From model-free control to HEOL setting

Cédric Join

Workshop on data-driven control and analysis of dynamical systems

UNIVERSITÉ DE LORRAINE

cedric.join@univ-lorraine.fr

September 30th-October 1st, 2025, ENSEEIHT, Toulouse, France

1/ Story of Model-Free Control

2/ Principles of Model-Free Control

3/ Academic examples

4/ Industrial examples

5/ What to do with a model

6/ Conclusions

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Historical background

Key elements

Algebraic estimation techniques, early 2000s, [MF, MM, HSR]

Creation of INRIA AL.I.E.N. team, 2004, [MF, CJ, MM, FO, AS]

Non-asymptotic estimation of noisy signals derivatives, 2005, [MF, CJ, MM, HSR]

First publication with model-free control, 2006, [MF, CJ, HSR]

Foundational article, 2013, [MF, CJ], citations > 1000

Collaboration of more than 20 years with Michel Fliess

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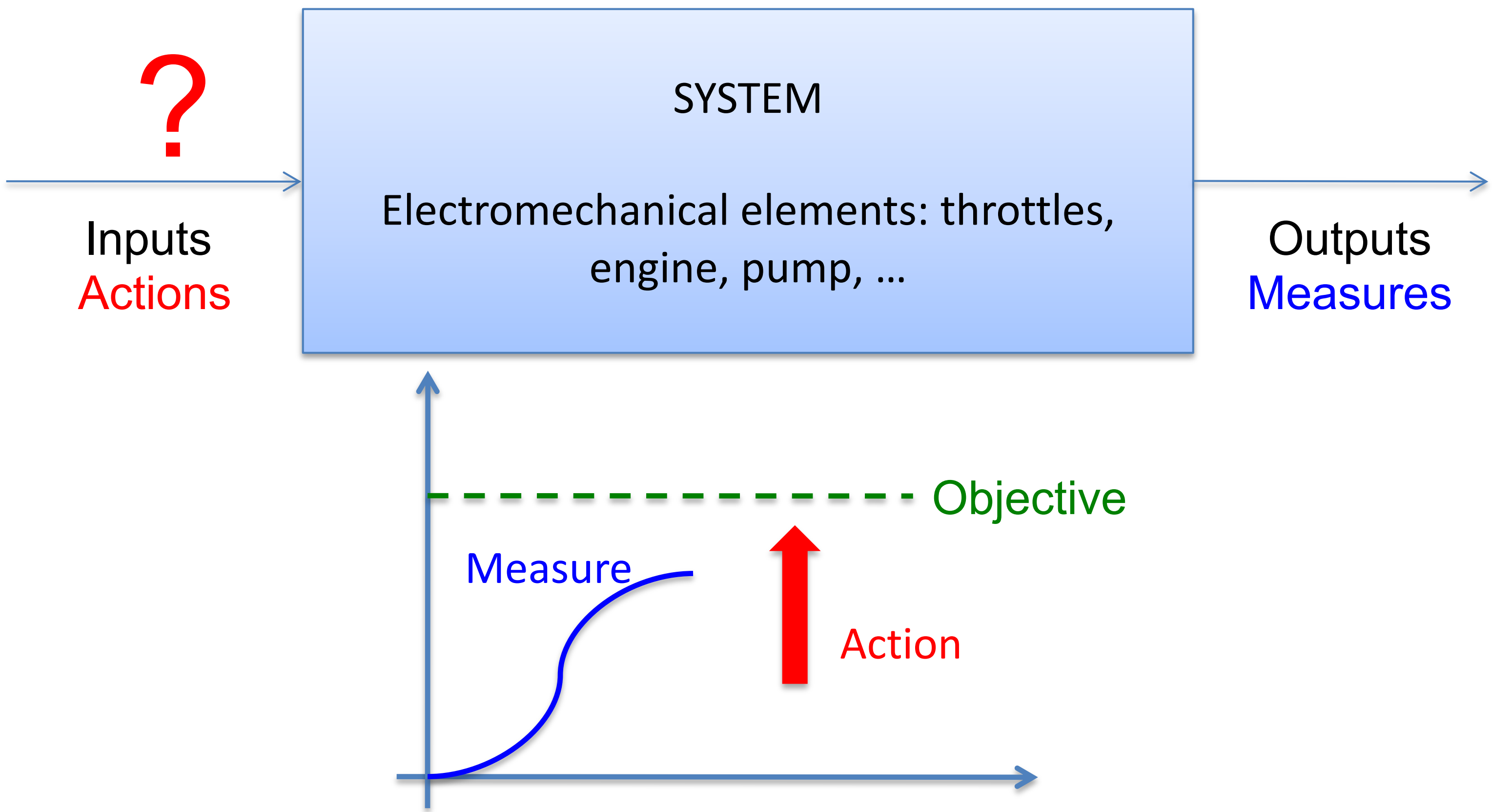
Model-Free Control: introduction

The control problem

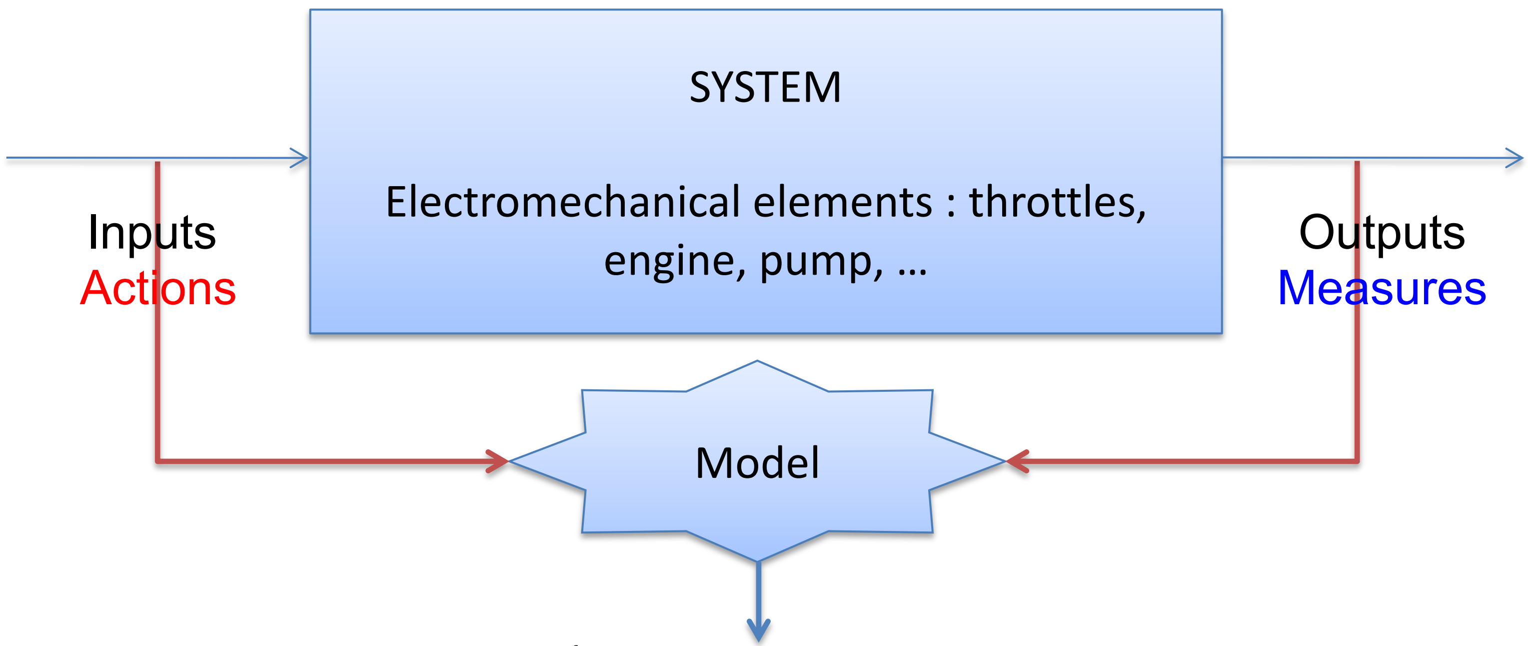
How to act on a system in order to accomplish a task successfully with good perfomances?



Model-Free Control: fundamental principle

Usual approach

Based on prior knowledge, mathematical equations/models are designed to reproduce the behavior of the system as accurately as possible.



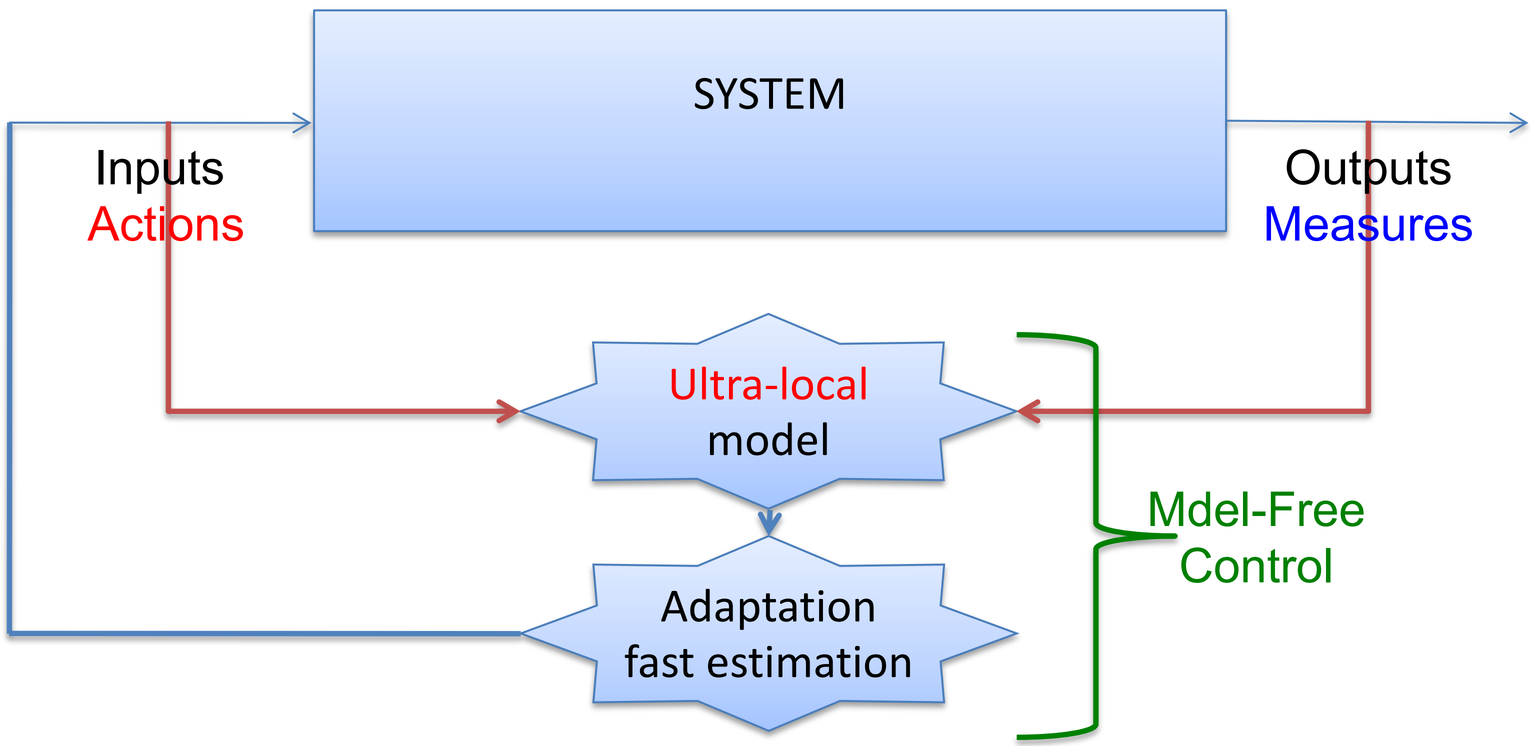
$$\begin{cases} \dot{x} = f(x, u, t) \\ y = g(x, u, t) \end{cases}$$

Model-Free Control: fundamental principle

Proposed approach

Control dessign:

- Without paramtric estmation
- Fast and non-asymptotic algebraic estimation tools



Model-Free Control: fundamental principle

Proposed approach

Estimated and updated at each time lapse

Complex model

$$\cancel{\begin{cases} \dot{x} = f(x, u, t) \\ y = g(x, u, t) \end{cases}}$$

Replace by ultra-local model

$$y^{(\nu)} = \alpha u + \boxed{F}$$

Ultra-local model control based

$$u = \frac{1}{\alpha}\left(-F + y_*^{(\nu)}\right) + Correction(e)$$

Model-Free Control: fundamental principle

Proposed approach

$$y^{(\nu)} = \alpha u + F$$

$$\nu \leq 2$$

$$u = \frac{1}{\alpha}\left(-F + y_*^{(\nu)}\right) + Correction(e)$$

With perfect estimation of F

Iterative integrals

F estimation is decisive

$$e^{(\nu)} = Correction(e)$$

Model-Free Control: fundamental principle

Algebraic estimation of F

For the example, consider the ultra-local model

$$\dot{y} = F + \alpha u$$

"good" approximation: piecewise constant approximation Φ,

$$sY = \frac{\Phi}{s} + \alpha U + y(0)$$ Laplace domain

$$Y + s\frac{dY}{ds} = -\frac{\Phi}{s^2} + \alpha\frac{dU}{ds}$$ after $\frac{d}{ds}$

time domain

$$F_{est}(t) = -\frac{6}{\tau^3}\int_{t-\tau}^{t} (\tau - 2\sigma)y(\sigma) + \alpha\sigma(\tau - \sigma)u(\sigma)d\sigma$$

$$\begin{matrix} u(\sigma) \\ y(\sigma) \end{matrix} \in [t-\tau, t]$$

Model-Free Control: in summary

- Ultra-local Model estimated at each laps of time
- No distinction between different sources of uncertainty (model, disturbance, fault, …)

- Process adaptability
- Highly robust
- Very lightweight implementation

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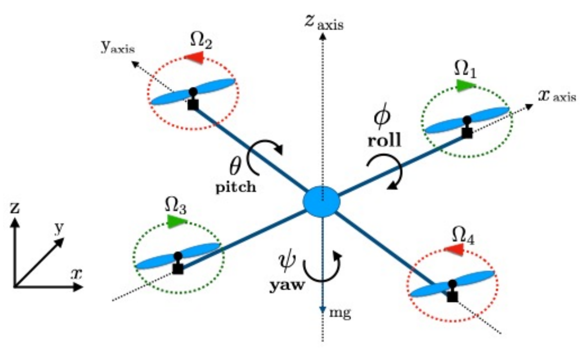
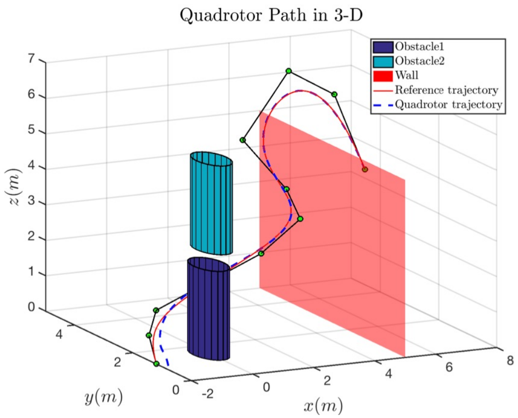
UAV

- **Drone**
  - *Cascaded Model-Free Control for trajectory tracking of quadrotors, M Bekcheva, C Join, H Mounier, International Conference on Unmanned Aircraft Systems (ICUAS), 1359-1368, 2018* (**Centrale/Supélec**)





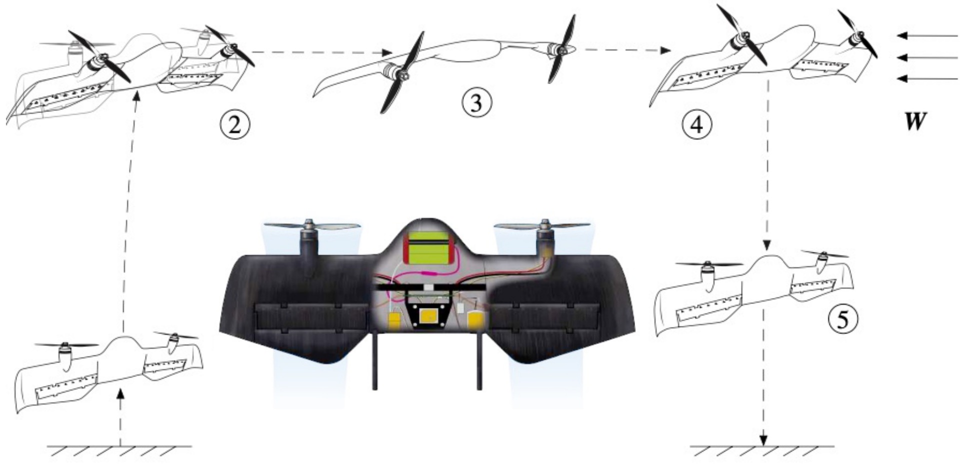
  - *A robust but easily implementable remote control for quadrotors: Experimental acrobatic flight tests, M. Clouatre, M. Thitsa, M. Fliess, C. Join,* https://hal-polytechnique.archives-ouvertes.fr/hal-02910179 (**Mercer University, USA**)

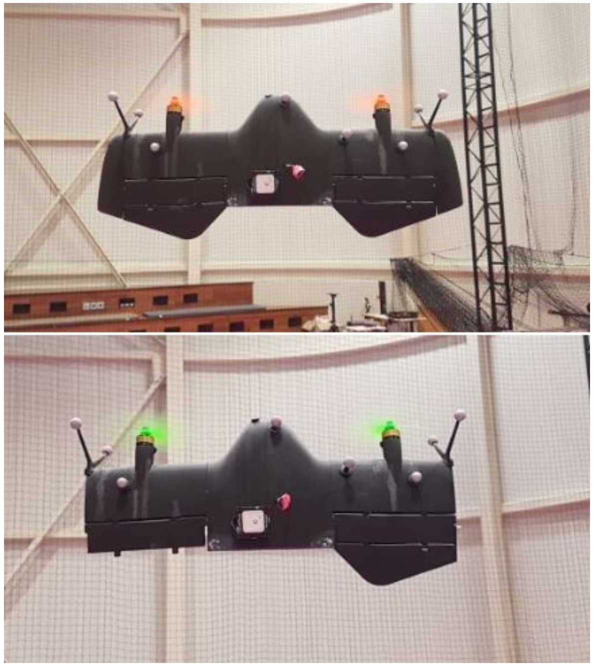
https://www.youtube.com/watch?v=wtSLalA4szc&t=35s

UAV

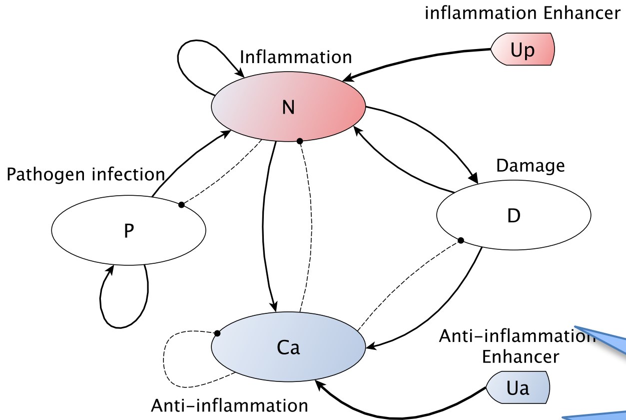
- **Fixed wing**
  - « Best Paper Award 2020 » décerné par l'American Institute of *Aeronautics and Astronautics (AIAA)*

  *Towards a unified model-free control architecture for tailsitter micro air vehicles: Flight simulation analysis and experimental flights, J. M. Olszanecki Barth, J.-P. Condomines, M. Bronz, G. Hattenberger, J.-M. Moschetta, C. Join, M. Fliess, AIAA Scitech 2020 Forum, 2020 (***ISAE/SUPAERO***)*





Inflammation control



in the process of recovery

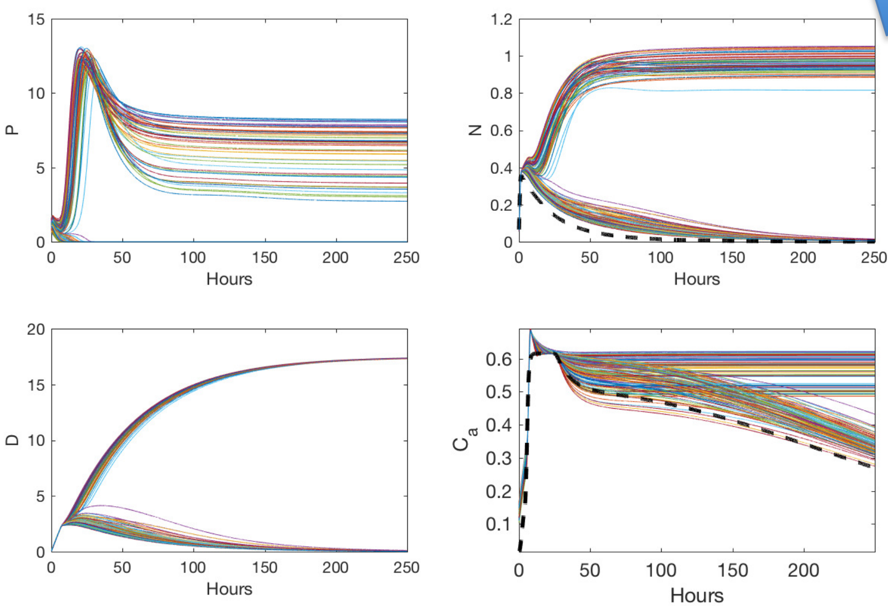
369 dead

1000 virtual patients

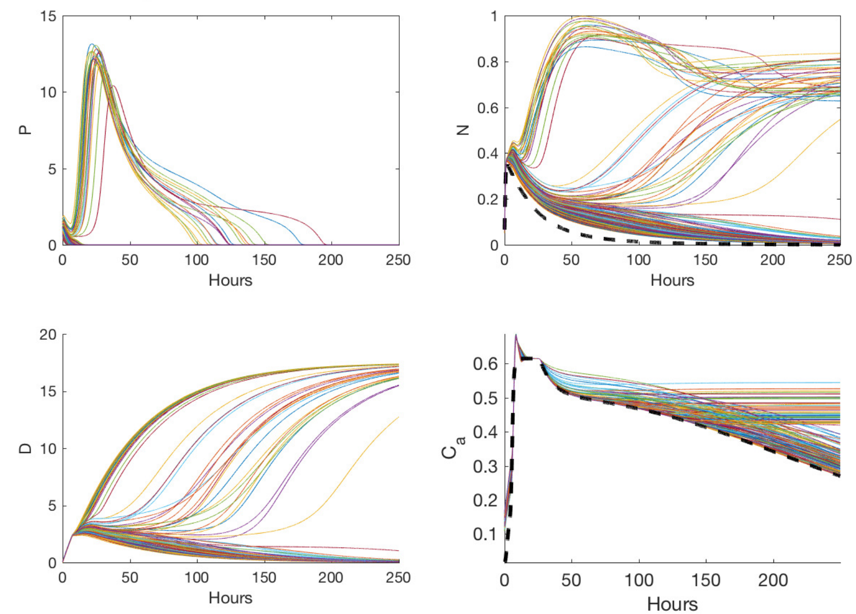
	Therapy Type:	Placebo	Model-free control therapy
N<0.05	Percentage Healthy:	40% (252)	85.66% (518)
P=0	Percentage Aseptic:	37% (228)	6.4% (40)
	Percentage Septic:	23% (141)	7.8% (49)
	Percentage Harmed (out of 252)	n/a	0% (0/252)
	Percentage Rescued (out of 369)	n/a	75.88% (280/369)

The choice of trajectory is importantin

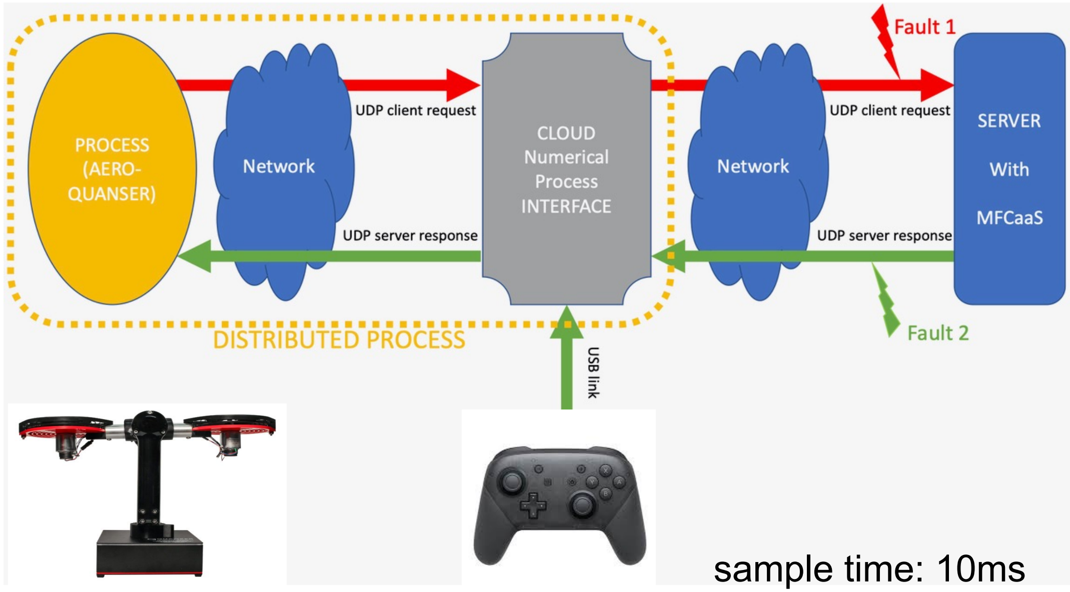
141 septic patients



228 aseptic patients



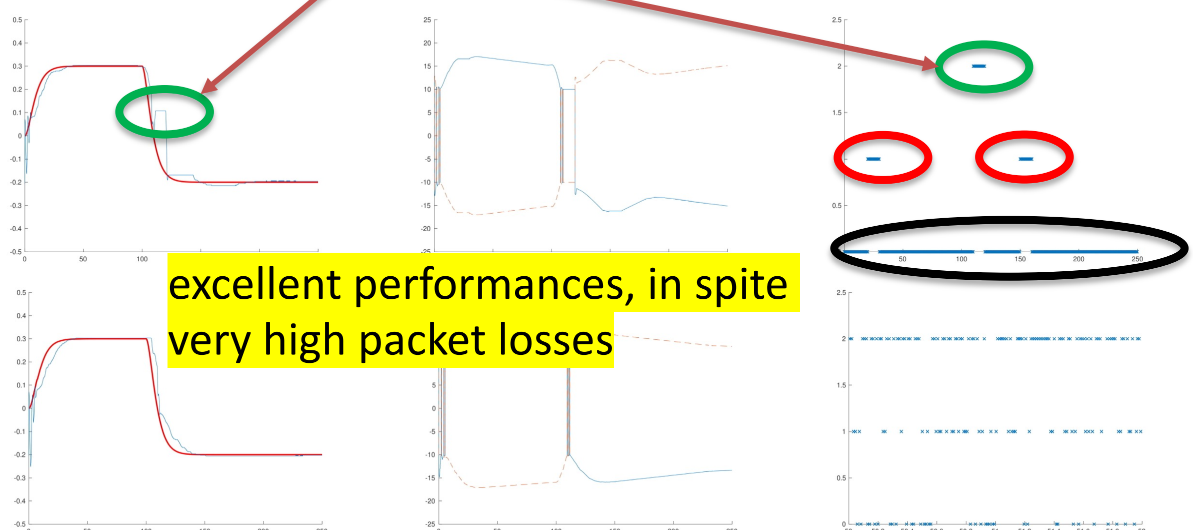
MFC as a service



tracking quality decreases

3 longues pertes de transmission

80% of transmission faults



excellent performances, in spite very high packet losses

Control do not reach the plant

Measurements do not reach the server

No loss

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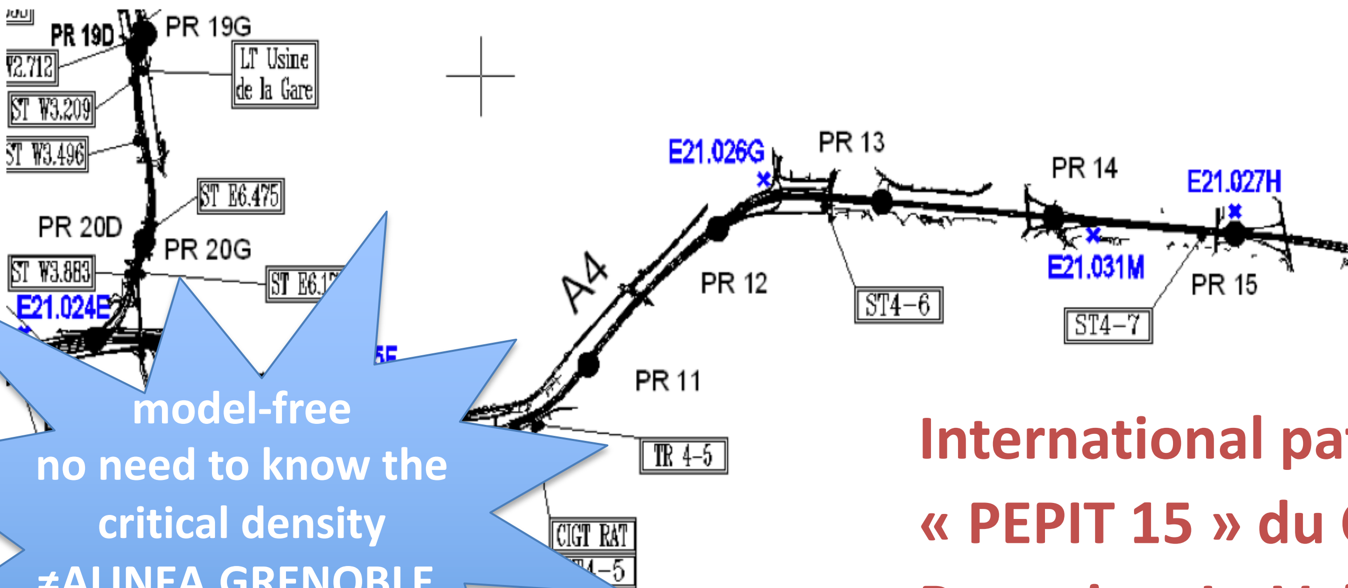
Examples of industrial applications

Traffic control (DIR IF & N)



model-free
no need to know the critical density
≠ALINEA,GRENOBLE, BERKELEY

International patent
« PEPIT 15 » du CRAN
Paper in « La Voix du Nord »

In operation on the A25, A4
Deployment on the A1, A22, and A23

Examples of industrial applications

Speed control for ALSTOM buses

Training of 20 engineers in our techniques

« Dans le logiciel embarqué d'APTIS, nous avons implémenté une régulation de vitesse basée sur l'algorithme Commande Sans Modèle de la société AL.I.E.N.

Cette régulation de vitesse doit répondre à des critères :

- de dynamique : temps de réponse
- de charge : 14 tonne à vide jusqu'à 20 tonne en charge maximale
- et enfin de pente: du profil plat jusqu'à une pente de 12%!

Avec **un jeu de paramètre**, la Commande Sans Modèle a pu répondre à l'ensemble de ces exigences.

Comparée à un PI classique, la CSM est **plus robuste** et présente un gain indiscutable sur **le temps de validation** sur simulateur et sur bus électrique. »

Other applications

Collaborations

Other industrial applications
- EdF (hydroelectric dam regulation) : international patent
- ENGIE (Degrémont, Suez) (pressure regulation) : international patent
- GE, PSA, Renault, …

Other academic collaborations
- Autonomous car (J. Villagra, Madrid)
- Computer network management (E. Delaleau, Brest; H. Mounier, Paris)
- Fuel cell control and diagnosis (M. Ait Ziane, Belfort-Réunion, Longwy)
- Pandemic control (A. D'Onofrio, Trieste)
- …

Other independent external applications
- Electric motor speed regulation, Princeton/Oak Ridge, USA
- Building and grid energy management, ORNL, USA
- Power control, Université de Heifi, Chine
- Autonomous vehicle, Université de Kanagawa, Japon
- ….

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What to do with a Model?

- Legitimate question
- Why not take advantage of *a priori* knowledge?
- How?

Flatness-based Control, 1992, [MF, JL, PM, PR]

What to do with a Model?

- Flatness-based control: better Model Predictive Control?

$$\begin{cases} \dot{x} = f(x, u, t) \\ y = g(x, u, t) \end{cases}$$

Optimal or non-optimal reference trajectory

$z^\star$

$y^\star$

$$u^\star = h(z^\star, \dot{z}^\star, \ldots)$$

$$u = u^\star + \boxed{feedback(z - z^\star)}$$

Model based: observer,
Sliding mode, Kalman filter, …

What to do with a Model?

Control along the reference trajectory

flat or partially flat model

$$\begin{cases} \dot{x} = f(x,u,t) \\ y = g(x,u,t) \end{cases}$$

$z^\star$

$$\Delta u = u - u^\star$$
$$\Delta y = y - y^\star$$

Stabilization at 0

$$\Delta y^{(\nu)} = \alpha \Delta u + F$$

$$u = u^\star - \frac{F}{\alpha} + Correction(\Delta y)$$

What to do with a Model?

Control along the reference trajectory: HEOL (soleil)

Modèle partiel et plat

$$\begin{cases} \dot{x} = f(x,u,t) \\ y = g(x,u,t) \end{cases}$$

$$\Delta y^{(\nu)} = \alpha \Delta u + F$$

Relative degree

Calculated form of α

$$\frac{\partial}{\partial u} y^{(\nu)} \neq 0$$

$$\alpha = \frac{\partial}{\partial u} y^{(\nu)}$$

Function of time and flat output $z^\star$

What to do with a Model?

Control along the reference trajectory: invariant error

$$\Delta u = u - u^\star$$
$$\Delta y = y - y^\star$$

$z^\star$

Projection into invariant space
- Error behaviour
- Simplified form of α
- Singularaty vanishing

Stabilization at 0

$$\Delta y^{(\nu)} = \alpha \Delta u + F$$

$$u = u^\star - \frac{F}{\alpha} + Correction(\Delta y)$$

What to do with a Model?

HEOL : in summary

flat or partially flat model

$$\begin{cases} \dot{x} = f(x, u, t) \\ y = g(x, u, t) \end{cases}$$

$$u^\star$$

$$u = u^\star + \cancel{\boxed{feedback(z - z^\star)}}$$

Homeostasis

$$u = u^\star \boxed{- \frac{F}{\alpha} + Correction(\Delta y)}$$

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Conclusions

- New paradigm: « model-free control »
- Limitations of “pure” CSM
  - non-minimal phase shift
  - physical pure control delay [MD,FH]
- Price to pay: sampling, noise level, dynamics
- Combining flatness + MFC: recently published HEOL offering answers to recurring questions

References

General references

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UAV

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