Journée

GT-CPNL & GT-MEA

Model Predictive Control and its Applications to Some Mechatronic Systems

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Paris, April, 03rd, 2014

- Context of Mechatronic systems
  - ✓ Introductory example
  - ✓ Basic definitions in Mechatronics
  - ✓ Main technical areas (applications)
- **Example 1 :** One-leg hopping robot
  - ✓ System description and dynamics
  - ✓ Control problem formulation
  - ✓ Proposed predictive controller
  - ✓ Simulation results
- **Example 2 :** Hard disc drive
  - ✓ System description and dynamics
  - ✓ Control problem formulation
  - ✓ Proposed predictive controller
  - ✓ Simulation results
- **Example 3 :** Inertia wheel inverted pendulum
  - ✓ System description and dynamics
  - ✓ Control problem formulation
  - ✓ Proposed predictive controller
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Context of Mechatronic systems

Introductory example : Adaptive cruise control (ACC)

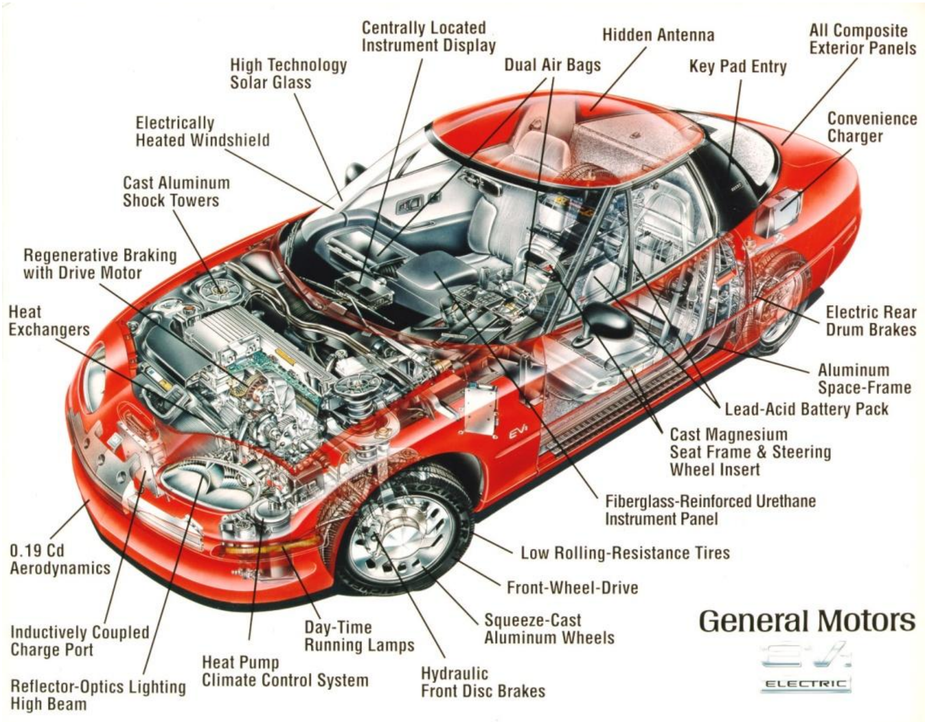
In the cars of today

There are more thane 100 microprocessors controlling various systems

The more complicated systems are not just on/off control

Examples :

- ✓Speed control
- ✓Active vibration control
- ✓Trajectory control
- ✓Transmission control
- ✓Adaptive cruise control
- ✓ Autonomous Emergency Braking (AEB)
- ✓ … etc



A very complex multi-integrated system !

Introductory example : Adaptive cruise control (ACC)

Cruise control is not a more convenience option than a safety feature !

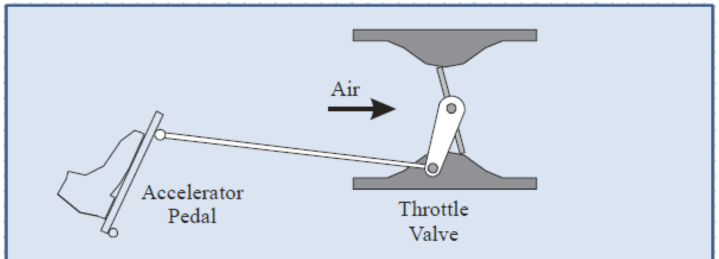
Conventional cruise control systems simply maintain a preset speed :

How does it work ?

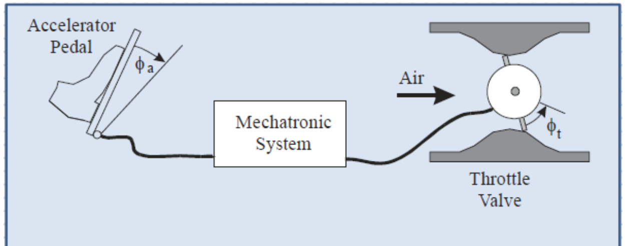
1- The driver presses a button to set the speed,

2- Cruise control system controls the speed by adjusting the throttle position,

3- The control is deactivated if the driver steps on the brake, changes the speed setting, or press the button.



Non-mechatronic, mechanical throttle



Mechatronic throttle

However

1- It is not aware of other vehicles' movement,

2- The driver must be always aware → Possibility of mistakes !

3- Possibility of collision with the leading car if not manually slowed down.

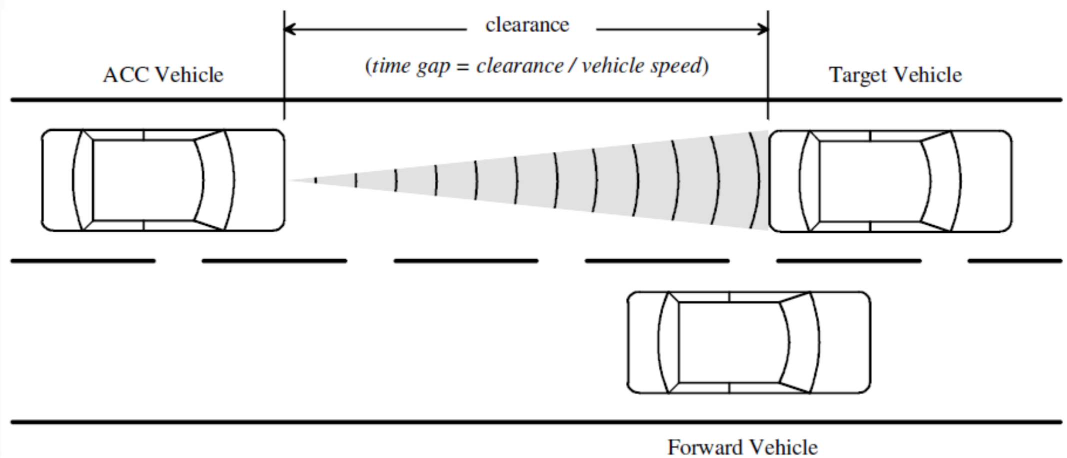
Introductory example : Adaptive cruise control (ACC)

Adaptive cruise control (ACC), is an enhancement to a conventional cruise control system which allows the vehicle to follow a forward vehicle at an appropriate distance.
It actively maintains a preset distance between vehicles rather than a preset speed.

How does it work ?

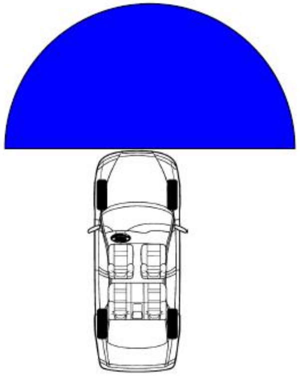
1- A laser or radar sensor in the front of the vehicle measures the distance to the vehicle ahead.
2- The driver then selects a distance that suits the driving conditions.
3- The system automatically maintains that distance as traffic speeds up and slows down.

✓ Adaptive cruise control is much better than conventional cruise control in heavy traffic.
✓ It reduces the risk of rear ending another vehicle if the driver isn't paying attention.



Introductory example : Adaptive cruise control (ACC)

Radar sensor
Detection field



Laser sensor
detection field

Example of Laser sensor
From IBEO

Technical specifications

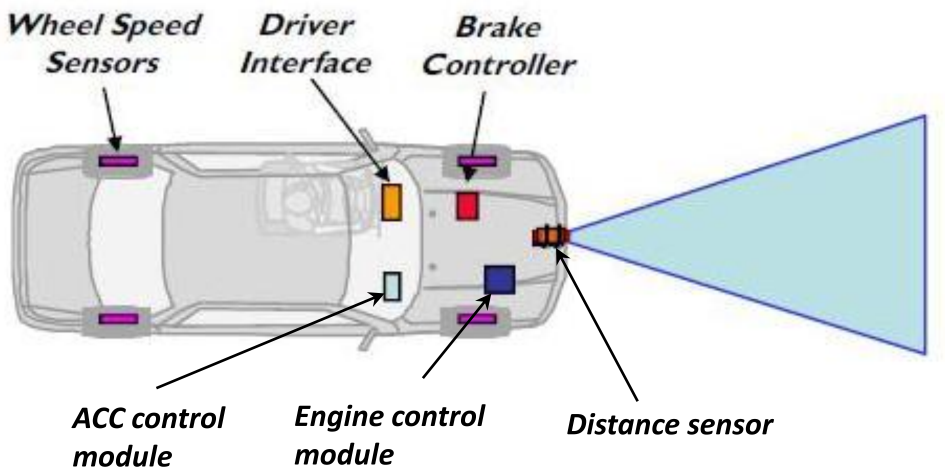
Autoliv-CelsiusTech Electronics	
Modulation characteristics	Modulation type FMCW
Radar scanning principle	Mechanical scanning
Frequency	76-77 GHz
Transmitted power	10mW
Minimum tracking distance	2 m
Maximum tracking distance	200 m
Update rate of radar	10 Hz
Field of view	24°
Angle resolution	0.1°
Distance resolution	1 m

Technical specifications

IBEO Laser scanner LD Automotive	
Minimum tracking distance	0.4 m
Maximum tracking distance	100 m
Update rate of laser	10 Hz
Field of view	up to 270°
Angle resolution	0.25°
Distance resolution	0.004 m

Introductory example : Adaptive cruise control (ACC)

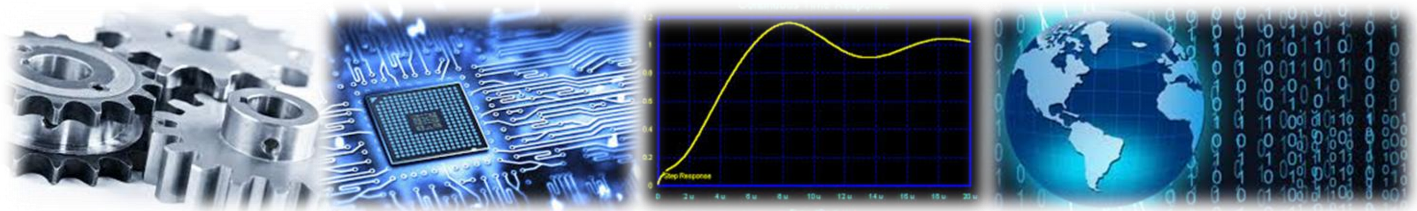
- The ACC module interacts with the throttle, the brake system to speed up or slow down



Sensors:
- Four wheel sensors
- Brake pedal sensor
- Throttle pedal sensor
- Laser/radar sensor
- ...

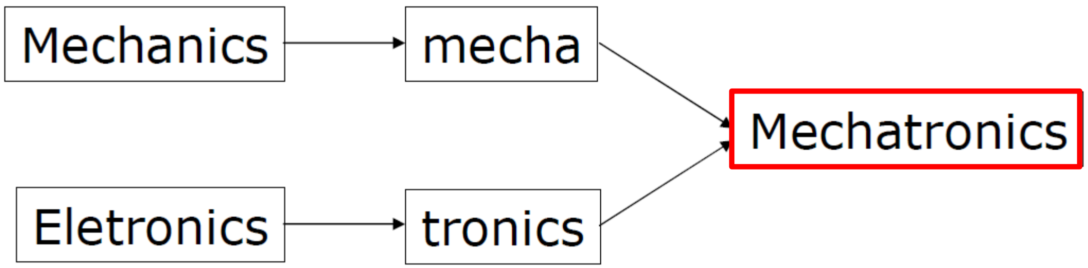
Actuators :
- Brake actuator
-Throttle actuator

Basic definitions in Mechatronics



What is Mechatronics ?

- The word **Mechatronics** was first coined by a senior engineer of the Japanese company Yaskawa, in 1969, and the company was granted trademark rights on the word in 1971
- Initially, the word Mechtronics was defined as the combination of "mecha" of mechanics and "tronics" of electronics



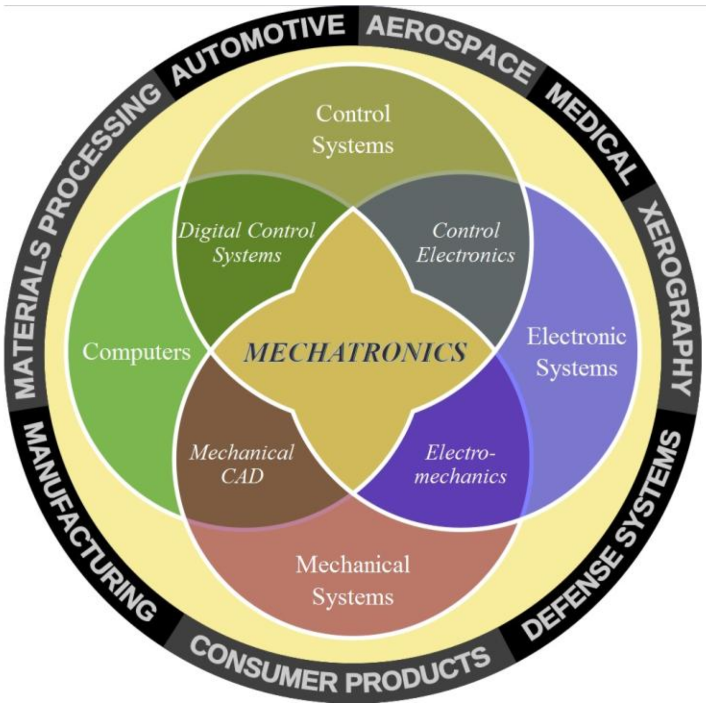
- The word soon received broad acceptance in industry and has taken a wider meaning and is now widely being used as a technical jargon to describe a philosophy in engineering technology
- In order to allow its free use, Yaskawa decided to abandon his rights on the word in 1982

What is Mechatronics ?

- For this wider concept of Mechatronics, different definitions has been proposed within the scientiffic community
- The most commonly used definition is the following :

Mechatronics is the synergistic integration of :
- ✓ Mechanical engineering,
- ✓ Electronics,
- ✓ Control engineering, and
- ✓ Computer technology

in the design and manufacture of products and processes



Rensselaer Polytechnic Institute

Synergistic integration means that the Mechatronic engineers have to study the aspects of engineering that are vital for the design and manufacture of products.

Brief history of Mechatronics

- **The first stage [late 60s]** :
  - ✓ This period corresponds to the years when this term was introduced.
  - ✓ During this stage, **technologies** used in Mechatronic systems **developed** rather **independently** and **individually**.
- **The second stage [early 80s]** :
  - ✓ A **synergistic integration** of different **technologies** started taking place.
  - ✓ The notable example is **optoelectronics**.
  - ✓ The concept of **hardware/software co-design** also started in this period.
- **The third stage [Early 90s]** :
  - ✓ The most notable aspect of this stage is the increased use of **computational intelligence** in Mechatronic products and systems.
  - ✓ Another important achievement is the possibility of **miniaturization** of components; in the form of **micro actuators** and **micro sensors** (i.e. Micro Mechatronics).

Different levels of Mechatronics

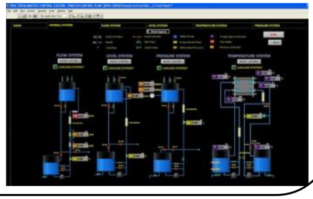
- Mechatronics has evolved through the following stages [Gera, 2006]:

✓ **Primary Level Mechatronics**: Integrates electrical signaling with mechanical action at the basic control level for e.g conveyors, and fluid valves.

✓ **Secondary Level Mechatronics**: Integrates microelectronics into electrically controlled devices for e.g. DC motors.

✓ **Tertiary Level Mechantronics**: Incorporates advanced control strategy using microelectronics, microprocessors and other application specific integrated circuits for e.g. automotive systems.

✓ **Quaternary Level Mechatronics**: This level attempts to improve smartness a step ahead by introducing intelligence (artificial neutral network and fuzzy logic) and fault detection and isolation (F.D.I.) capability into the system.



Main technical areas (applications)

- ✓ Robotics (industrial and special)
- ✓ Automotive systems (ACC, AEB, vibrations, …)
- ✓ Transportation and Vehicle Systems
- ✓ Actuators and sensors
- ✓ Computer facilities (printers, plotters, HDD, …)
- ✓ Simulators for training of pilots and operators
- ✓ Manufacturing (machine tool, laser cutting, …)
- ✓ Micro devices and optoelectronics
- ✓ Vibrations and noise control
- ✓ Power and energy devices
- ✓ Medical mechatronic systems
- ✓ Consumer Products
- ✓ Photo and video equipment (cameras, DVD players)
- ✓ Show industry
- ✓ … etc

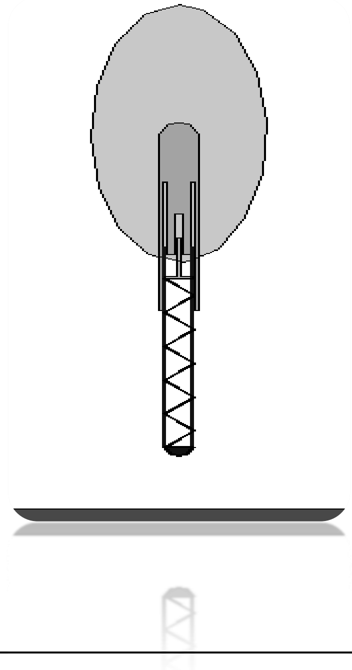







Example 1

One-Leg Hopping Robot



From natural to artificial hopping

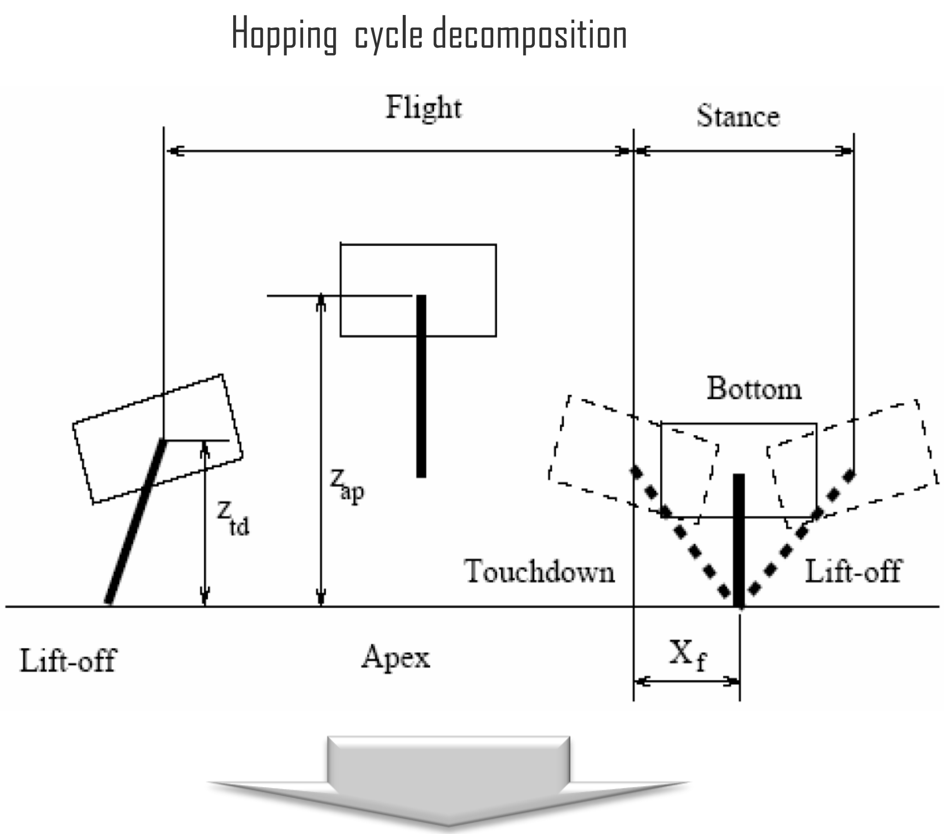
Kangaroos have a very performant locomotion

- ✓ Speed : Up to 90 km/h
- ✓ 70% of energy stored in Achilles' tendon
- ✓ Jumps : Up to 3.5m height and 13m length

Kangaroo (Australia)

One-leg hopper (Ohio University)

Problem formulation



- ✓ Two main phases : stance / Flight
- ✓ Two transition phases : take off / landing

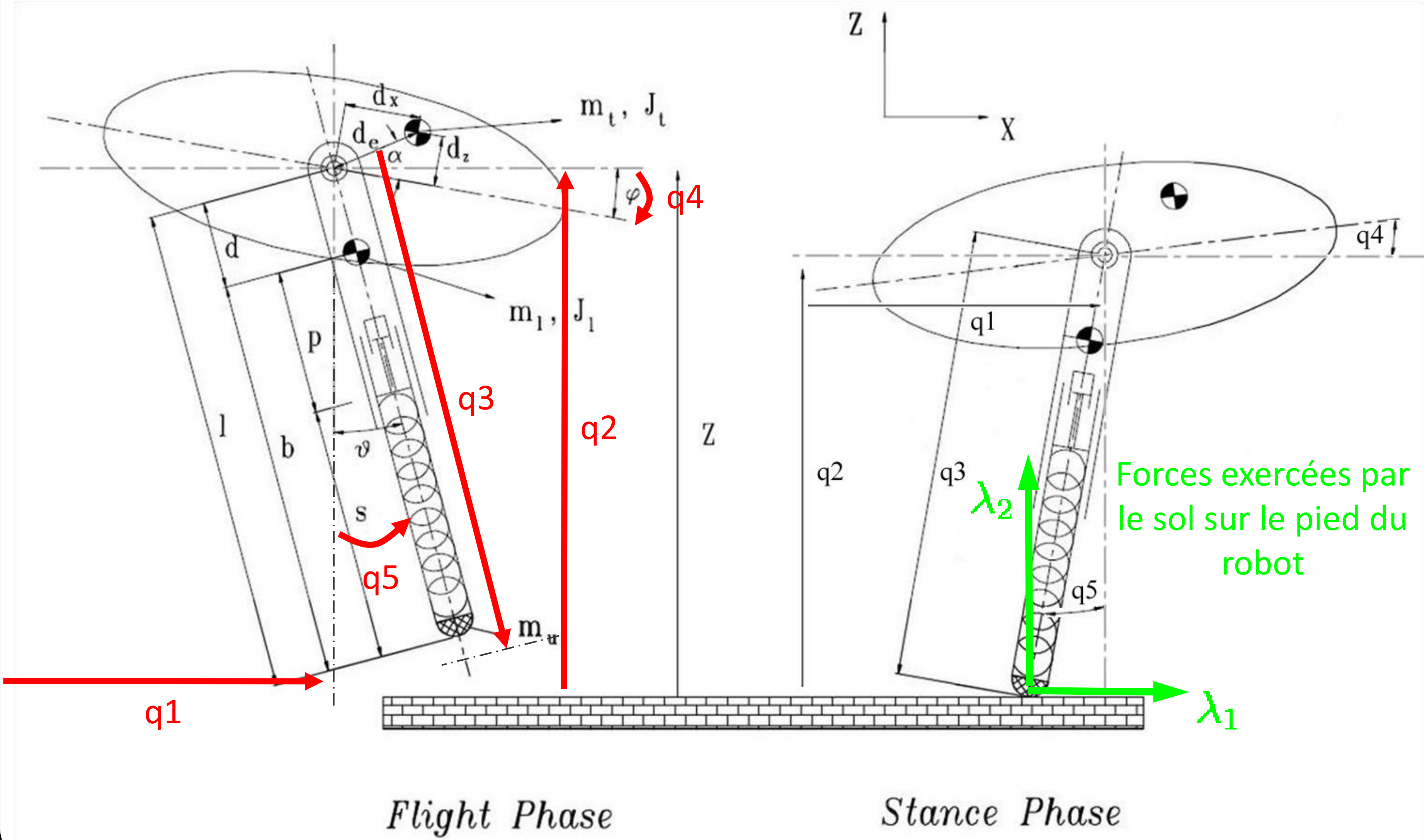
Objective:

Design controllers to achieve stable periodic jumps for a one-leg hopping robot

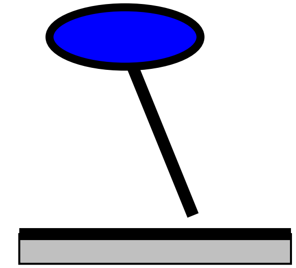
Difficulties:

- ✖ High nonlinear dynamics
- ✖ Hybrid dynamics
- ✖ Underactuated system
- ✖ Very instable

Description of the robot



Dynamic modelling of the robot

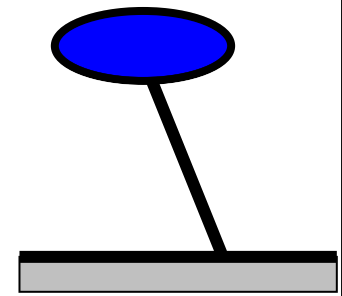


Flight phase :

Lagrange formulation : $\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} + \frac{\partial F}{\partial q_i} = Q_i$

Dynamics in a matrix form: $M(q)\ddot{q} + N(q,\dot{q})\dot{q} + F(q) + G(q) = Su$

$q, \dot{q}, \ddot{q} \in \mathbb{R}^5 \qquad u \in \mathbb{R}^2$ Underactuated system



Stance phase : Can be deduced from the flight phase model

$$\Phi(q) = 0 \Rightarrow J(q)\dot{q} = 0 \Rightarrow J(q)\ddot{q} + P(q,\dot{q}) = 0$$

$$\begin{cases} M(q).\ddot{q} + N(q,\dot{q}).\dot{q} + F(q) + G(q) = U + J(q)^T\lambda \\ J(q)\ddot{q} + P(q,\dot{q}) = 0 \end{cases}$$

$J \in \mathbb{R}^{2\times 5}$: Jacobian matrix of constraints

$\lambda \in \mathbb{R}^2$: Lagrange multipliers

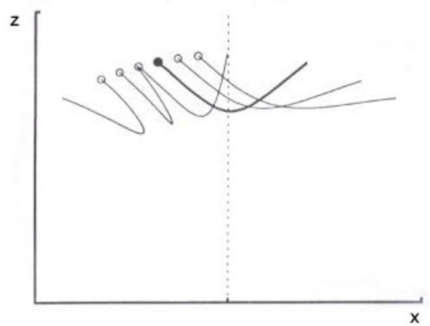
Proposed control scheme

Raibert's controller includes three parts

Control of the length of the leg :

$$F_l = cte$$

Control of the foot placement :

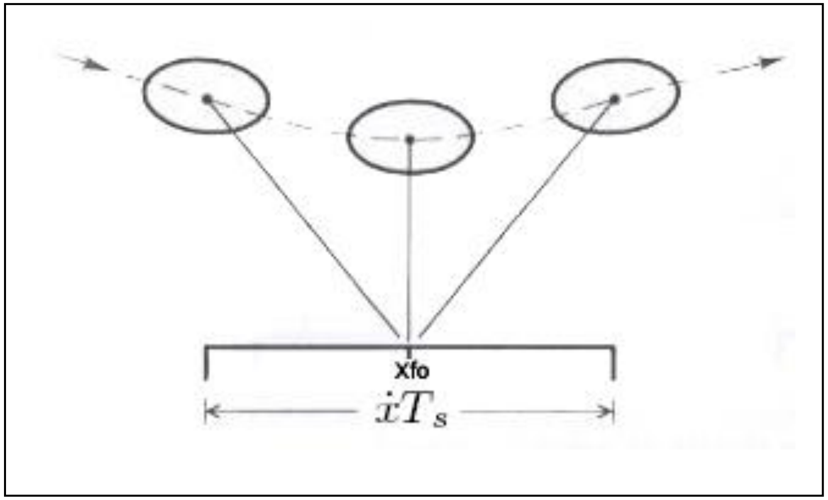


$$x_f = \frac{\dot{x}T_s}{2} + k_{\dot{x}}(\dot{x} - \dot{x}_d)$$

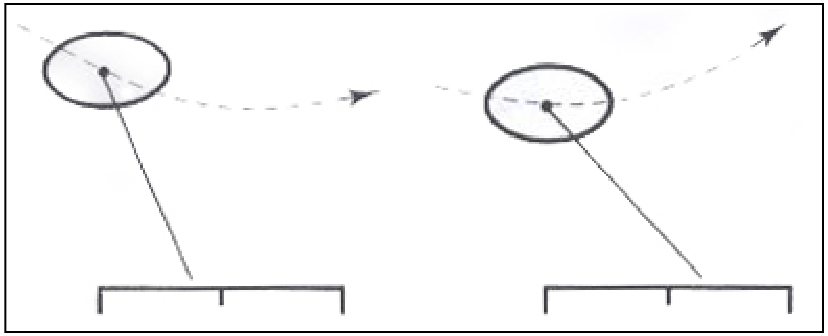
Control of the behavior of the robot :

$$\Gamma = k_p(\phi_d - \phi) - k_v(\dot{\phi})$$

Symmetrical trajectory of the robot



Foot placement of the robot :
(asymmetrical trajectory)



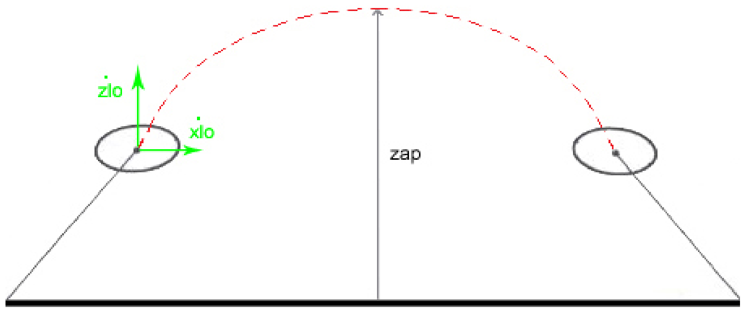
Proposed control scheme

Basic idea :

Replace the controller of the length of the leg by a NMPC

Ballistic trajectory

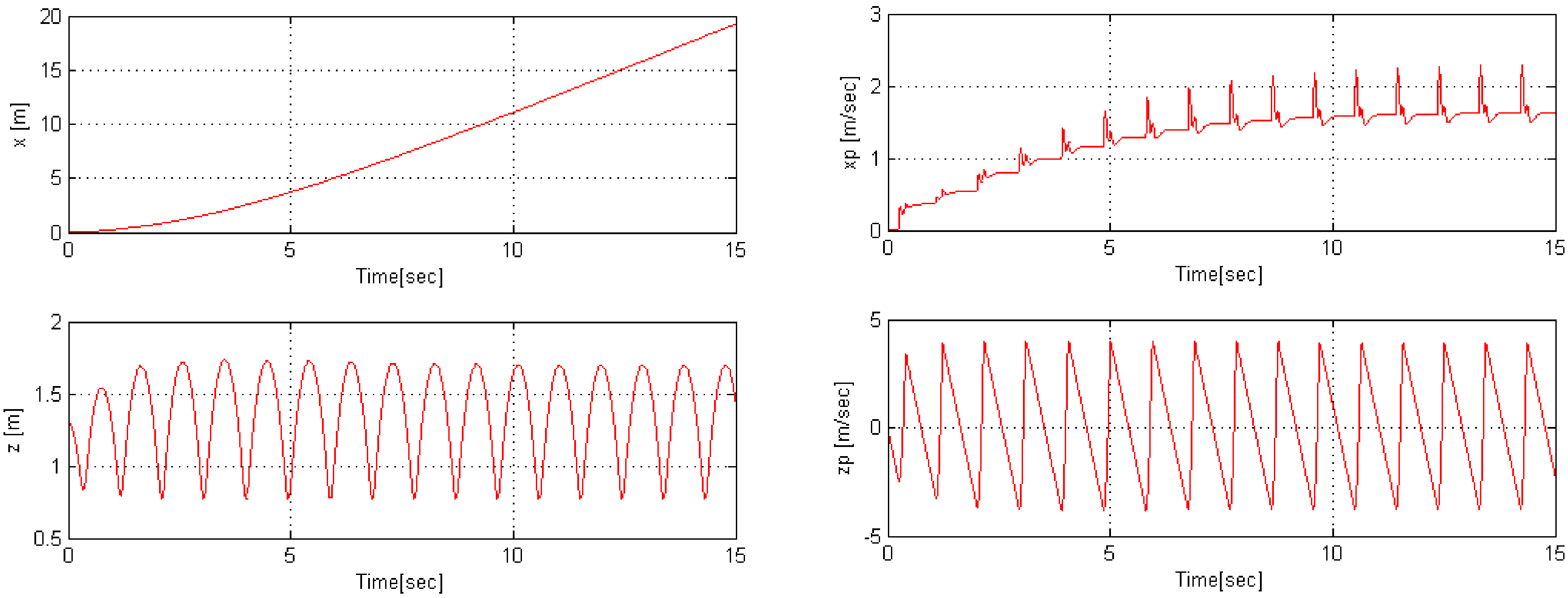
$$\begin{cases} \dot{x}_{lo} = \dot{x}_d \\ \dot{z}_{lo} = \sqrt{2g(z_{ap} - z_{lo})} \end{cases}$$



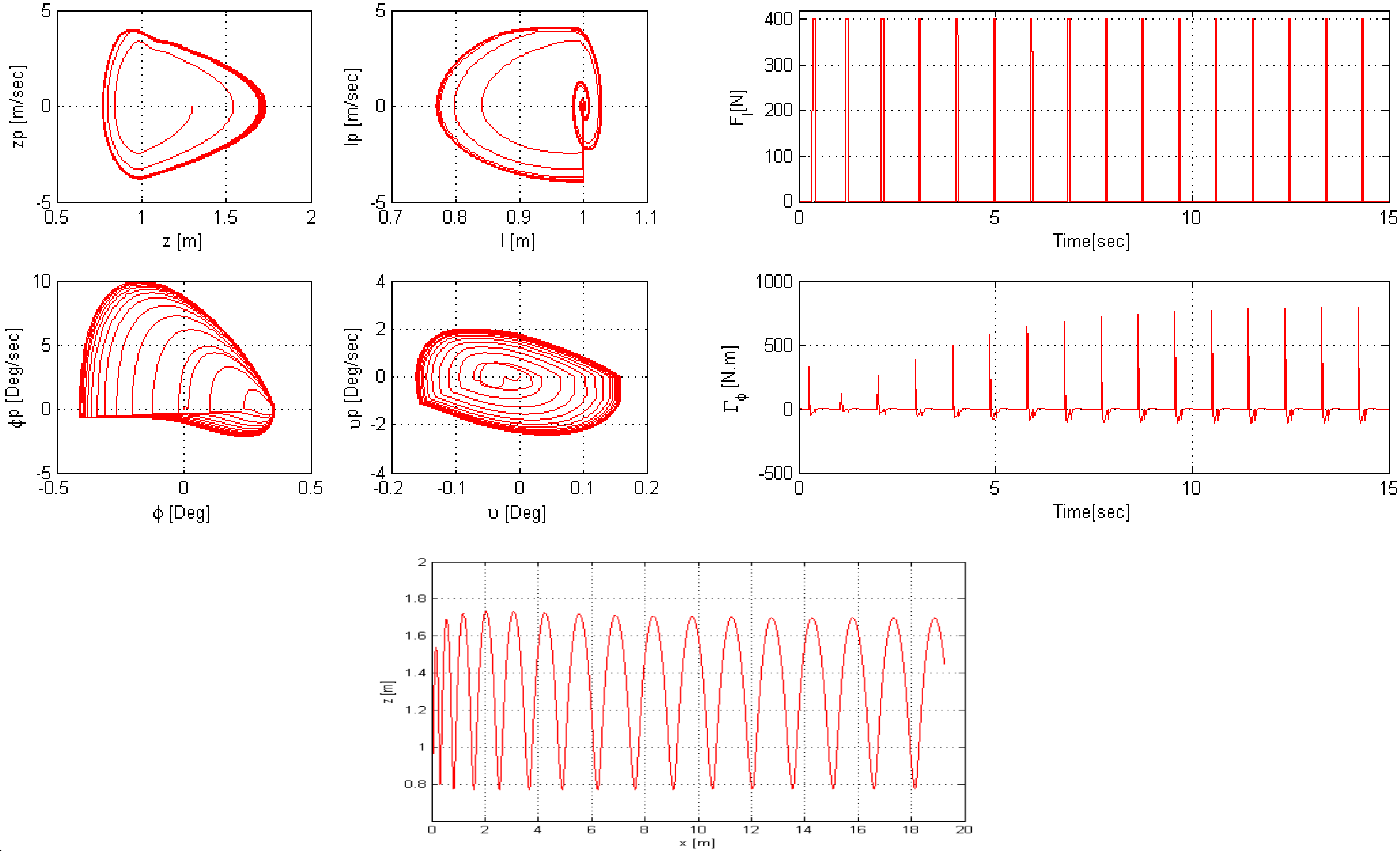
$$\min_u \quad J = \sum_{k=1}^{Np} Q_1(l_0(k) - l(k))^2 + Q_2(\dot{x}_{lo}(k) - \dot{x}(k))^2 + Q_3(\dot{z}_{lo}(k) - \dot{z}(k))^2$$

$$sous \quad |u| < u_{max}$$

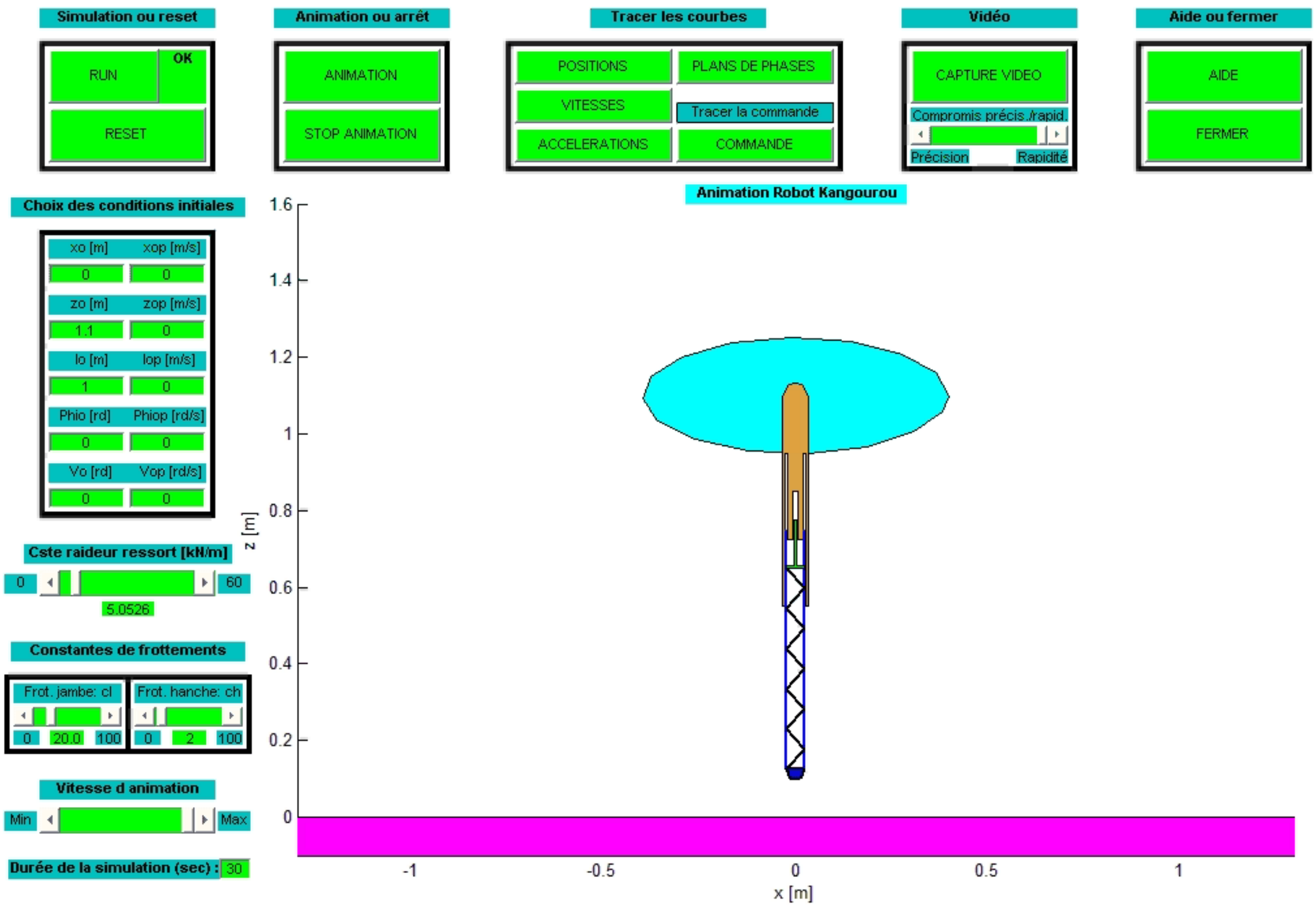
Simulation results



Simulation results



Illustrative movie in the simulator



Example 2

Hard Disc Drive

What is a Hard Disc Drive (HDD)?

Computer, laptop, or server

One of the main components

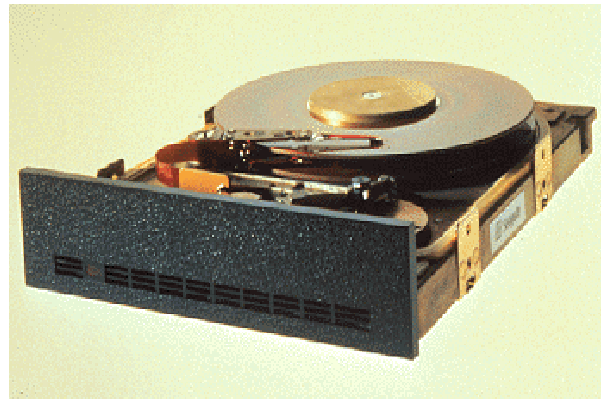
Hard Disc Drive

- It's a data **storage device** (in binary form 0/1)
- It consists of **one** or **more rigid** rotating **magnetic disks** (platters)
- A HDD **retains its data** even when **powered off**
- Data is read in a **random-access** manner
- Individual **blocks** of data can be **stored** or **retrieved** in **any order** rather than **sequentially**
- With a **magnetic head** arranged on a moving **actuator arm**
- To **read** and **write** data **to the surface**

A brief history of HDD

In 1956

- ✓ IBM's RAMAC
- ✓ First machine with HD
- ✓ 50 platters
- ✓ 2 feet diameter
- ✓ 100,000 characters
- ✓ Equivalent to 5 MB



In 1979

- ✓ By Seagate Technology
- ✓ First 5.25" hard disk
- ✓ The ST506's is 5 MB
- ✓ 10 times as much as the RAMAC at a fraction of its size

In 1998

- ✓ 4 Decades after RAMAC
- ✓ Seagate Technology
- ✓ 47 GB was impressive
- ✓ Store 100,000 times
- ✓ On the same surface

In 2005

- ✓ World smallest HD
- ✓ Toshiba
- ✓ 0.85" hard drive
- ✓ Size of a postage stamp
- ✓ 4 GB (2005), 8GB (2007)

Inside a Hard Disc Drive

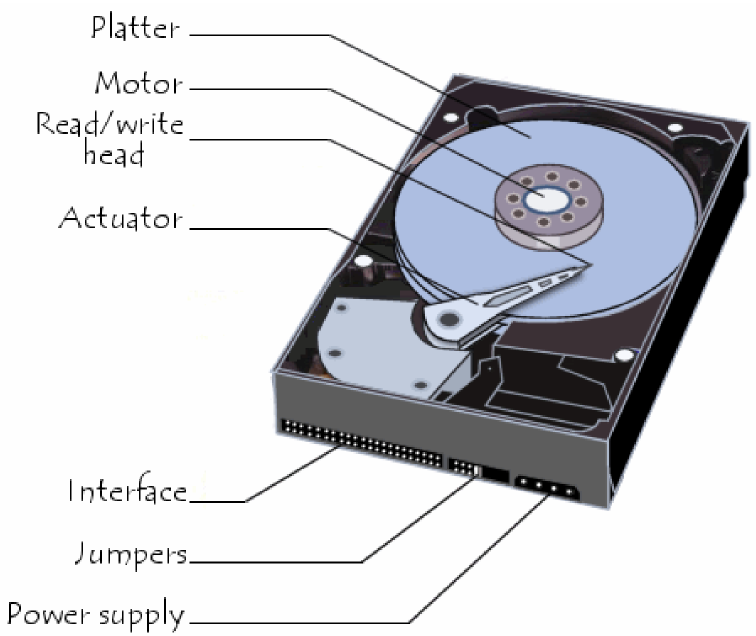
www.letheonline.net

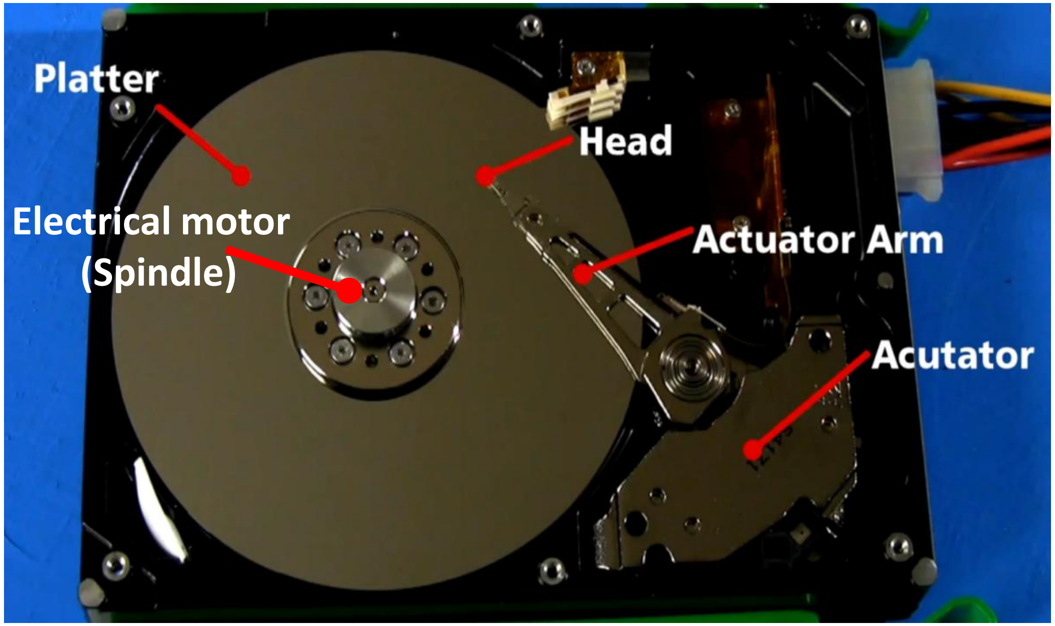
- ✓ In order to **read/write** data the head needs to be **physically moved** to the **correct position** on the disc
- ✓ That is a **key reason** why HDD suffer from **slow access time** w.r.t **RAM** for instance

- ○ Initialization
- ○ Deleting a folder
- ○ Copy past task

- ✓ The triangular-shaped head arm holds the R/W head
- ✓ Able to move the head from the hub to the edge of the drive

Main components of a Hard Disk Drive



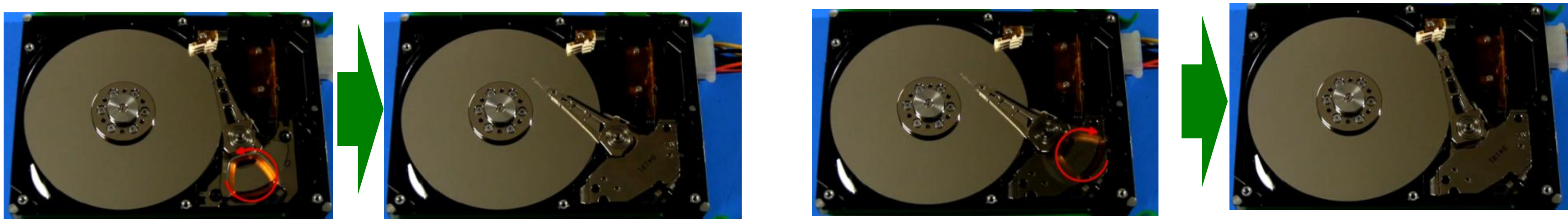


A typical HDD consists of 5 main parts :

- **Electric motor :** Spins the rotating discs (at 7200 rpm)
- **Disc platters :** Made of magnetic material used to store data
- **Actuator :** Called Voice Coil Motor (VCM)
- **Actuator arm :** Holds and moves the head to write/access data up to 60 times/s
- **Head :** is the most crucial part → R/W data on surface

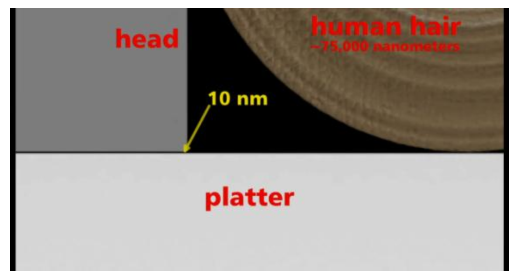
How does it work ?

1. Moving the head : *Arm moves according to the Lorenz force*



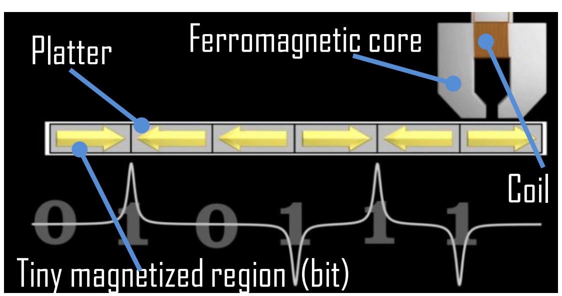
The sense of the force depends on the sense of the current (force ~ current)

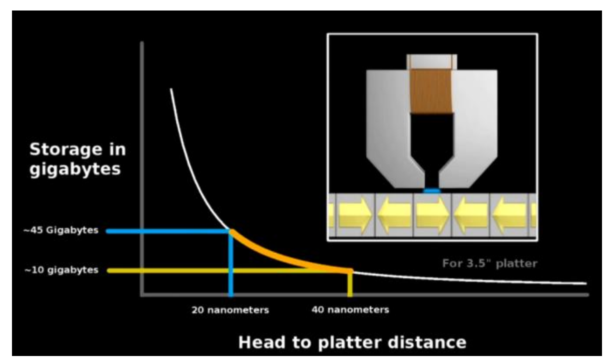
2. Recording data : *(All the data is stored using a basic form as series of 1 and 0)*



Distance : Head / platter
10 – 100 nm

Based on Faraday's Law :
A change in magnetization produces a voltage in the coil





Dynamic modeling of a HDD

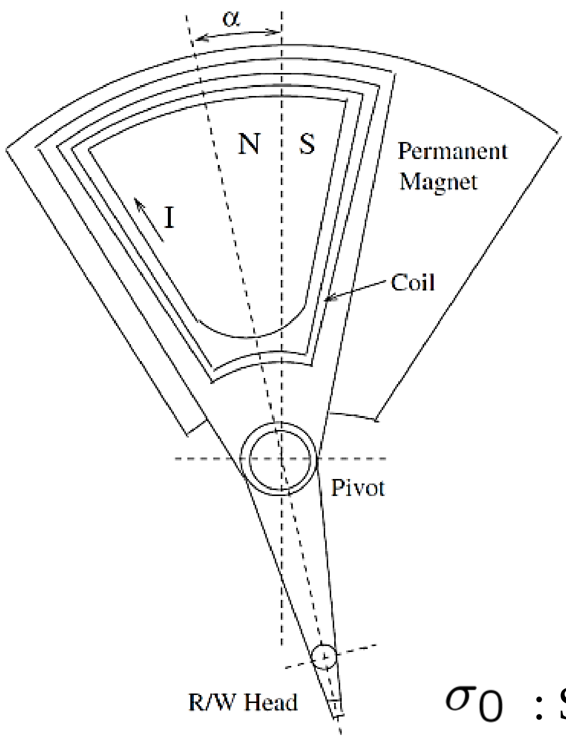
- A **VCM** can be modeled including **hysteresis friction nonlinearity** from **pivot bearing**
- At **low frequencies** the dynamics is given by [San P. P. et al. 2011] :

$$M\ddot{q} + F(q,\dot{q}) = u$$
$$y = q + w_{out}$$

- M is the inertia of the system,
- q , $\dot{q}$, and $\ddot{q}$ are position, velocity and acceleration of the VCM actuator head tip,
- u is the control input,
- y is the output displacement,
- $F(q,\dot{q})$ is the nonlinear function representing the pivot bearing hysteresis friction,
- ω_{out} is an output disturbance.

Dynamic modeling of a HDD

- The nonlinear function $F(q,\dot{q})$ is presented by the LuGre function [Liu. X,et al. 1999]
- The static & dynamic characteristics of the hysteresis function are expressed as:



$$F(q,\dot{q}) = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 \dot{q}$$

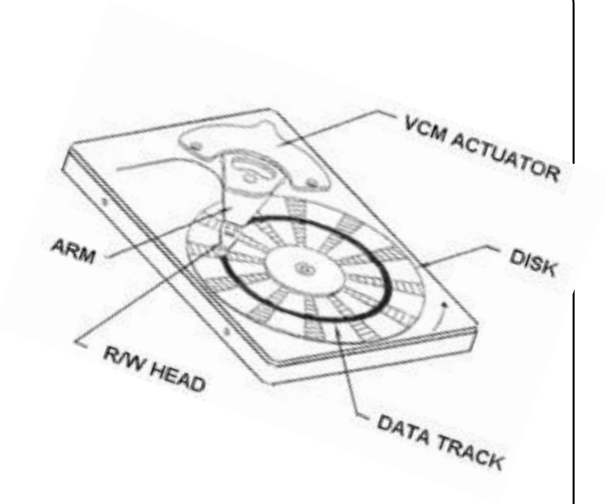
$$\dot{z} = \dot{q} - \alpha(\dot{q}) \mid \dot{q} \mid z$$

$$\alpha(\dot{q}) = \frac{\sigma_0}{f_c + (f_s - f_c) e^{-\left(\frac{\dot{q}}{\dot{q}_s}\right)^2}}$$

σ_0 : Stiffness coefficient,
σ_1 : Micro damping ratio, and
σ_2 : Viscous coefficient

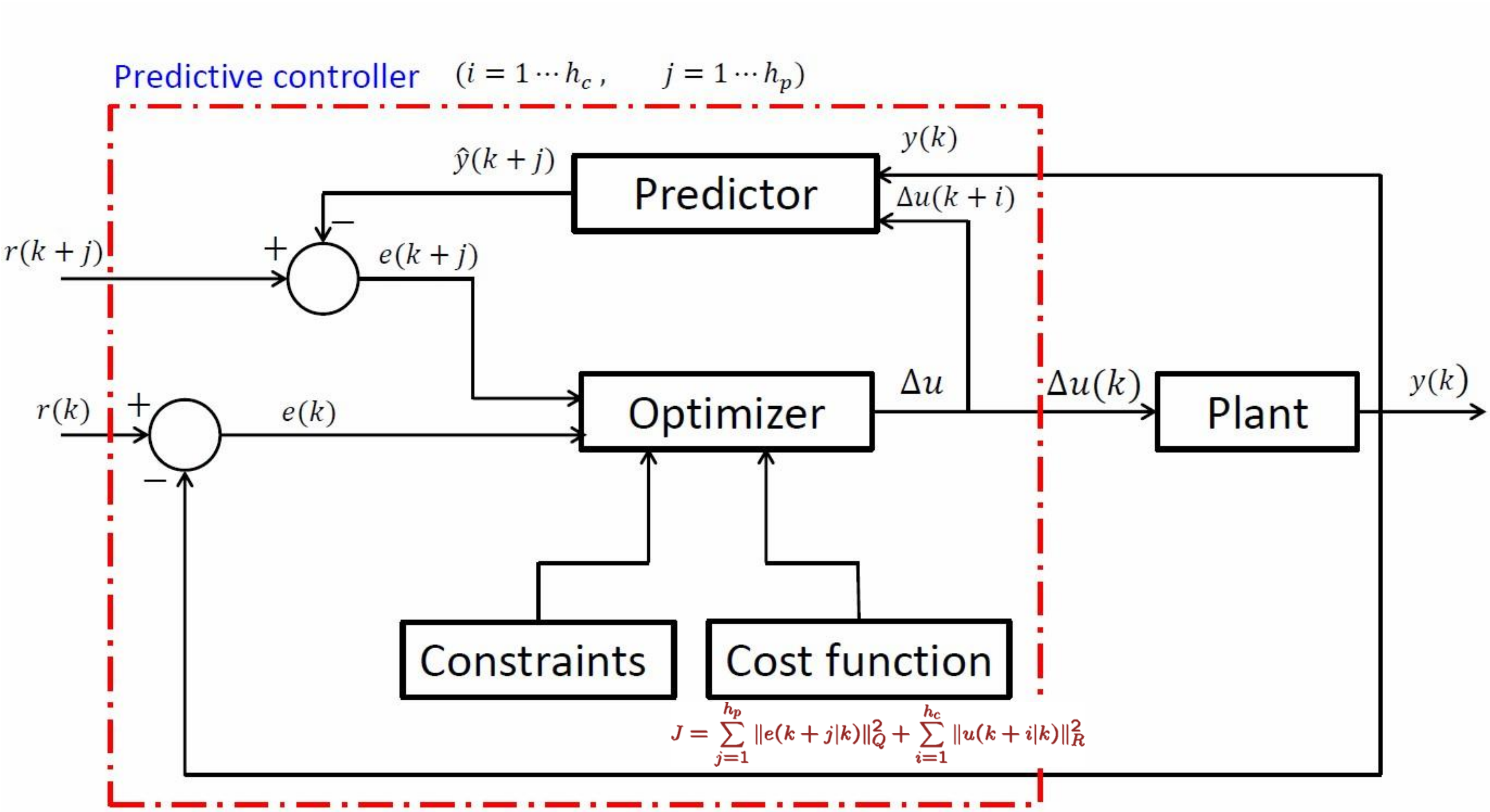
f_c : Coulomb friction force,
f_s : Stiction force, and
$\dot{q}_s$: Stribeck velocity

Control problem



- ✓ Two problems: **Track seeking / Track following**
- ✓ Second one : keep the **head** closed to the **desired track**
- ✓ Both **precision** and **rapidity** are required (**robustness**)
- ✓ **Bounded** control input
- ✓ **Uncertain** nonlinear system
- ✓ **Implementation** of the proposed control architecture in **simulation**
- ✓ Tests in various operating conditions
  - *Nominal conditions with noise*
  - *External disturbance rejection*
  - *Robustness towards parameters' uncertainties*
- ✓ **Proposed solution** : Nonlinear Model Predictive Control (**NMPC**)

Proposed control solution

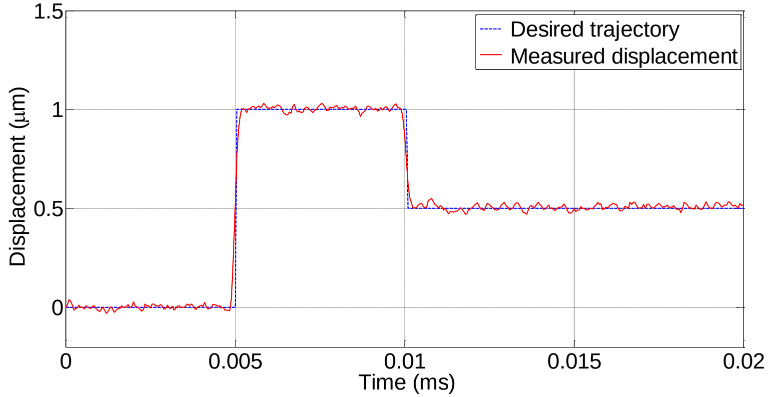


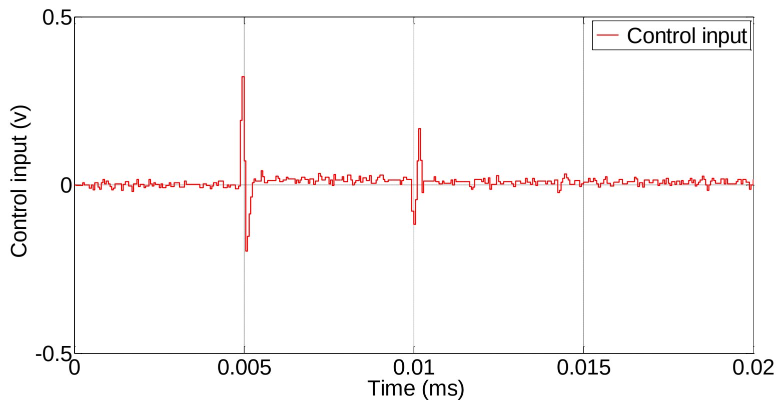
Simulation results

- ✓ Scenario 1: Nominal case
- ✓ Scenario 2 : External disturbance rejection
- ✓ Scenario 3 : Robustness towards parameters' uncertainties

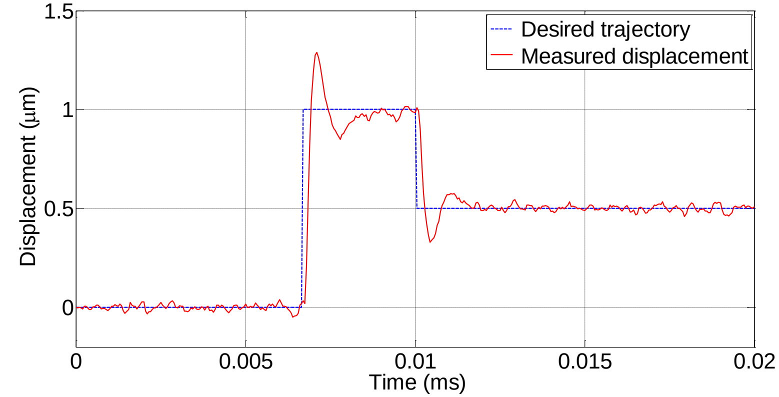
Scenario 1 : Nominal case with noise

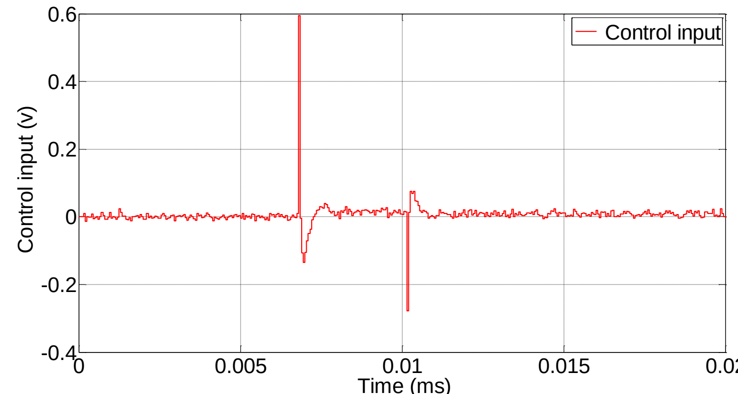
NMPC





PID

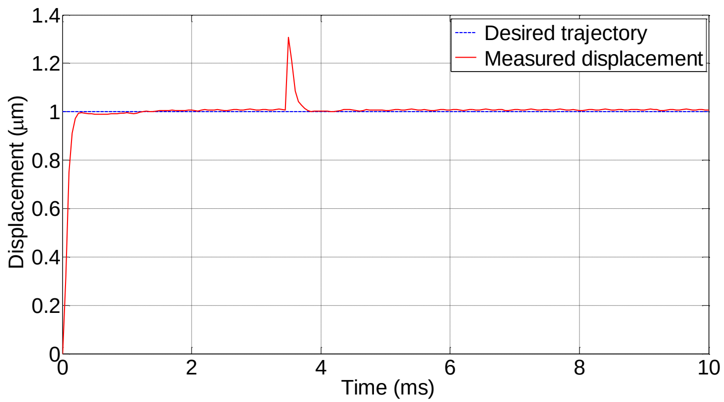


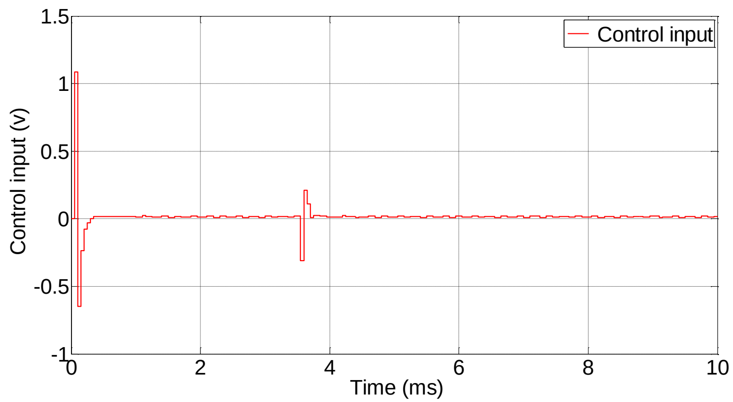


	Settling time (ms)	Maximum overshoot
PID controller	2,07	31%
NMPC controller	0,33	4%

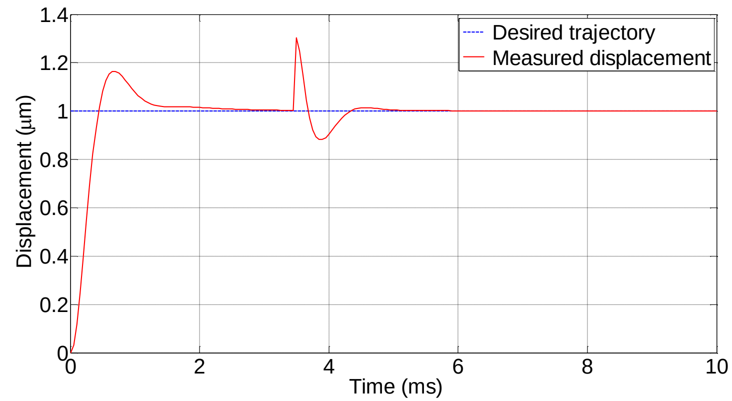
Scenario 2 : External disturbance rejection

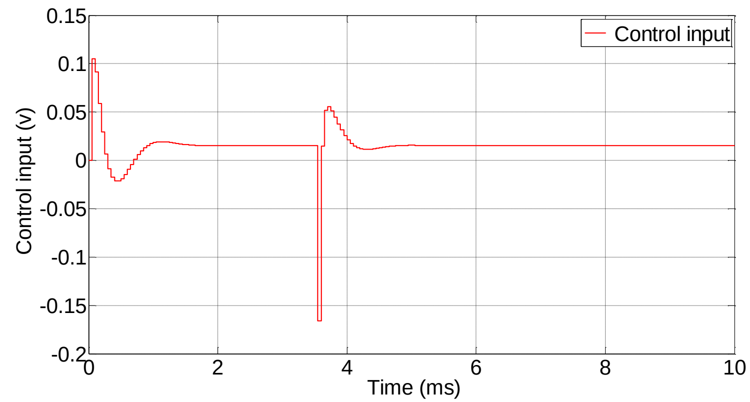
NMPC





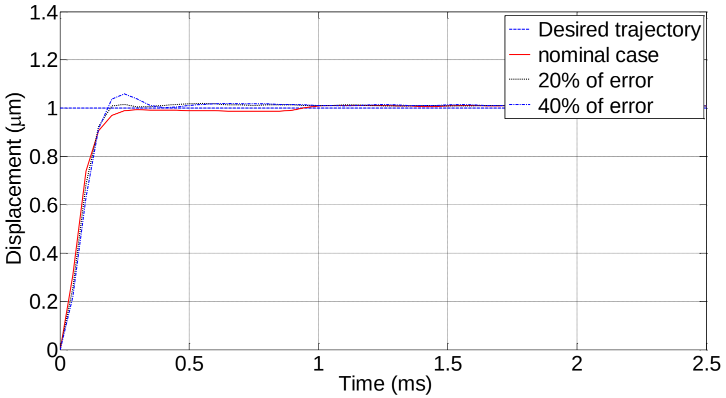
PID

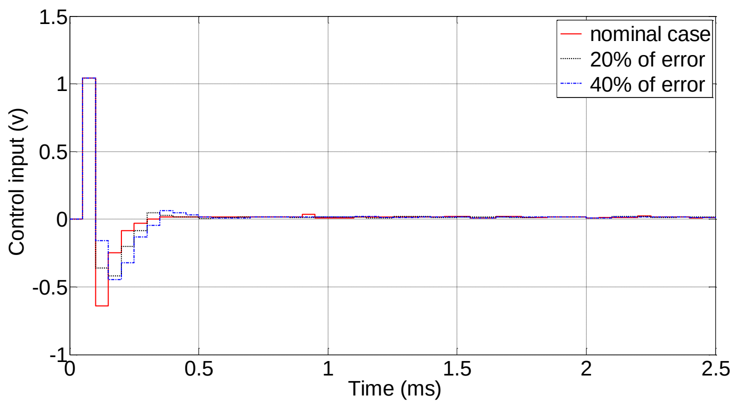




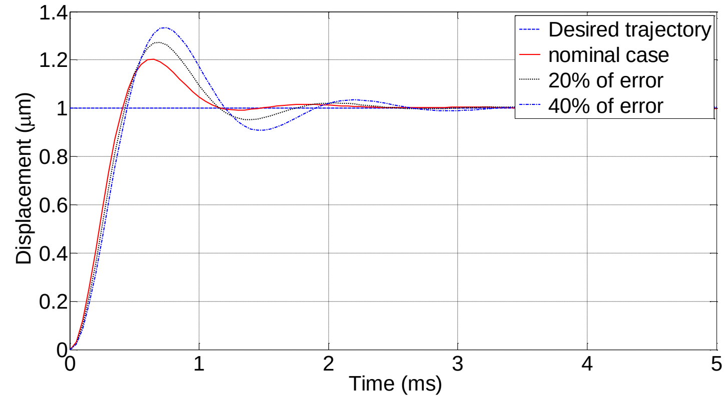
Scenario 3 : Robustness towards uncertainties

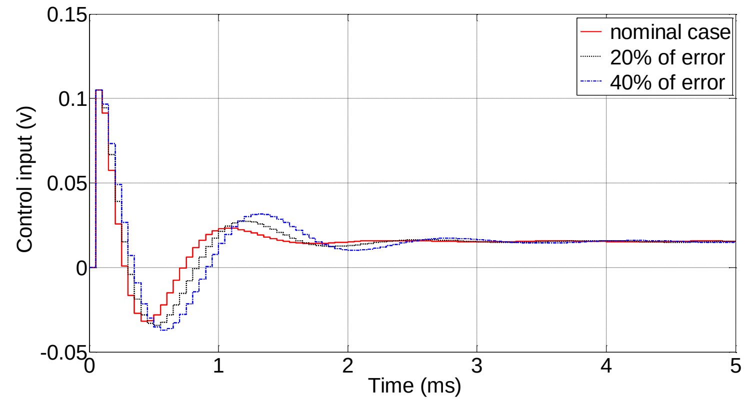
NMPC





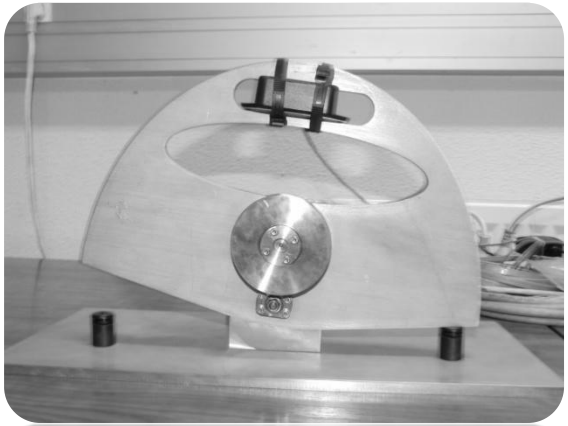
PID





Example 3

Inertia Wheel Inverted Pendulum



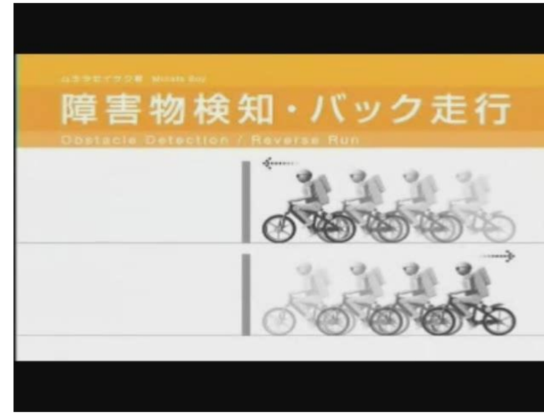
Principle of the gyrostabilizer

- The effect of a torque (e.g. gravity / excitation moments)

Causes a variation in the spin axis

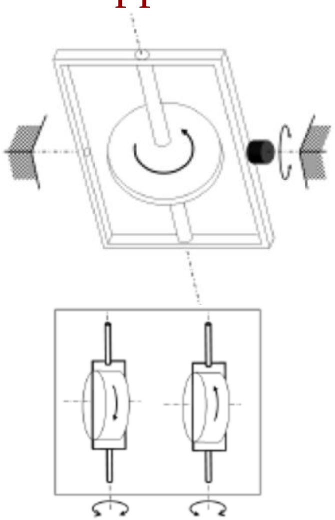
Reaction of a spinning wheel

Output torque orthogonal to the input torque and spin axes



- The phenomenon provides an effective means of motion control and balance
- Gyro's flywheel must be in motion to resist gravity
- Two early examples of application :

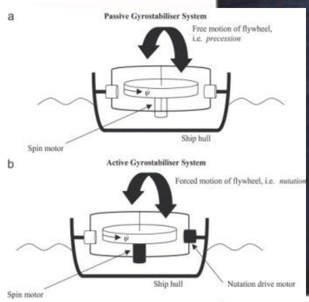
The Schilovski Gyrocar (1914)



- ✓ Single gimbal active stabilizer unit
- ✓ With 40 inch diameter & 4.5 inch thick
- ✓ Flywheel operated at 2000-3000 rpm

- ✓ Twin type active stabilizer system (3000 rpm)
- ✓ 40 feet long and weighted 22 tons
- ✓ Developed primary for military applications

Examples of some applications



[Townsend et al 2007]

Marine systems

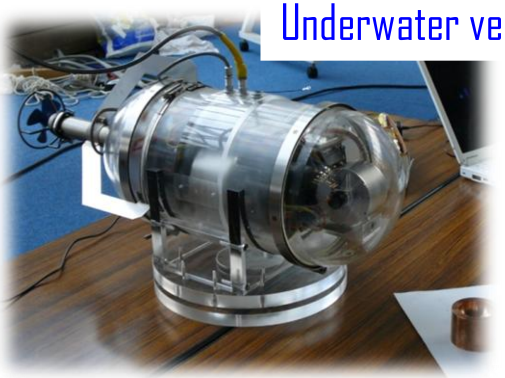
Robotics

Aerospace

Gyrostabilizer Applications

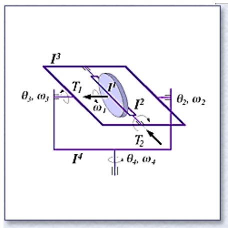
Monorails

Underwater vehicles



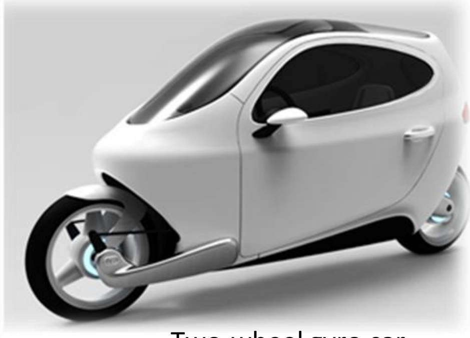
IKURA AUV

Academic



ECP 750

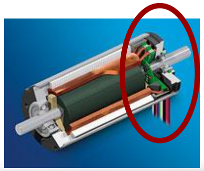
Cars



Two-wheel gyro car

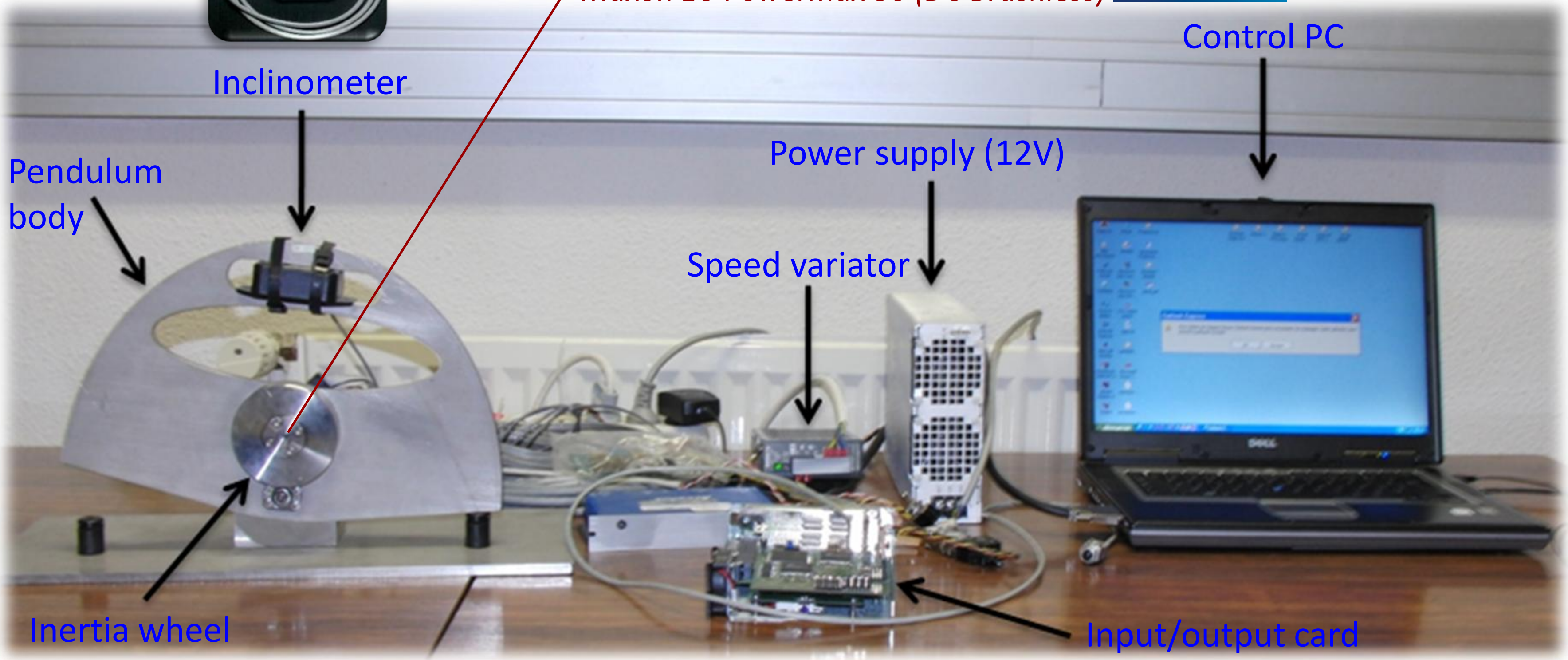
Description of the experimental testbed





Micro strain FAS-G

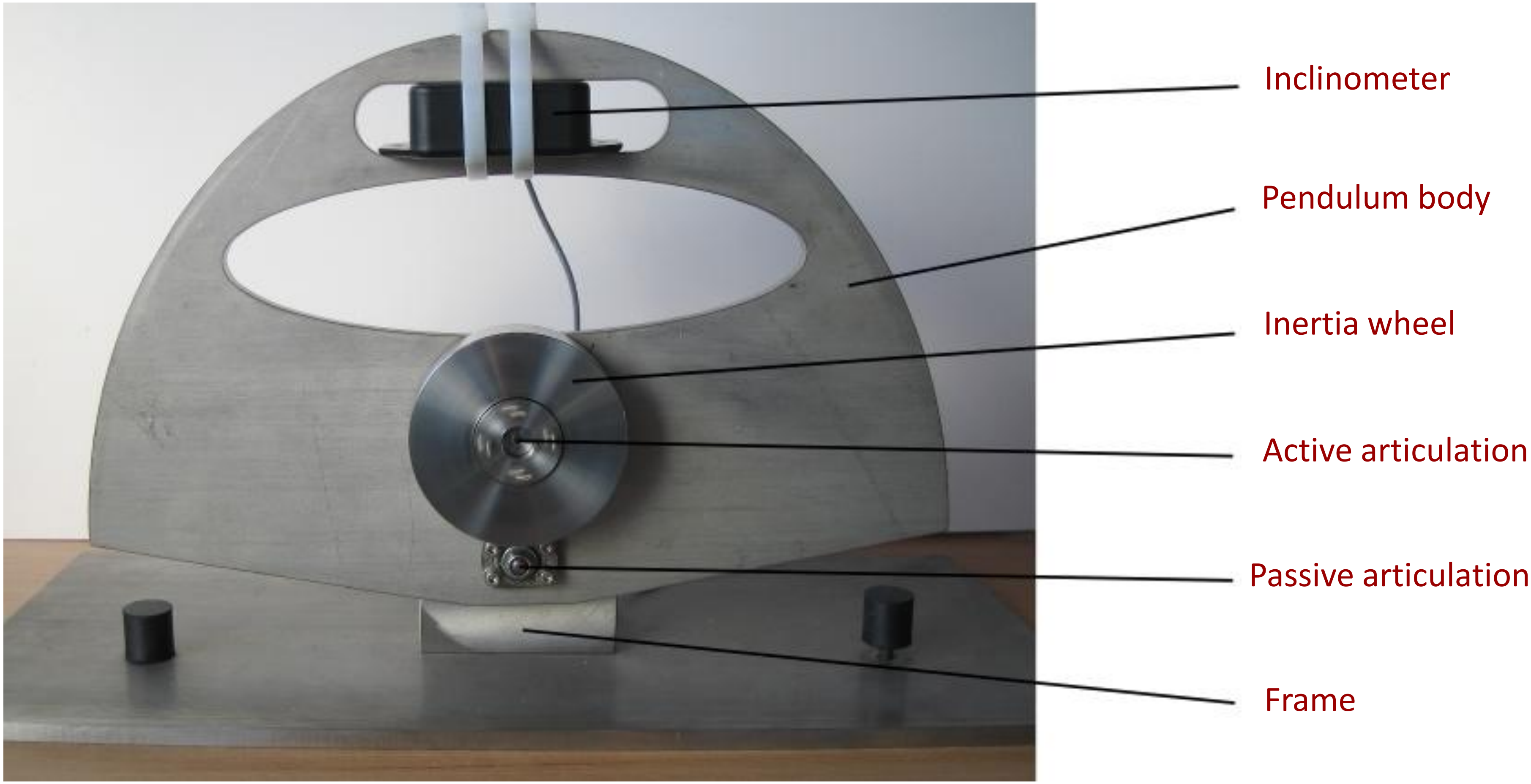
Maxon EC-Powermax 30 (DC Brushless)



Mechanical part

Electric/electronic part

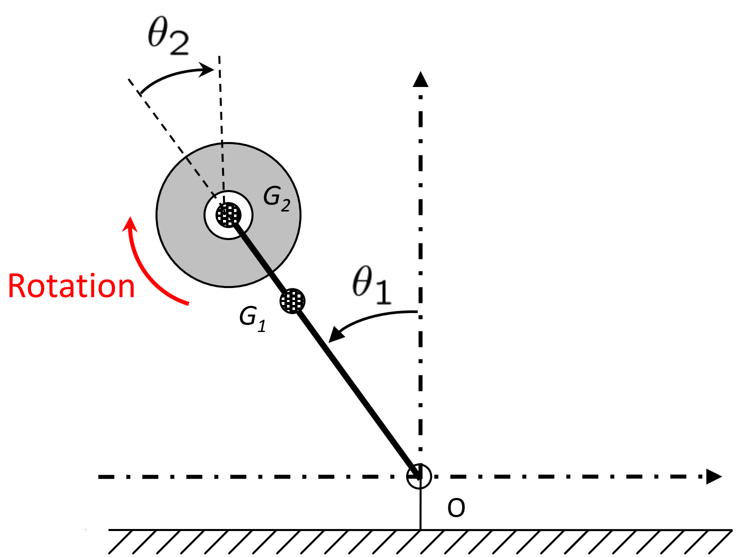
Description of the mechanical part



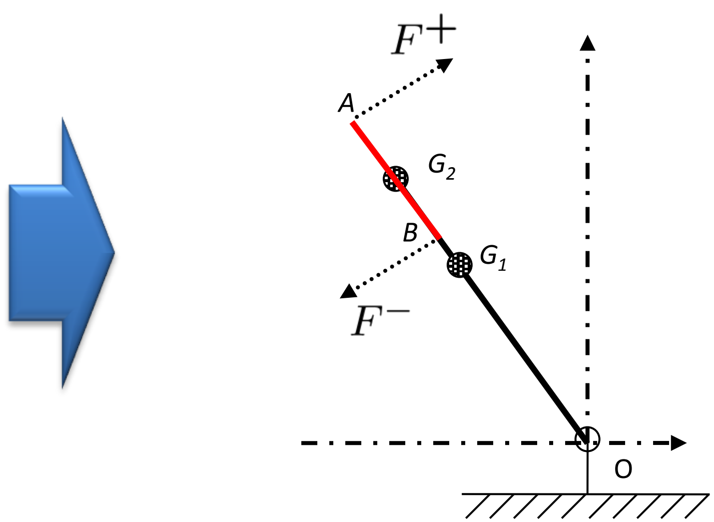
Mechanical part of the system : inertia wheel inverted pendulum

Functioning principle

- The actuator is controlled to produce a torque on the inertia wheel
- Torque can produce an acceleration of the rotating wheel
- Thanks to the dynamic coupling, a torque acting on the passive joint is generated
- This passive joint can be controlled through the acceleration of the inertia wheel

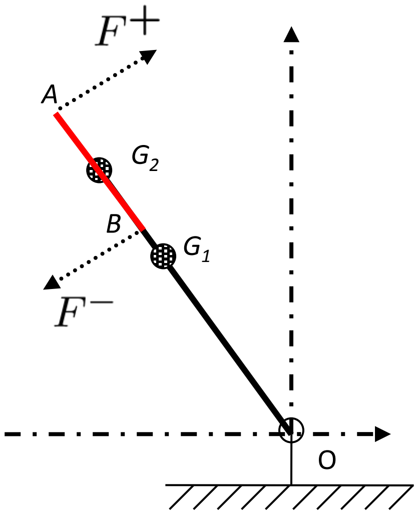


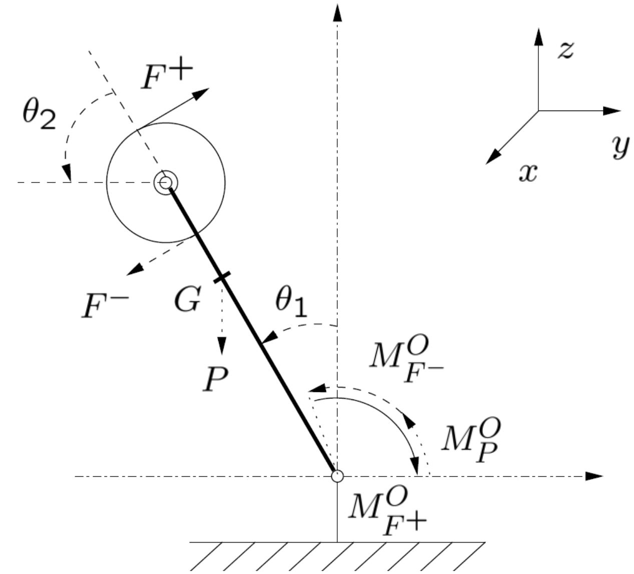
Initial mechanical model



Equivalent mechanical model

Functioning principle



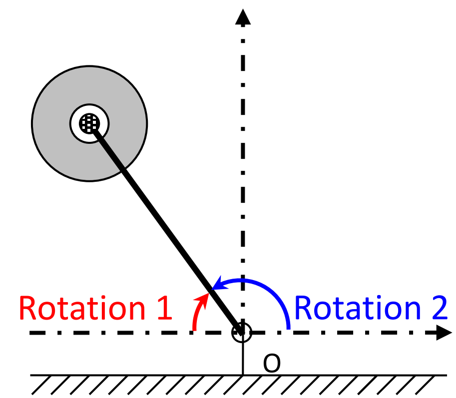


Three moments are acting on the passive joint :

- ✓ Moment relative to the force : F^+
- ✓ Moment relative to the force : F^-
- ✓ Moment du to the gravity force : P

$$M^O_{F+} > M^O_{F-} + M^O_P$$

$$M^O_{F+} < M^O_{F-} + M^O_P$$



One moment (torque of actuator) is acting on the active joint (inertia wheel)

Dynamic modeling

- Generalized coordinates : $q_1 = \theta_1 \quad , \quad q_2 = \theta_2$
- Propose to use the formalism of Lagrange : $\frac{d}{dt}\Big(\frac{\partial L}{\partial \dot{q}_i}\Big) - \frac{\partial L}{\partial q_i} = Q_i \quad , \quad i = 1..2$
- The application of Lagrange principle gives :

$$T = \tfrac{1}{2}(m_1 l_1^2 + m_2 l_2^2 + i_1)\dot{\theta}_1^2 + i_2(\dot{\theta}_1 + \dot{\theta}_2)^2 \qquad V = (m_1 l_1 + m_2 l_2) g \cos(\theta_1)$$

$$L = T - V = \tfrac{1}{2} I \dot{\theta}_1^2 + i_2(\dot{\theta}_1 + \dot{\theta}_2)^2 - \overline{ml} g \cos(\theta_1)$$

$$\overline{ml} = m_1 l_1 + m_2 l_2$$

$$I = m_1 l_1^2 + m_2 l_2^2 + i_1$$

$$\begin{cases} \ddot{\theta}_1 &= \dfrac{1}{I}\big[-\tau_2 + \overline{ml} g \sin\theta_1 \big] \\ \ddot{\theta}_2 &= \dfrac{1}{I i_2}\big[(i_2 + I)\tau_2 - i_2 \overline{ml} g \sin\theta_1 \big] \end{cases}$$

$$\boxed{\begin{bmatrix} I + i_2 & i_2 \\ i_2 & i_2 \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} \overline{ml} g \sin\theta_1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ \tau_2 \end{bmatrix}}$$

$$M(q)\ddot{q} + H(q,\dot{q}) + G(q) = Ru$$

Control problem formulation

- Assume the system in some initial condition
- Find a control input u to bring $x(t)$ to x_e and maintain it around this point

- Proposed solutions :
  - ✓ State feedback control
  - ✓ Optimal control
  - ✓ Sliding mode control
  - ✓ **Generalized Predictive Control (GPC)** → Linear discrete dynamics

Linearization of the dynamics

- Recall the nonlinear dynamics : $\begin{cases} \ddot{\theta}_1 = \frac{1}{I}[\tau_1 - \tau_2 + \overline{ml}g \sin\theta_1] \\ \ddot{\theta}_2 = \frac{1}{Ii_2}[-i_2\tau_1 + (i_2 + I)\tau_2 - i_2\overline{ml}g\sin\theta_1] \end{cases}$

- Consider the state vector : $x = [\theta_1 \quad \dot{\theta}_1 \quad \dot{\theta}_2]^T$ and $\tau_1 = 0 \quad , \quad \tau_2 = u$
- The nonlinear dynamics can be written in nonlinear state space as :

$$\dot{x} = f(x) + g(x)u$$

- The unstable equilibrium of the system : $x_e = [0 \quad 0 \quad 0]^T$
- The linearization of the dynamics around the unstable equilibrium gives :

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases}$$

With :

$$A = \begin{bmatrix} 0 & 1 & 0 \\ \overline{ml}g/I & 0 & 0 \\ -\overline{ml}g/I & 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ -1/I \\ (I + i_2)/i_2 I \end{bmatrix}, \quad C = [1 \quad 0 \quad 0], \quad D = [\ 0\ ]$$

Discritization of the dynamics

- Recall the linearized dynamics : $$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases}$$
- The discretization of the dynamics gives : $$\begin{cases} x_{k+1} = A_d x_k + B_d u_k \\ y_k = C_d x_k + D_d u_k \end{cases}$$

Summary of geometric and dynamic parameters of the system

Paramtre	Description	Valeur	unit
m_1	Masse du pendule	3.30810	Kg
m_2	Masse du volant	0.33081	Kg
l_1	Distance pivot / centre de gravit du pendule	0.06	m
l_2	Distance pivot / centre de gravit du pendule	0.044	m
i_1	Moment d'inertie du pendule	0.0314683	Kgm^2
i_2	Moment d'inertie du volant d'inertie	0.0004176	Kgm^2
g	Acclration de la pesanteur	9.81	ms^{-2}

Proposed control approach : GPC

- Consider the case of the GPC approach with penalty on the end-state
- Recall the discrete dynamics of the system :

$$\begin{cases} x(k+1) = A_d x(k) + B_d u(k) \\ y(k) = C_d x(k) + D_d u(k) \end{cases}$$

- Consider the extended state vector :

$$x_e(k+1) = \begin{pmatrix} x(k+1) \\ u(k) \end{pmatrix}$$

- The variation on the control input : $\Delta u(k) = u(k) - u(k-1)$

- The dynamics can be written as :

$$\begin{cases} x_e(k+1) = A_e x(k) + B_e \Delta u(k) \\ y_e(k) = C_e x_e(k) + D_e \Delta u(k) \end{cases}$$

with :

$$A_e = \begin{pmatrix} A_d & B_d \\ 0 & 1 \end{pmatrix} \qquad B_e = \begin{pmatrix} B_d \\ 1 \end{pmatrix} \qquad C_e = \begin{pmatrix} C & 0 \end{pmatrix} \qquad D_e = \begin{pmatrix} 0 \end{pmatrix}$$

This last dynamics will be used in the controller design

Proposed control approach : GPC

- Consider the following optimization function :

$$
\begin{aligned}
J(N_1, N_p, N_u, Q, \lambda) \;=\; & \sum_{j=N_1}^{N_p} [y(k+j) - w(k+j)]^T [y(k+j) - w(k+j)] + \\
& \sum_{j=N_1}^{N_u} \Delta u(k+j-1)^T \Delta u(k+j-1) + \\
& [x(k+N_p) - w_x(k+N_p)]^T Q [x(k+N_p) - w_x(k+N_p)]
\end{aligned}
$$

- From the system model one can have the state predictions :

$$
\begin{aligned}
x_e(k+1) &= A_e x_e(k) + B_e \Delta u(k) \\
x_e(k+2) &= A_e^2 x_e(k) + B_e \Delta u(k+1) \\
&\vdots \\
x_e(k+j) &= A_e^j x_e(k) + \sum_{i=0}^{j-1} A_e^{j-i-1} B_e \Delta u(k+i)
\end{aligned}
$$

- The prediction of future outputs be :

$$
y_e(k+j) = C_e A_e^j x_e(k) + \sum_{i=0}^{j-1} C_e A_e^{j-i-1} B_e \Delta u(k+i)
$$

Proposed control approach : GPC

- In a matrix form we have :

$$Y = \begin{bmatrix} y_e(k+1) \\ \vdots \\ y_e(k+j) \\ \vdots \\ y_e(k+N_p) \end{bmatrix} \quad ; \quad \Delta U = \begin{bmatrix} \Delta u(k) \\ \Delta u(k+1) \\ \vdots \\ \Delta u(k+N_u) \end{bmatrix}$$

$$Y = G\Delta U + f$$

$$G = \begin{bmatrix} CB & 0 & 0 & \dots & 0 \\ CAB & CB & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ CA^{N_1-1}B & CA^{N_1-2}B & CA^{N_1-3}B & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ CA^{N_p-1}B & CA^{N_p-2}B & CA^{N_p-3}B & \dots & CA^{N_p-N_u}B \end{bmatrix} \qquad f = \begin{bmatrix} CA \\ CA^2 \\ \vdots \\ CA^{N_1} \\ \vdots \\ CA^{N_p} \end{bmatrix} x(k) = Lx(k)$$

- The control input is computed as the minimum of : $\boxed{J_N = \frac{1}{2}\Delta u\, H\Delta u + b\Delta u + f_0}$

with

$$H = 2(G^T G + \lambda I + \bar{C}^T Q\,\bar{C})\,;$$
$$b = 2x(k)^T (L^T G + (A^N)^T Q\,\bar{C})\,;$$
$$f_0 = x(k)^T (L^T L + (A^N)^T Q A^N)x(k).$$

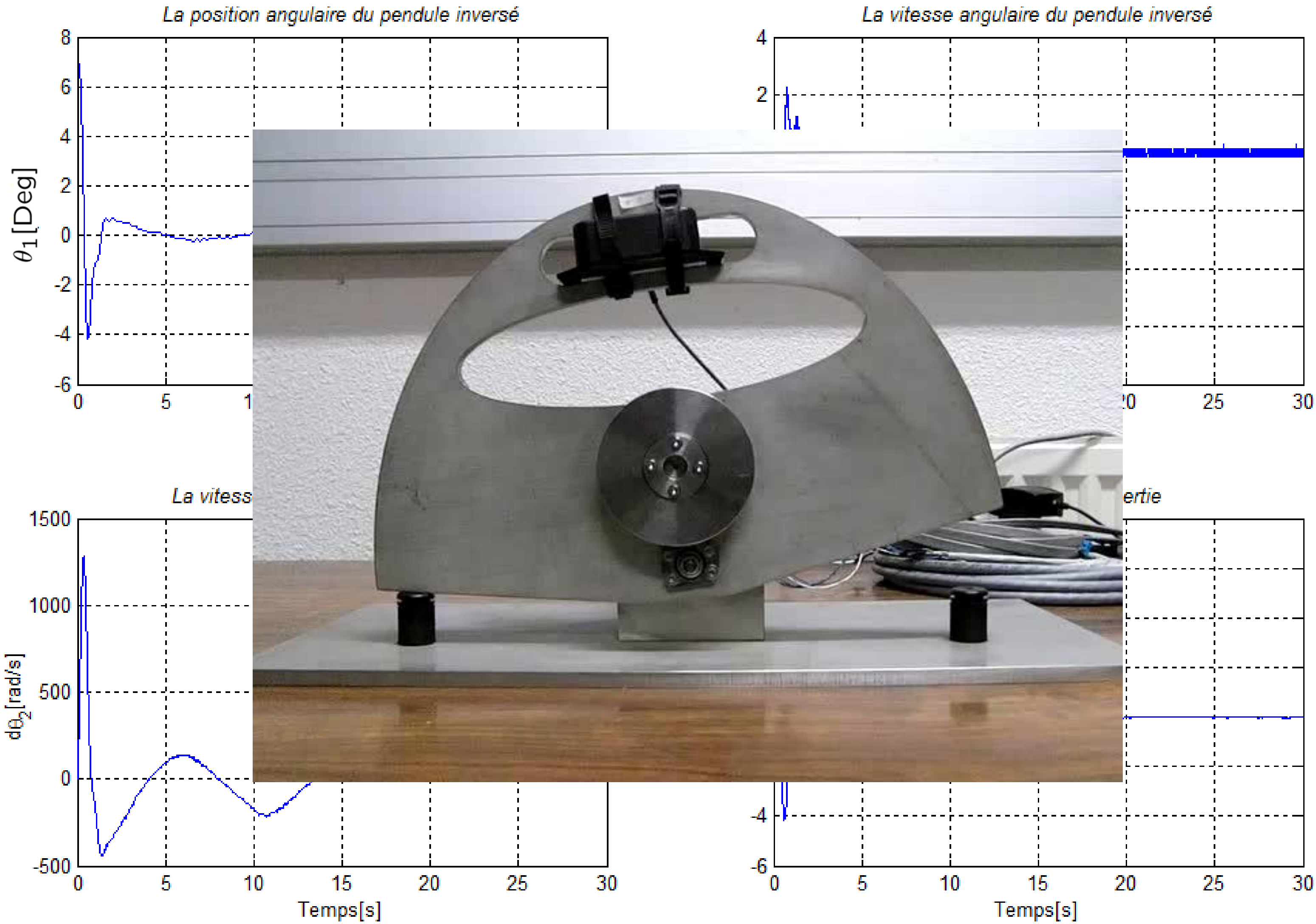
- The optimal solution is : $\boxed{\Delta u^* = -K\, x(k)}$

$$K = -(G^T G + \lambda\,\mathrm{I} + \bar{C}^T Q\bar{C})^{-1}(G^T + \bar{C}^T Q A^N)x(k).$$

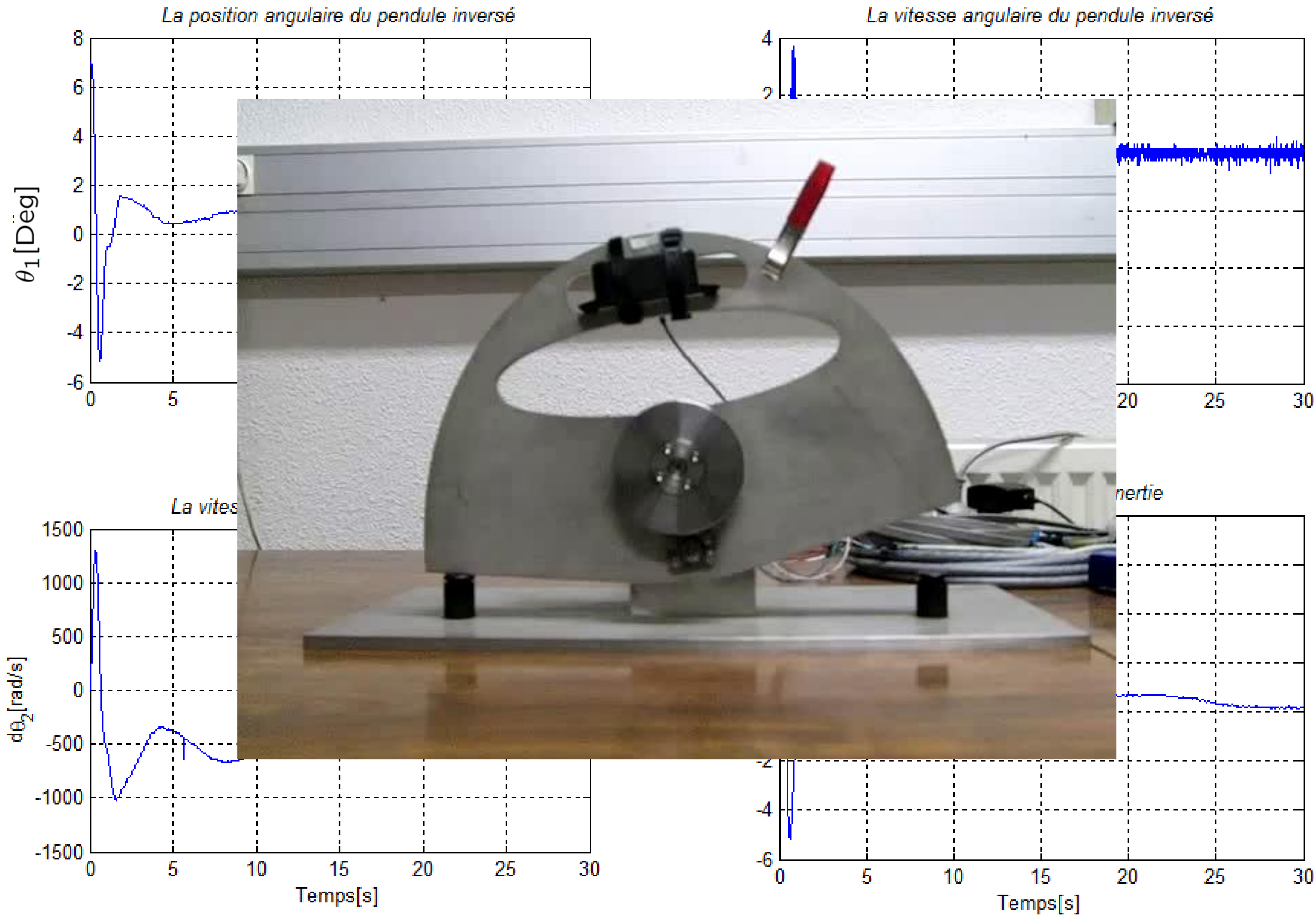
Real-time experiments

- ✓ Scenario 1 : Stabilization in the nominal case
- ✓ Scenario 2 : Case with persistent disturbance
- ✓ Scenario 3 : Case with punctual disturbance
- ✓ Scenario 4 : Combination of the two disturbances

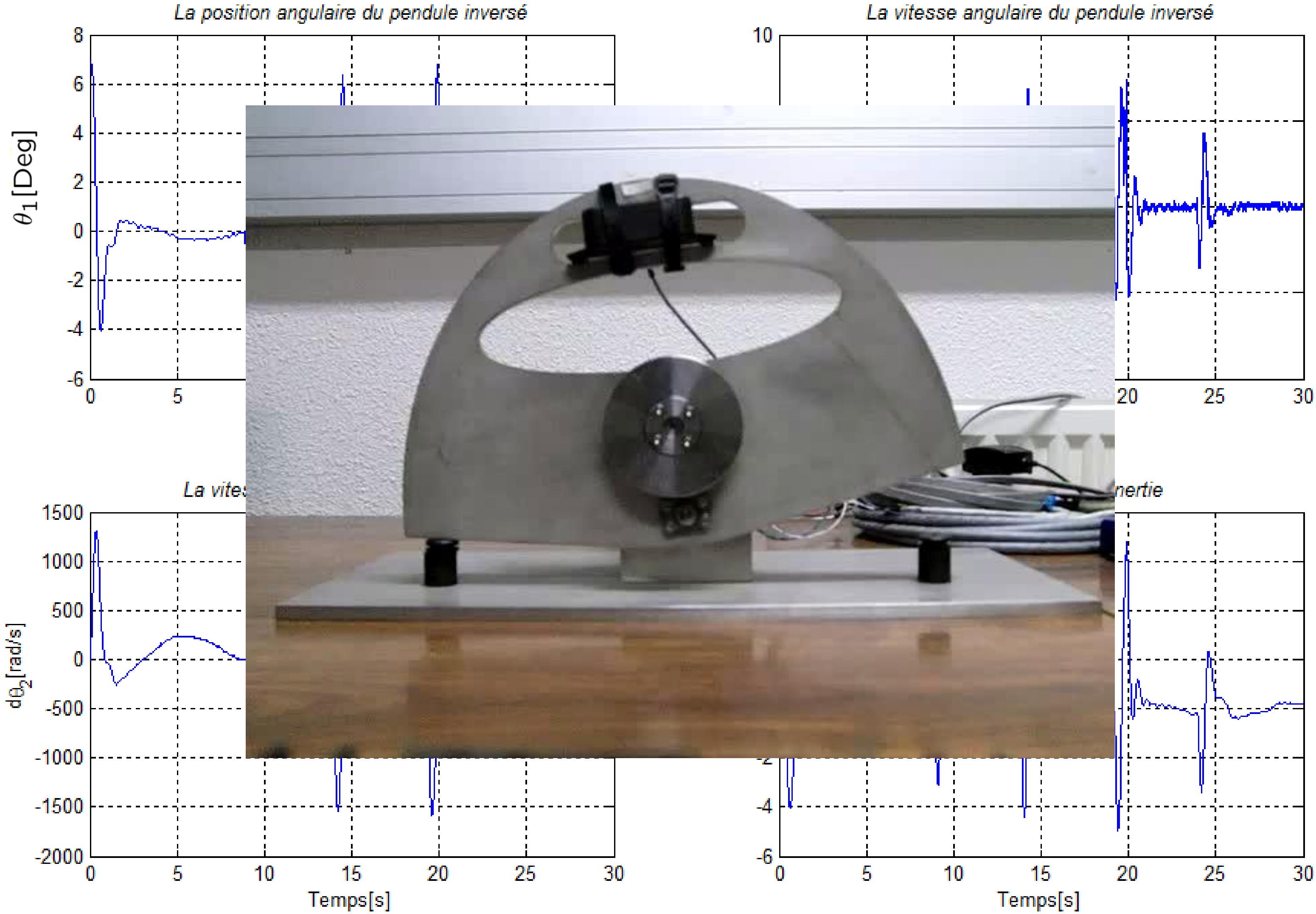
Scenario 1 : Stabilization in the nominal case



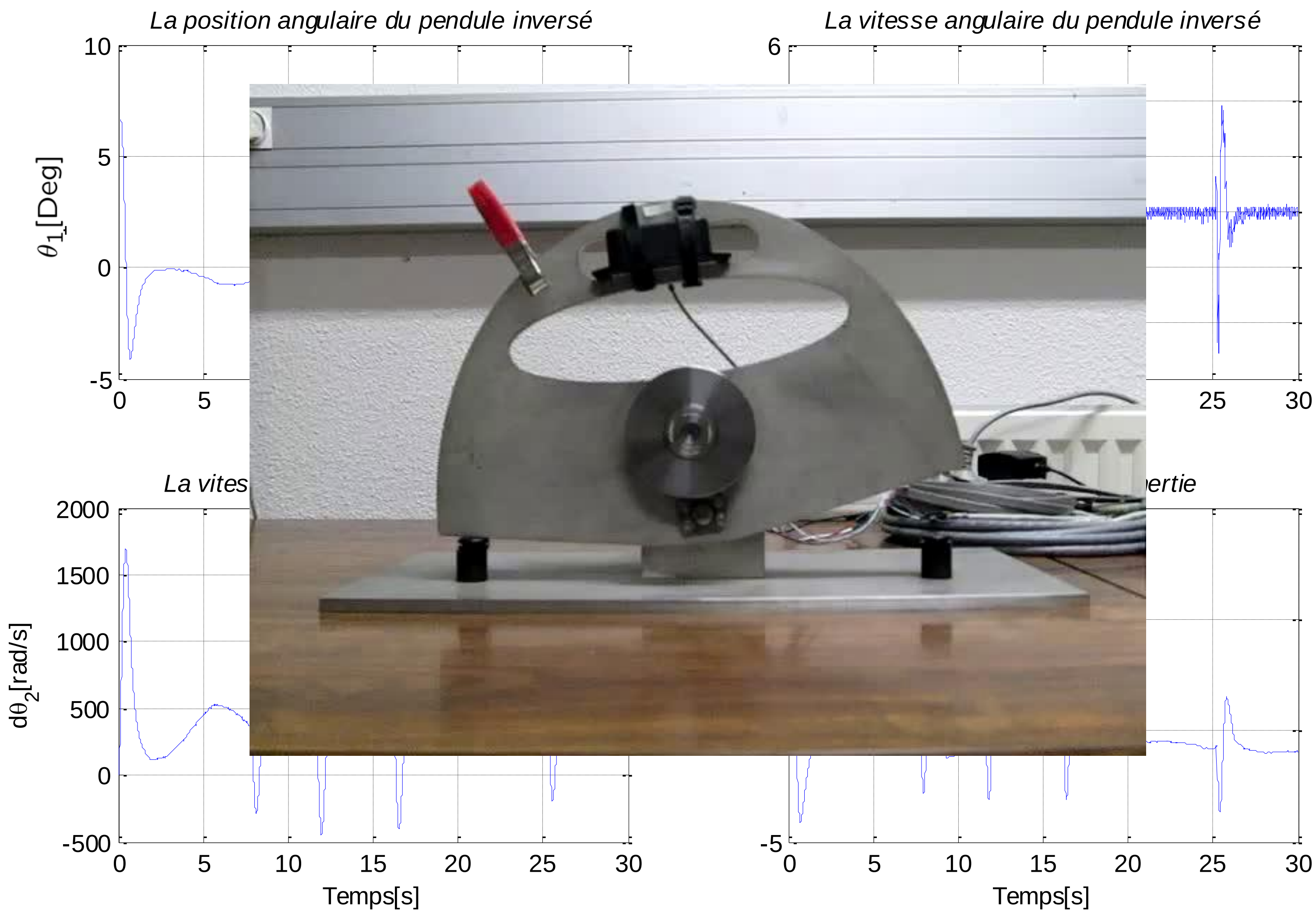
Scenario 2 : Case with persistent disturbance



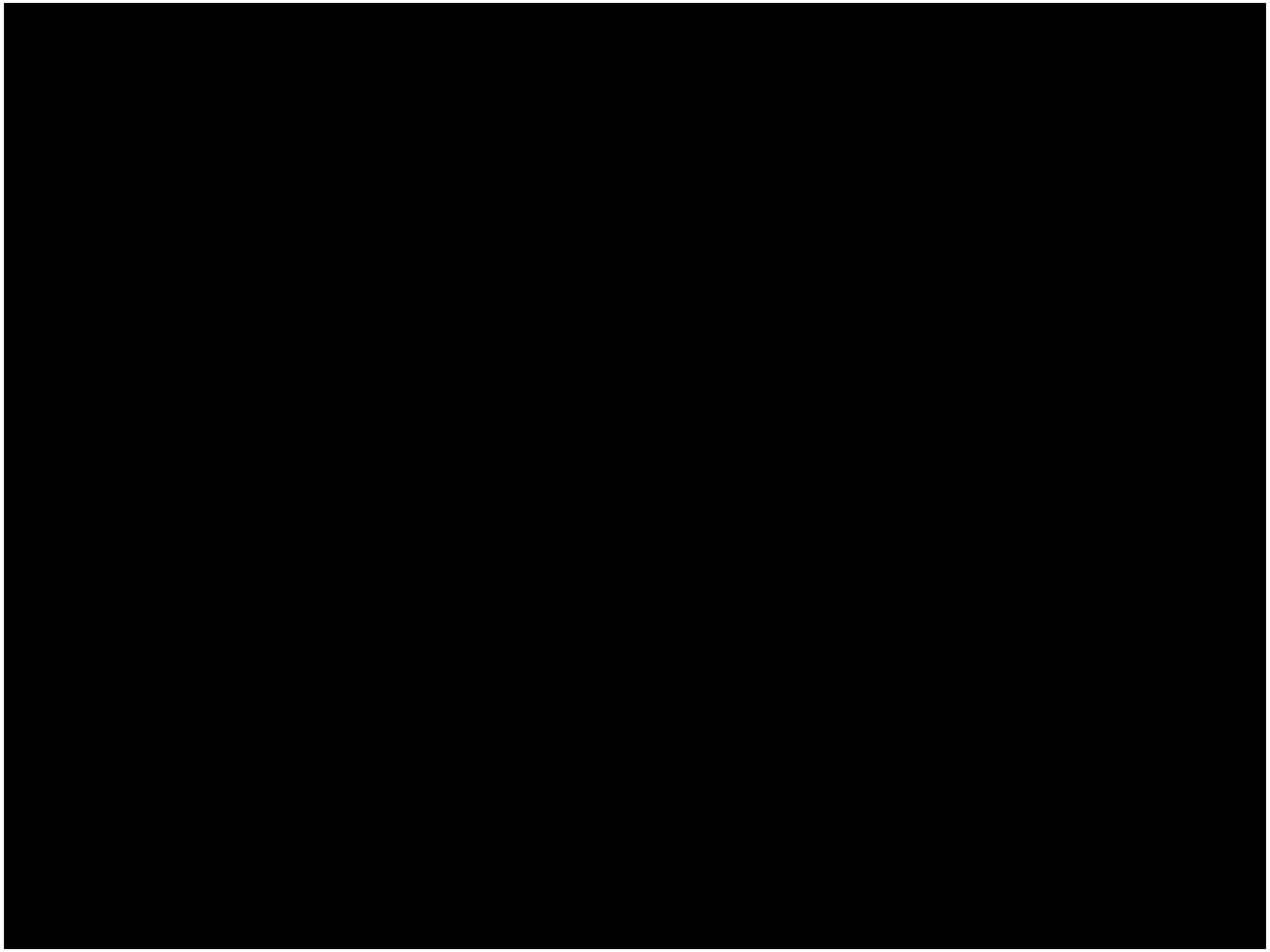
Scenario 3 : Case with punctual disturbance



Scenario 4 : Combination of the two disturbances



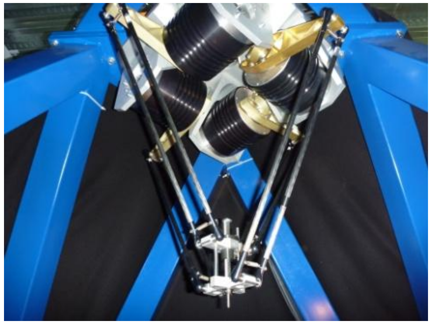
Stable limit cycle generation with
A prediction based optimal trajectories tracking



Conclusion & future work

Conclusion

- Control of Mechatronic systems
- Proposed controllers : Model predictive control
- Applications : 3 different examples of Mechatronic systems
  - ✓ One-leg hopping robot : NMPC
  - ✓ Hard disk drive : NMPC
  - ✓ Inertia wheel pendulum : GPC
- Validation : in simulation and real-time experiments
- Future work : control of more complex systems




For further reading ...

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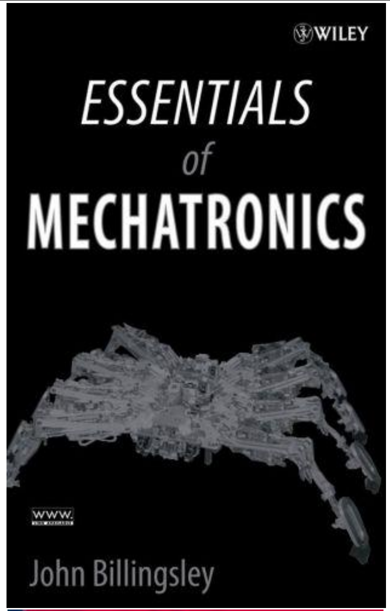
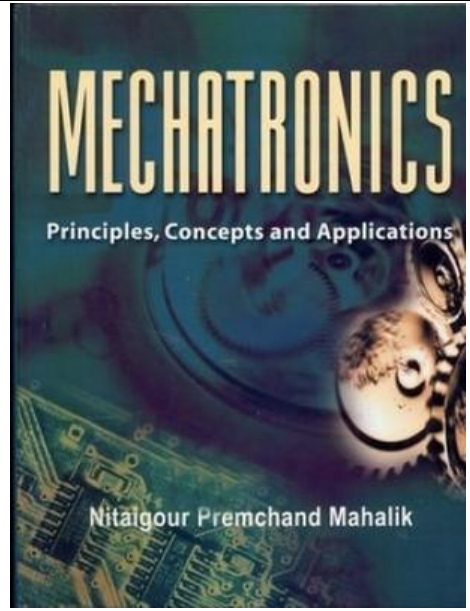
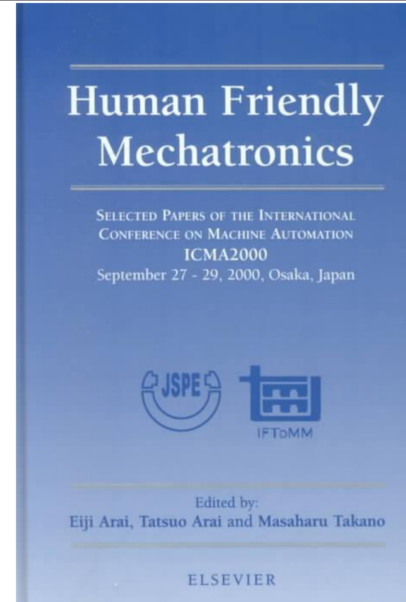
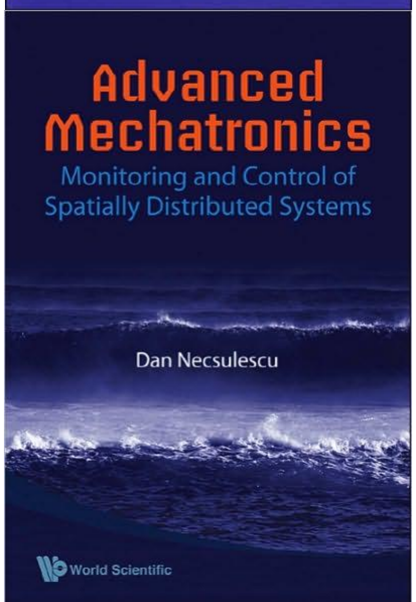
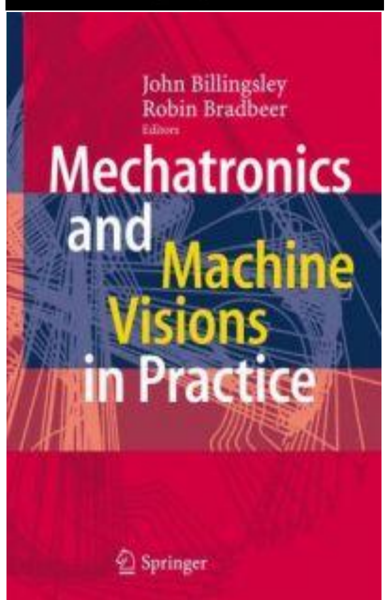
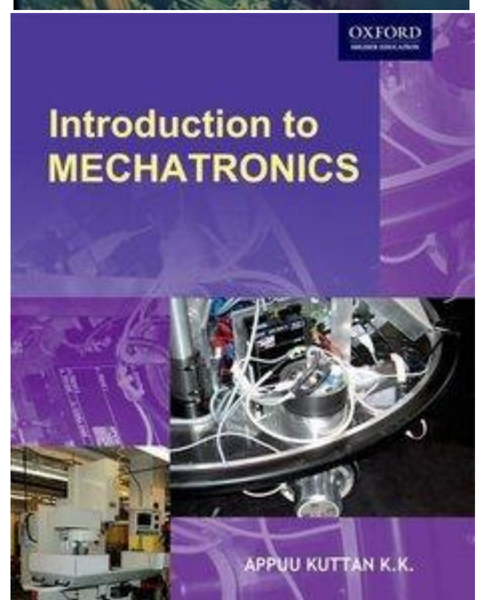


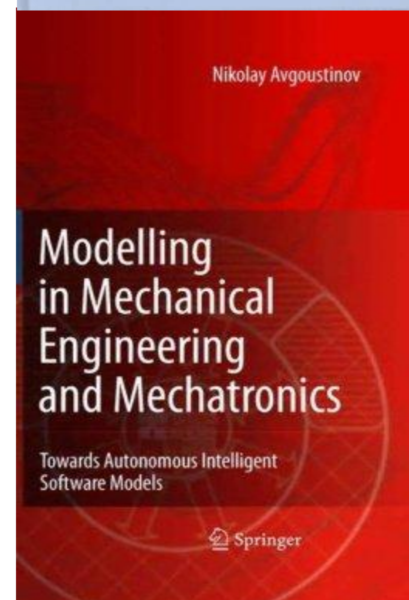




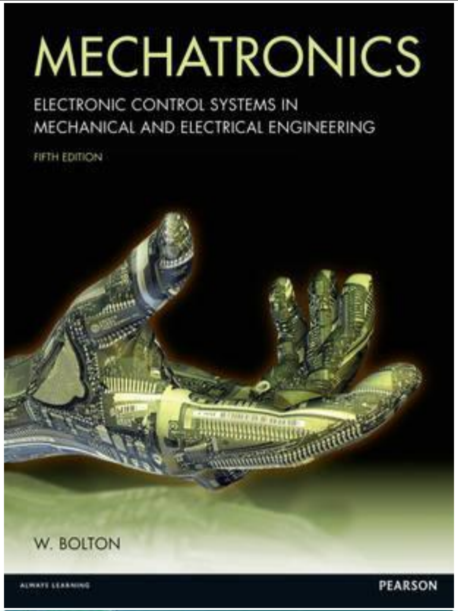


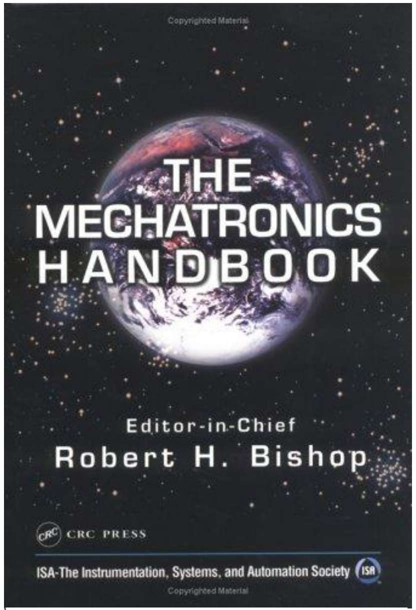


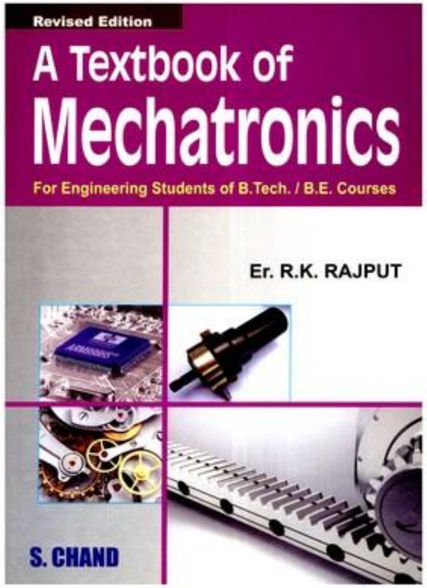


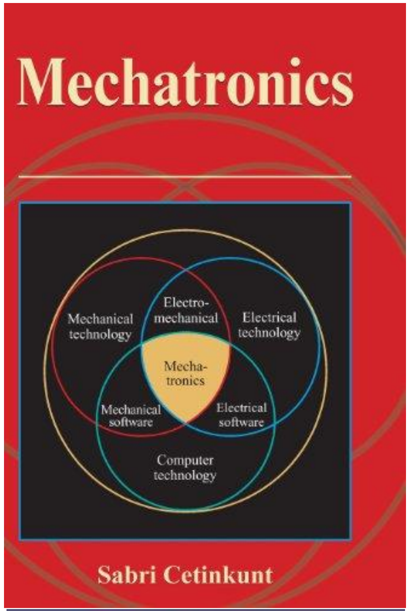


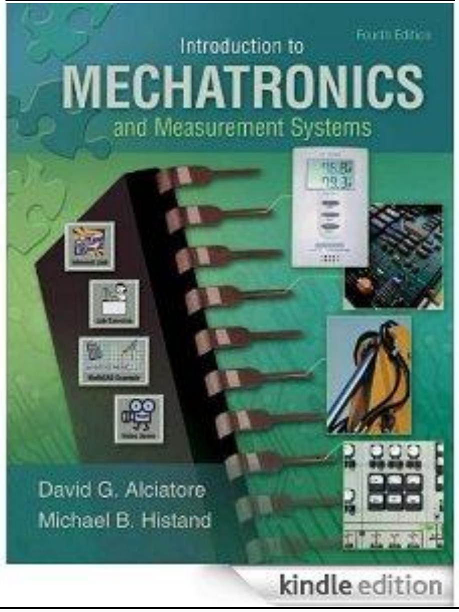
For further reading

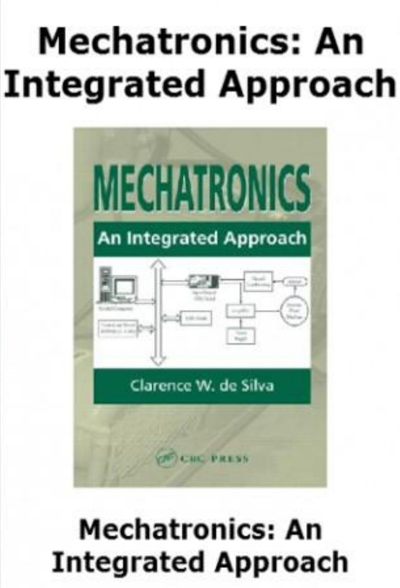


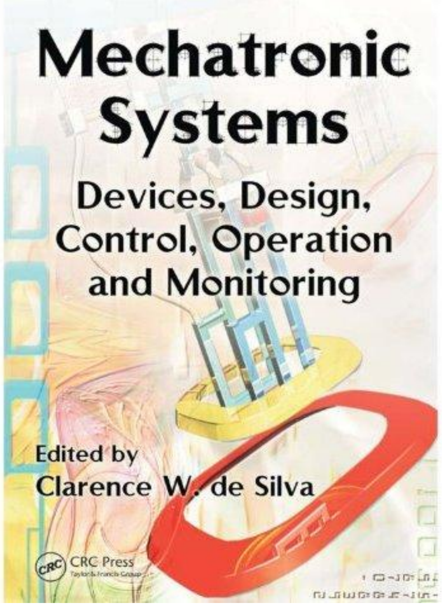


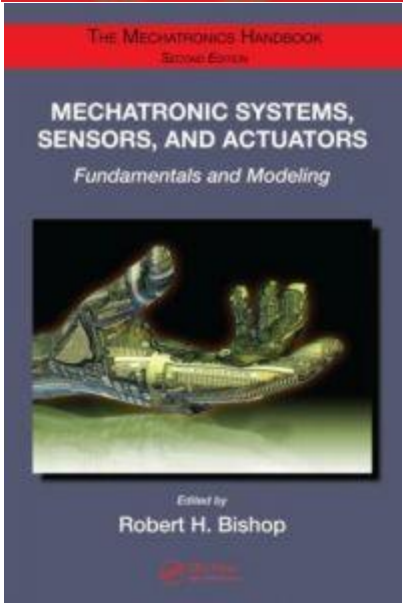












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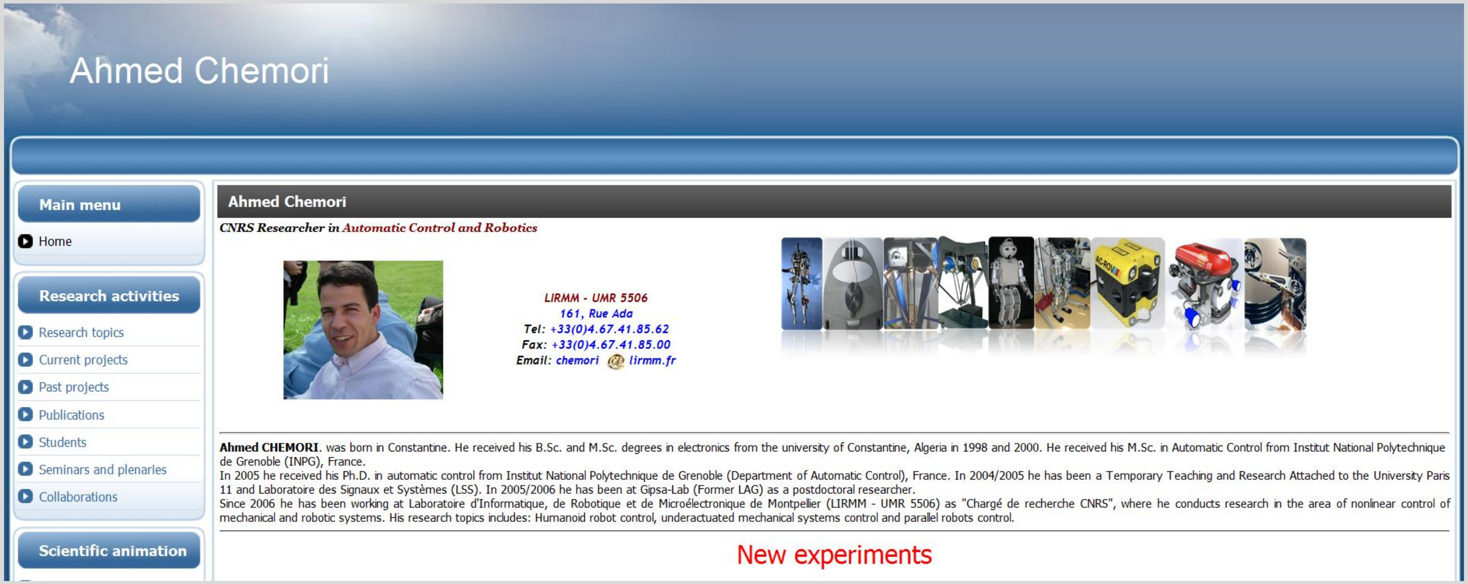

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