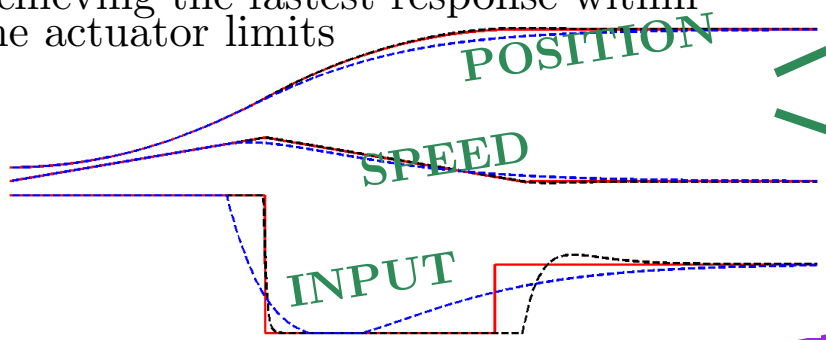
Enhancing saturated integrators



Tarbouriech (LAAS), Biannic (ONERA)

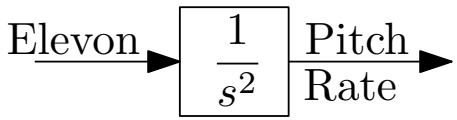
Nonlinear anti-windup for rate saturation
Preliminary results on high-performance aircrafts
Tarbouriech (LAAS), Burlion (ONERA)

Almost time-optimal control
Achieving the fastest response within the actuator limits



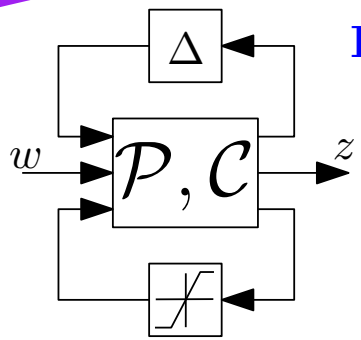
Satellite attitude control (reaction wheels)
Thales-Alenia (France)

High-performance flight control



Galeani (URTV), Tarbouriech (LAAS)

Saturated μ-analysis/synthesis
can extend current robust techniques used in the aerospace field to incorporate saturation effects

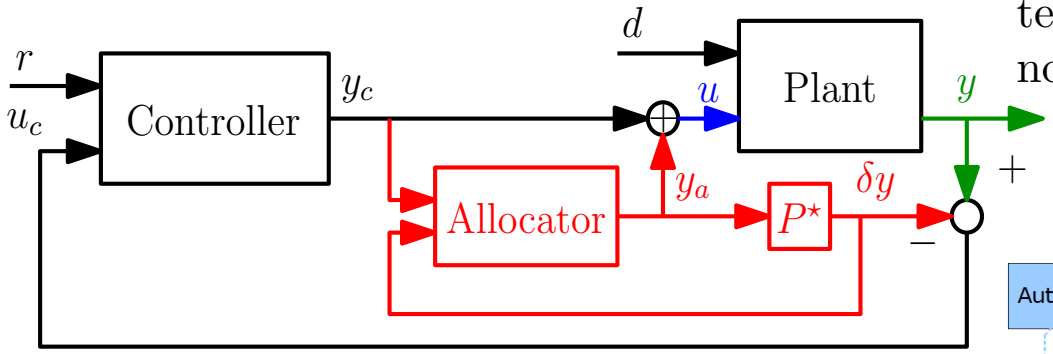


Design controllers achieving
robustness against structured perturbations, in the presence of saturation
Thales-Alenia (Italy)

Nonlinear hybrid solutions for aerospace systems @ LAAS

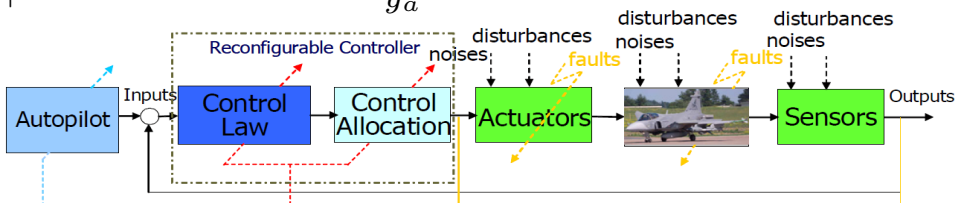
Nonlinear dynamic input allocation

Successful in Tokamaks and hybrid cars



Flight allocation Augment flight control systems with extra dynamics to induce desirable nonlinear plant input specifications, e.g.,

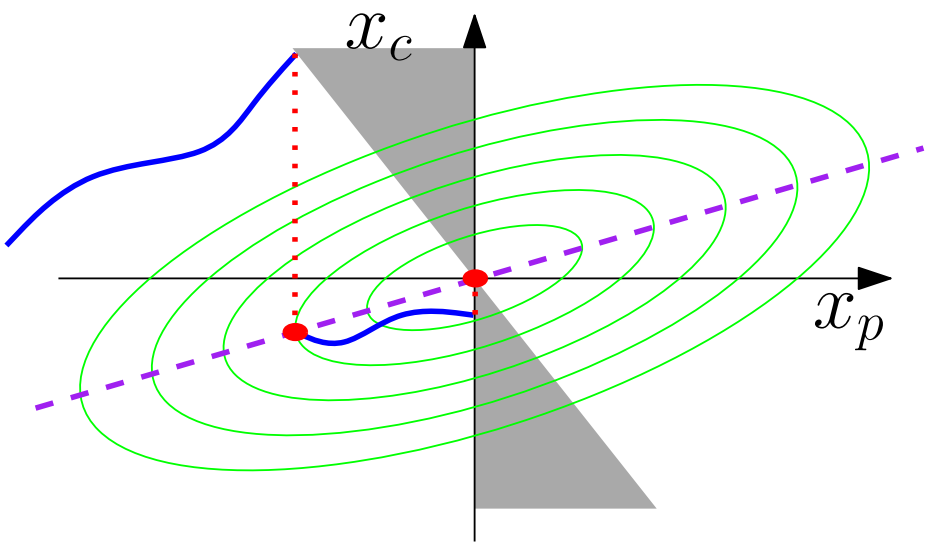
$$u^* = \arg\min_{y_a} J(y_c + y_a, \delta_y(y_a))$$



Overactuated regulator design applied to hypersonic aircrafts (using scramjet engines)

Preliminary Joint work with A. Serrani (Ohio State University, USA)

Hybrid control systems



Reset control Introduce jumps on the controller state when it belongs to certain regions ⇒ improve performance (e.g., reduce overshoot).

Tarbouriech (LAAS), Prieur (GIPSA-LAB)

Hybrid dynamical models/controllers

Exploit recent results on flow and jump dynamics to better describe/control physical plants. Use:

$$\dot{x} = f(x), \text{ if } x \in F$$
$$x^+ = g(x), \text{ if } x \in G$$

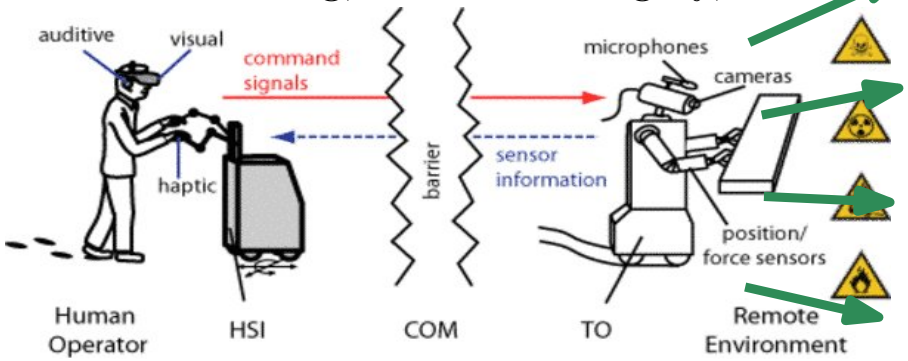
Joint work with Teel (USA), Nesic (Australia)

Nonlinear hybrid solutions for robotic systems @ LIRMM

[Several interesting topics emerged from a visit to LIRMM]

Remotely operated robots

Remote handling, robotized surgery,...



Handle actuator saturations

Use anti-windup for Euler-Lagrange systems

Ensure human-machine interaction stability

Adopt hybrid reset passivation techniques

Compensate communication channel delays

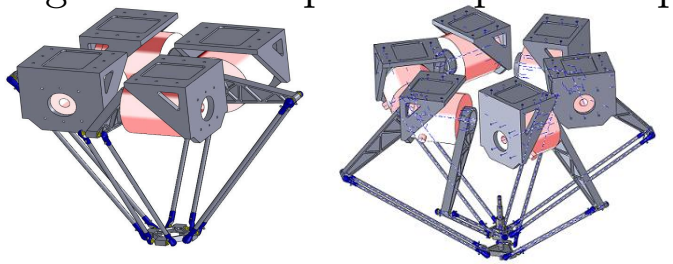
Use enhanced Smith predictors schemes

Reduce communication channel usage

Use hybrid event triggered transmission policies

Fast positioning systems

Achieving the fastest possible pick and place



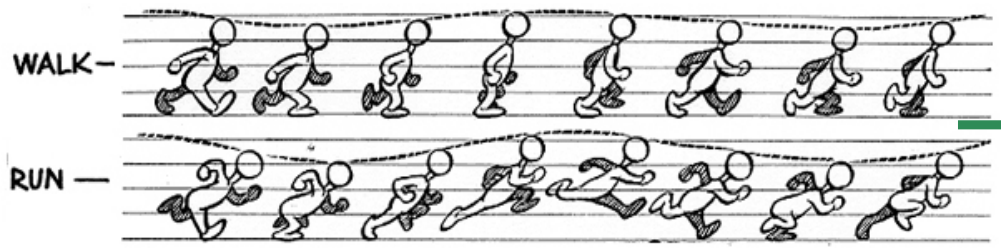
Fully exploit the available actuator power

Use Almost-time optimal control strategies

Suppress structural vibrations effects

Use modelling of elastic robots with similar tools to flexible aerospace systems (satellites)

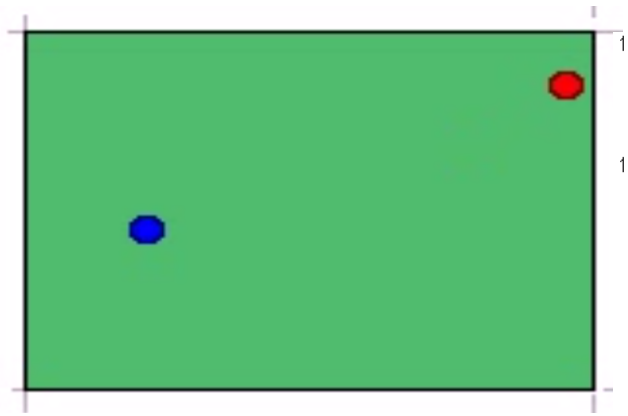
Walking and running humanoid robots - impacting robots



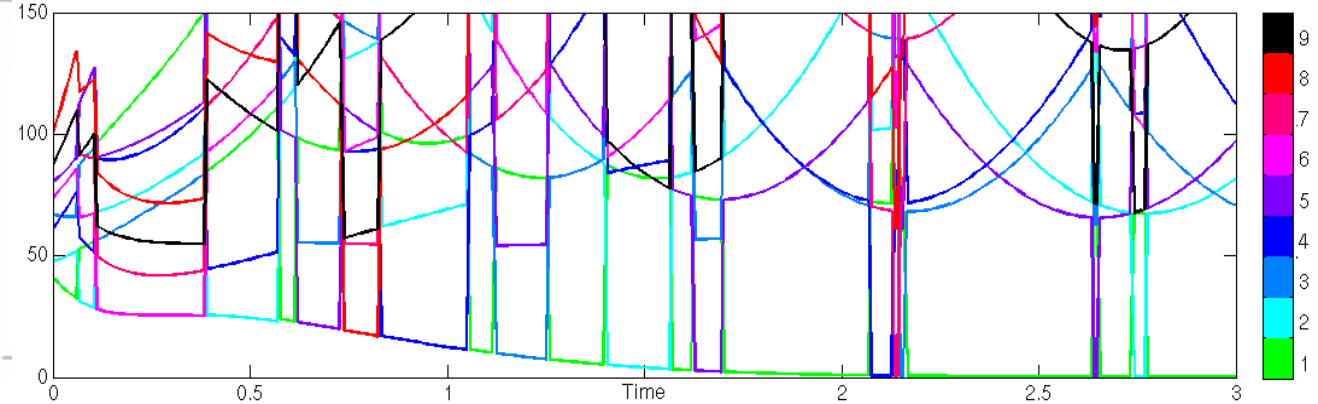
Use hybrid systems approach

see next slide for a very recent novel approach to the problem of impact mechanics

A hybrid highlight: ball x tracks billiard ball z



Lyapunov functions $V_i(x, z)$ along hybrid trajectory



Linear Feedback
Hybrid Feedback →

Idea: Follow the "closest" ball among all the target balls z mirrored by the walls

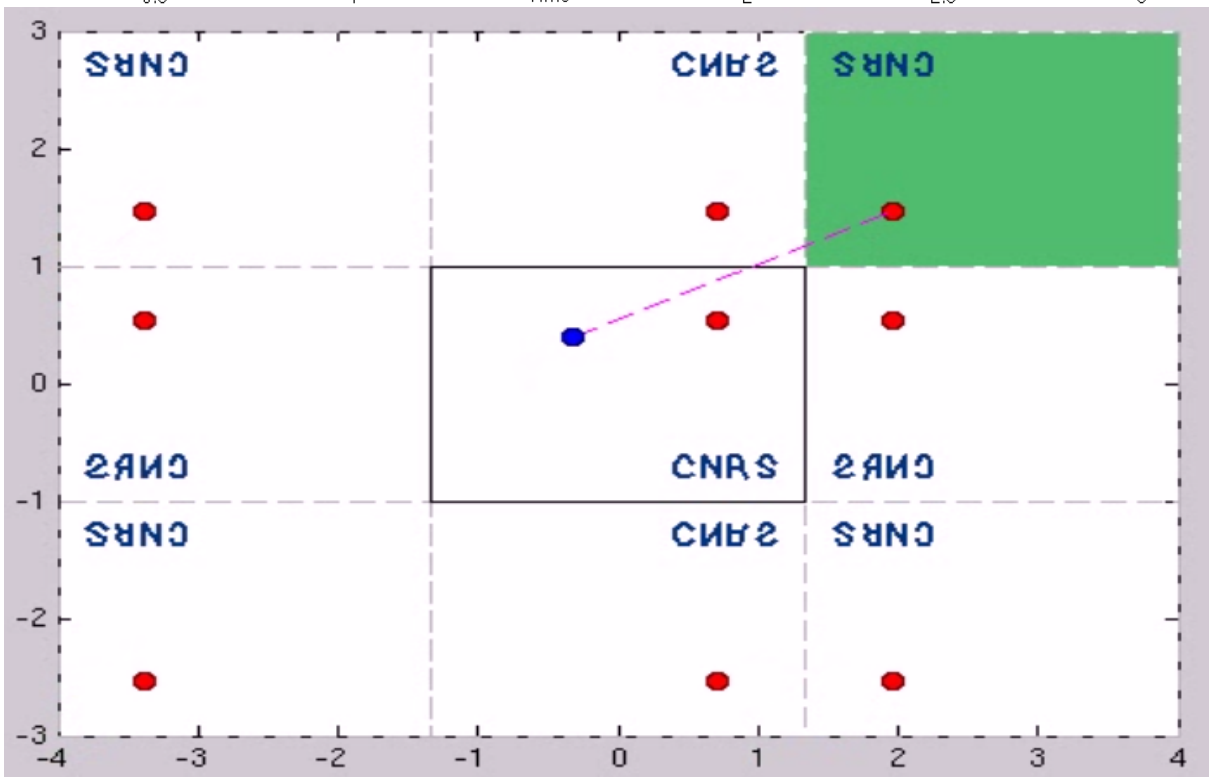
Use Hybrid Lyapunov function

$$V(x,z) = \min_{i\in\{0,\ldots,9\}} \underbrace{|x - m_i(z)|_P}_{V_i(x,z)}$$

where

$m_0(z) = z$ (real ball)

$m_k(z) = M_k z + c_k$, $k = 1, \ldots, 8$ (mirrored balls)



Research Program – Nonlinear hybrid control: from theoretical foundations toward leading edge applied solutions

Candidate:	Luca Zaccarian, age 42, married, 2 children
Job Position:	Associate professor, University of Rome, Tor Vergata, Italy
Awards and Honors:	2001 AACC O. Hugo Shuck award (control application) IEEE Senior Member
Teaching:	Experimental Robotics, Systems & Control ($\approx$ 2.5 Kstudents)
Theoretical Research:	Saturated nonlinear control (38% of journal papers) Hybrid systems (8% of journal papers) Robotics/Lyapunov results (14% of journal papers)
Applied Research:	Real-time architectures (14% of journal papers) Tokamak plasmas (14% of journal papers) Applied nonlinear control (12% of journal papers)
Grants:	Tokamaks (Euratom), Aerospace (ThalesAlenia, EDA), USA (NSF), Australia (ARC), Italy (MIUR)
Editorial:	Syst. & Cont. Lett. AE, IEEE-CSS Conf. Editorial Board member
IPC/Organizer:	MED '98, MSC '08+'09, CDC '08+'09+'11+'12, ROCOND '12, ADHS '12, NOLCOS '13, workshop, spec. issue, invited session