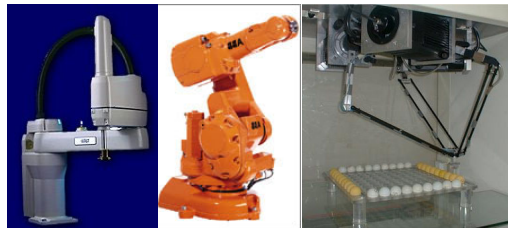


Control of robots of manipulation

Part1 – Control strategies



Ecole Polytechnique Fédérale de Lausanne

Dr M. Bouri,
REHAssist, Group leader

Dr M. Bouri, 2021

The robot and its numerical controller (NC)



Robot:

- *Mechanical structure,*
- *motorization,*
- *instrumentation.*

Cabling:

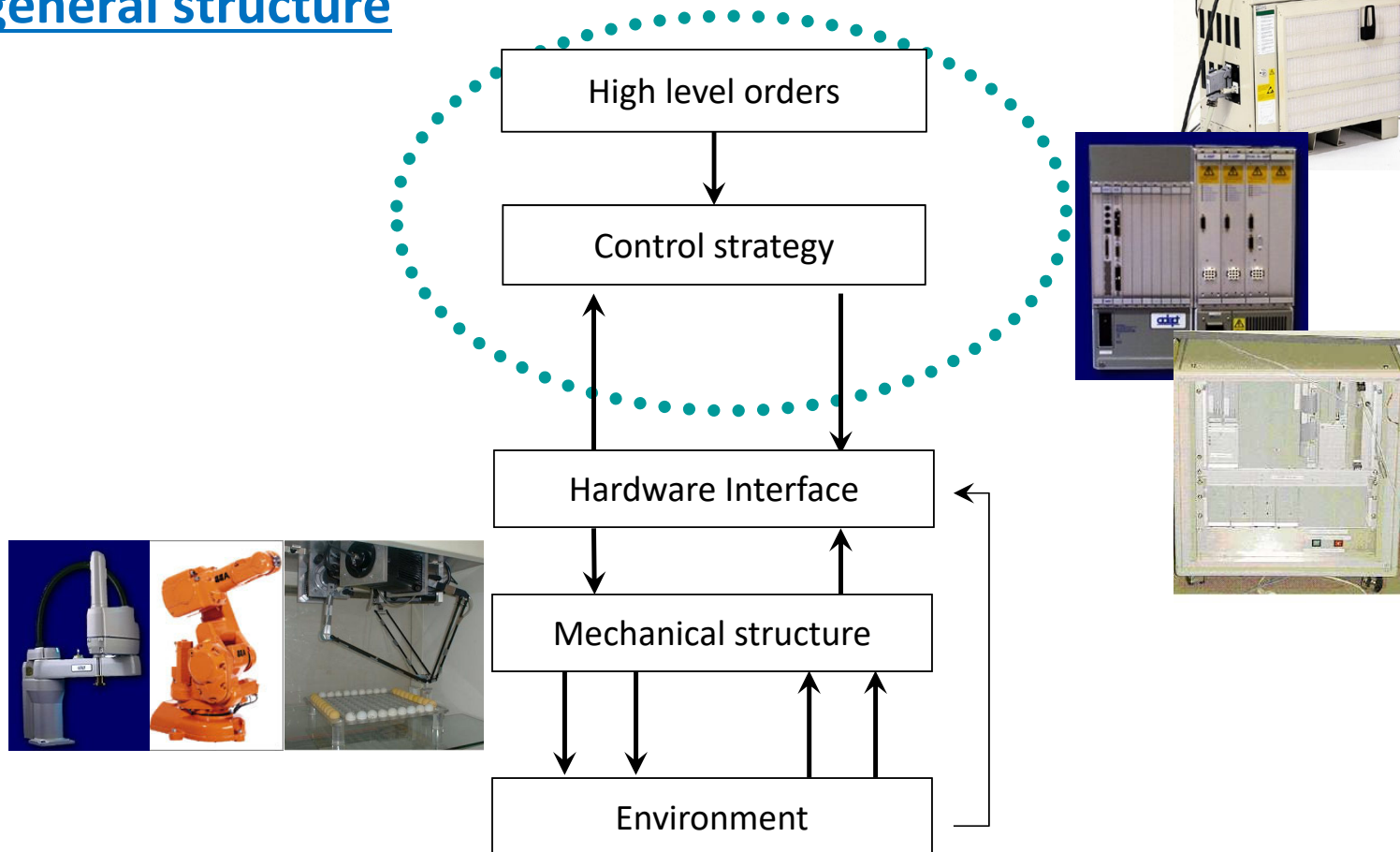
- Power,
- Signals.



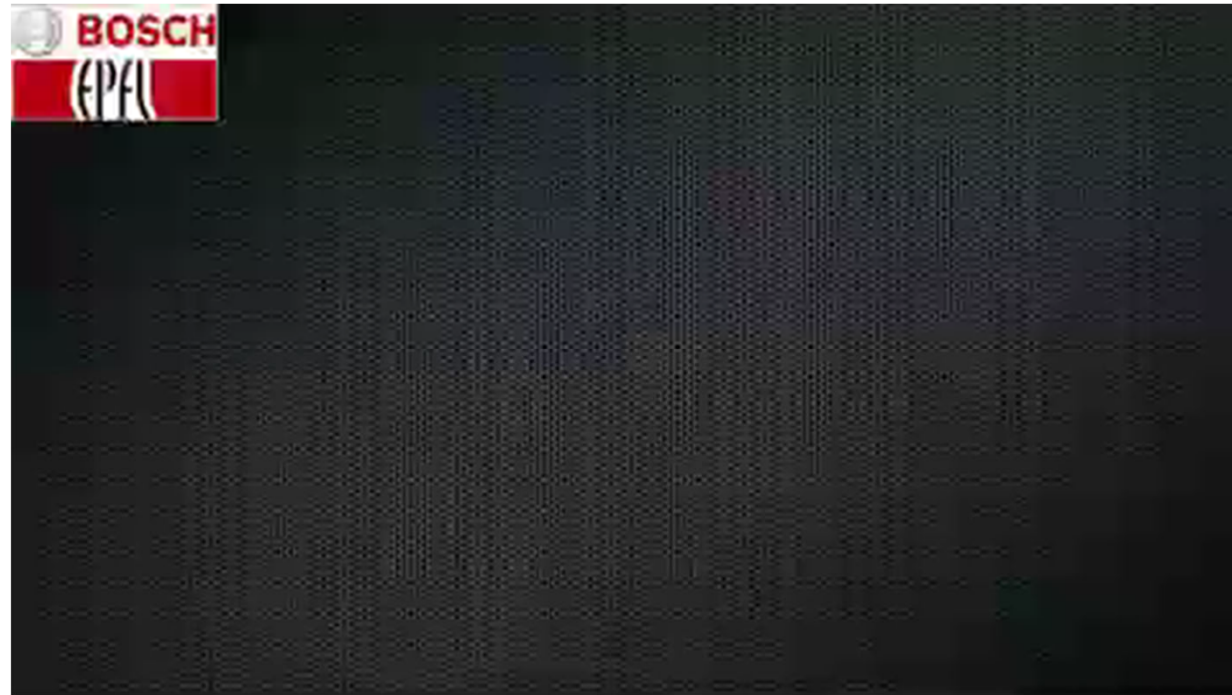
Control cabinet:

- *Intelligence*
- *I/O boards for the axes,*
- *I/O cards for safety,*
- *Power stage,*

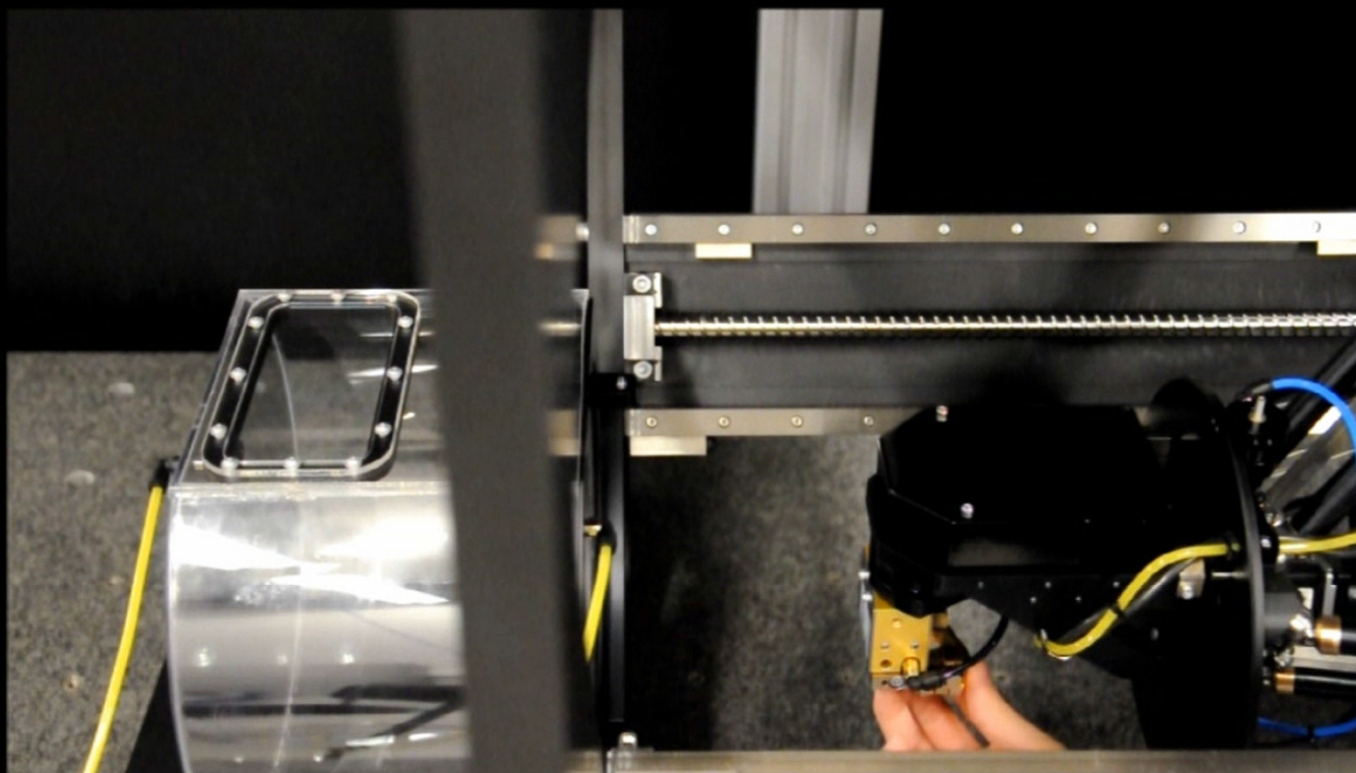
Robot : general structure



Direct Drive Actuated Delta realized for **BOSCH Packaging Technology**



[Patent 2015] Device For Moving And Positioning An Object In Space, Huser M., Tschudi M., Keiffer D., Teklits A., Bouri M., Clavel R., Demareux MO., Device For Moving And Positioning An Object In Space, reference WO2012152559



Ouverture de la pince

MINANGLE CONCEPT

Flexure-based tilting platform
for high rotation amplitudes ($\pm 15^\circ$)

Laboratoire de Systèmes
Robotiques LSRO
<http://lsro.epfl.ch>

Learning objectives

1. Control aspects :

- Control algorithms,
- Generation of trajectories,
- Profile generation

2. Hardware aspects:

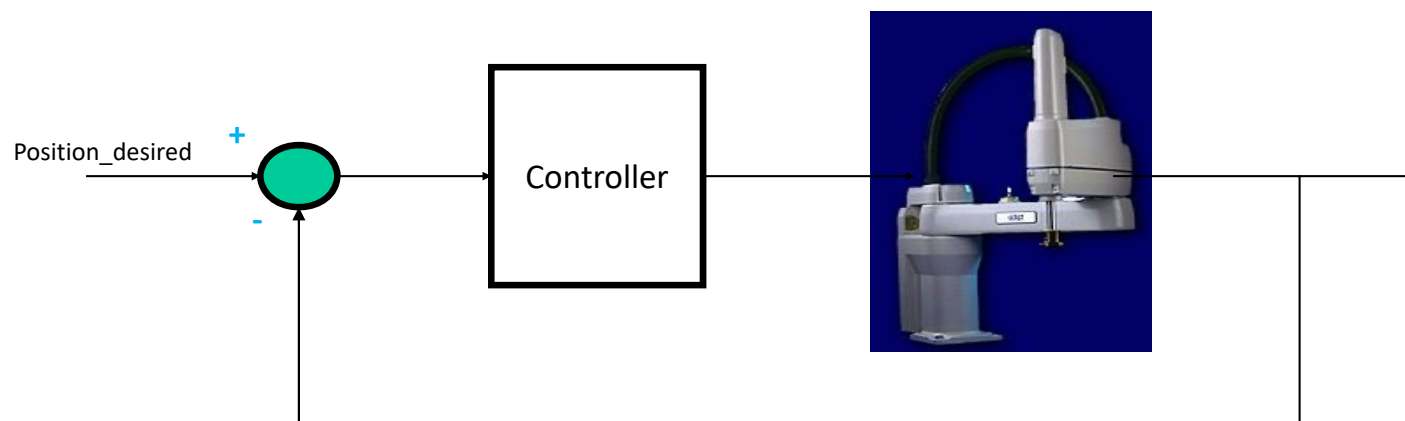
- Components for interfacing with axes
- Power and safety,
- Boards and buses

3. Software aspects:

- Multitasking structure of a control software,
- Need for real time,
- Development tools

Part 1

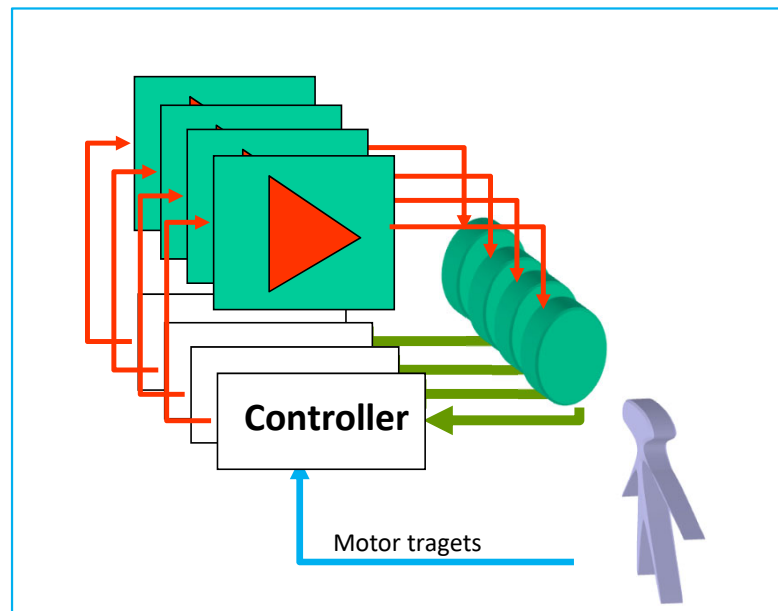
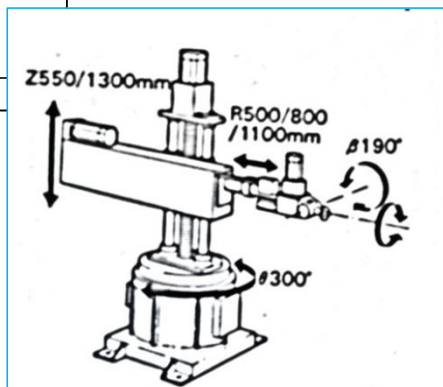
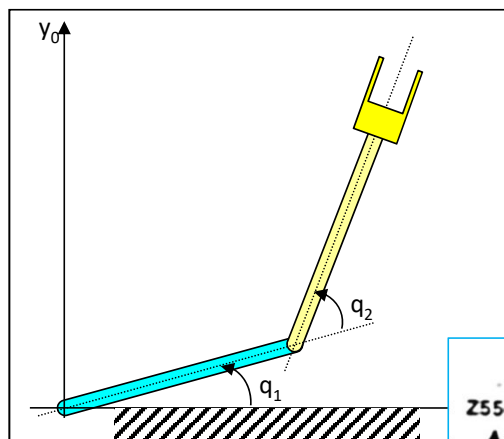
Objective CONTROL



Part 1

Objective CONTROL

Possibility 1 -

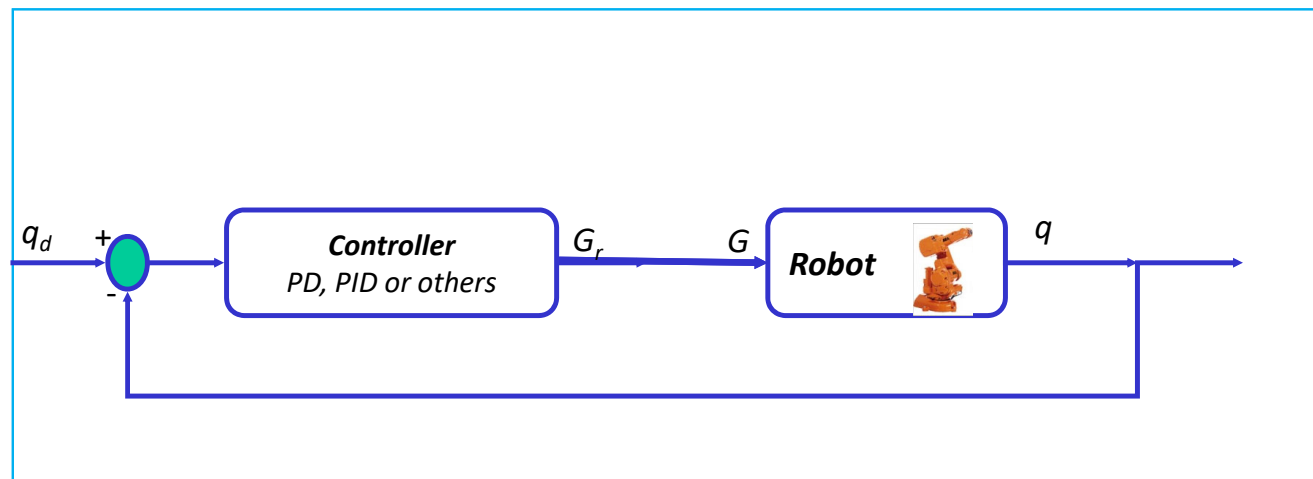


- Control of **several** motors
- **Decentralized** control – The controllers are independent from each others
- Control in the **joint space**

Simplest way to implement. Does not consider any coupling between the axes

Decentralized controllers

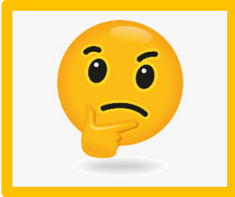
The simplest implementation



- 1 controller / axis
- All the controllers are independant

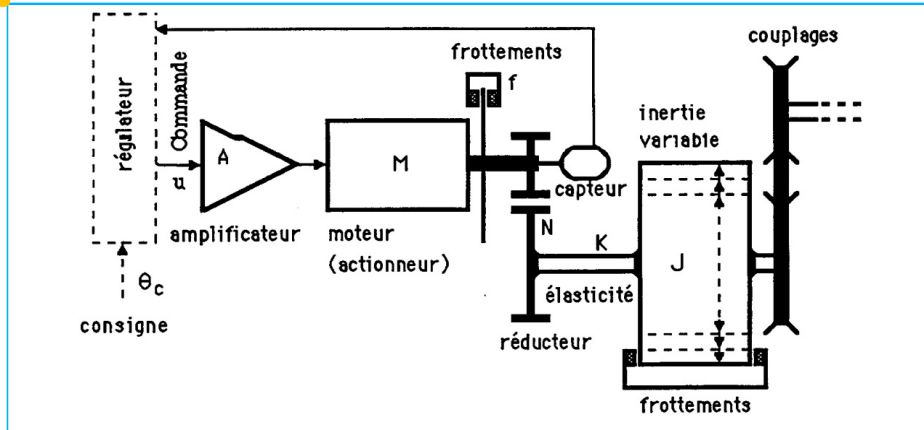
Decentralized controllers

Basics



Take Home

Motors may be controlled in **current** or in **voltage**.

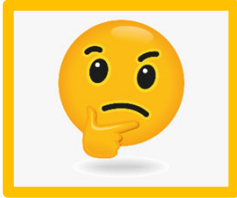


System parameters

- Loads
- Reduction ratio
- Efficiency
- Friction

Decentralized controllers

Second order systems



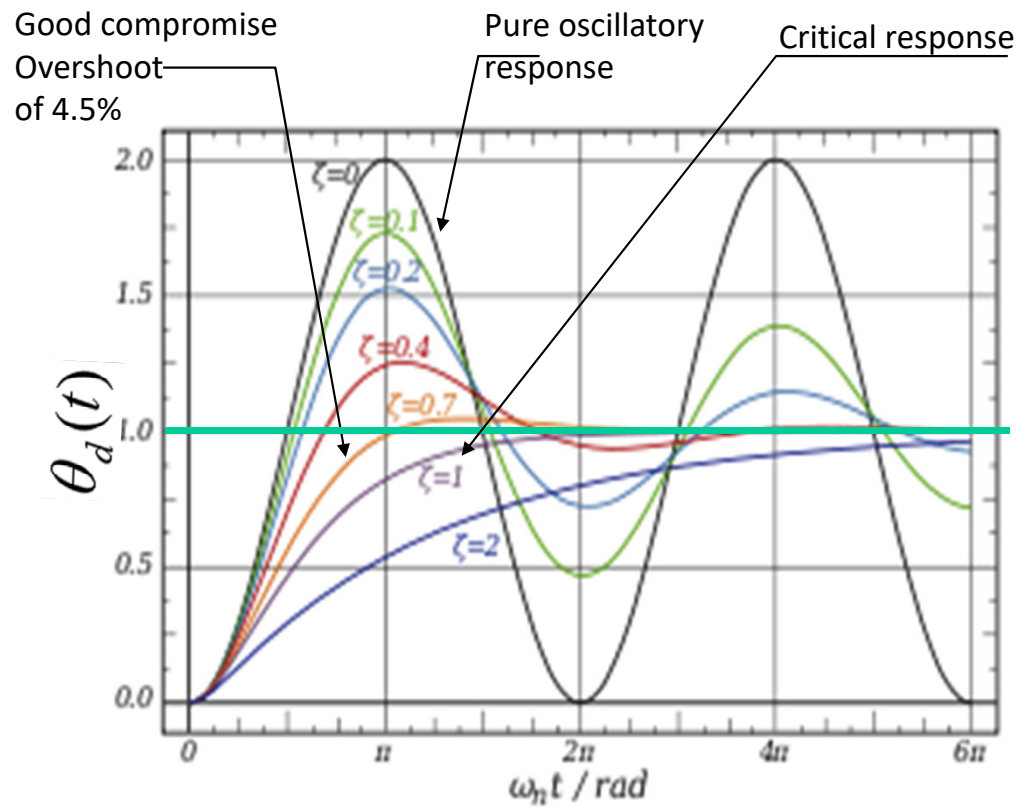
An electromechanical system (**Motor + Transmission + Load**) is a **second order system** with **input** q_d and **output** q (q_d is the position set point and q is the position to be controlled).

The transfer function (linear representation) of this electromechanical system corresponds to an asymptotically stable system, if it is in the following form:

$$\frac{\theta}{\theta_d} = \frac{\omega_n^2}{s^2 + 2 \cdot z \cdot \omega_n \cdot s + \omega_n^2}$$

Damping coefficient
Eigen pulsation

Typical responses of a linear second order system as a function of time normalized to the natural frequency.



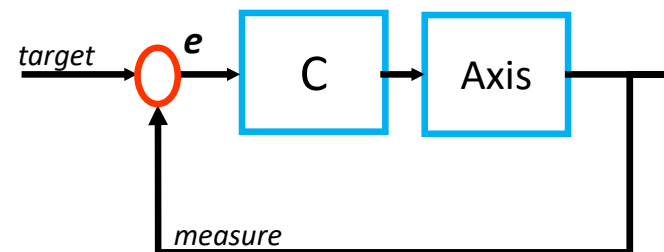


Please tell me about P, PD and PID controllers

P $\Rightarrow u = K_p \cdot e$

PD $\Rightarrow u = K_p \cdot \left(e + T_d \cdot \frac{de}{dt} \right)$

PID $\Rightarrow u = K_p \cdot \left(e + T_d \cdot \frac{de}{dt} + \frac{1}{T_i} \int_0^t e(\tau) d\tau \right)$



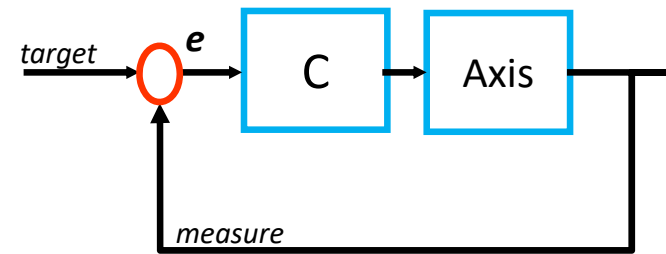
Understanding P, PD and PID controllers

**P, PD & PID
are the basic controllers to absolutely know !**

P $\Rightarrow u = K_p \cdot e$

PD $\Rightarrow u = K_p \cdot \left(e + T_d \cdot \frac{de}{dt} \right)$

PID $\Rightarrow u = K_p \cdot \left(e + T_d \cdot \frac{de}{dt} + \frac{1}{T_i} \int_0^t e(\tau) d\tau \right)$



Roles of the P – D and I

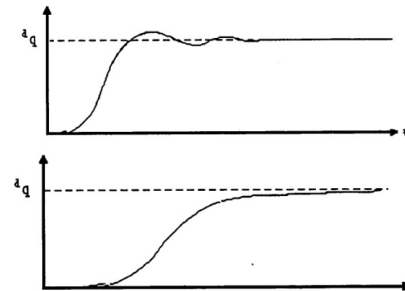
Together on the board

- K_p improves the time of response
- T_d adds damping to avoid oscillations
- T_i improves the steady state response, cancels the steady state error

P $\Rightarrow u = K_p \cdot e$

PD $\Rightarrow u = K_p \cdot \left(e + T_d \cdot \frac{de}{dt} \right)$

PID $\Rightarrow u = K_p \cdot \left(e + T_d \cdot \frac{de}{dt} + \frac{1}{T_i} \int_0^t e(\tau) d\tau \right)$



**IMPORTANT
NOTICE**

P / PD and PID position control of a DC motor

Details and claculations 😊

Document Moodle
CommandePID_DC_motor.pdf

Tuning of PID parameters

~~Ziegler-Nichols Open loop~~



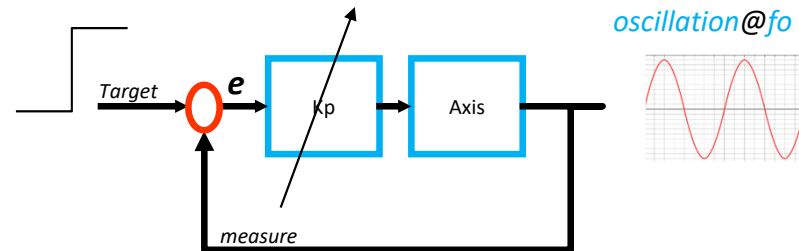
To be avoided as the system will run away without damping!

Ziegler-Nichols, closed loop

$$K_P = .6 K_o, \quad Nm / rad$$

$$K_i = 2 f_o K_P, \quad Nm / (rad \cdot sec)$$

$$K_d = \frac{K_P}{8 f_o}, \quad Nm / (rad / sec)$$



Other methods ????

Control

Discuss resolutions

Position sensors:

- Analog
- Incremental encoders

Velocity sensors:

- Tachymeters
- Numerical derivation

Numerical derivation

$$\omega(k) = \frac{\theta(k) - \theta(k-1)}{T_s}$$

or

$$\omega(k) = \frac{\theta(k) - \theta(k-2)}{2.T_s}$$

Resolution

$$R(\omega) = \frac{R(\theta)}{T_s}$$

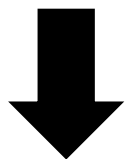
ou

$$R(\omega) = \frac{R(\theta)}{2.T_s}$$

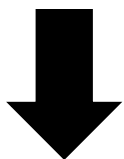
T_s : sampling period
 $R()$:Resolution

Cascaded controllers, Common in industrial drives

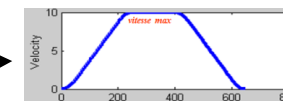
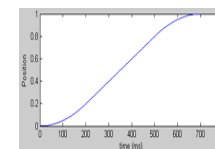
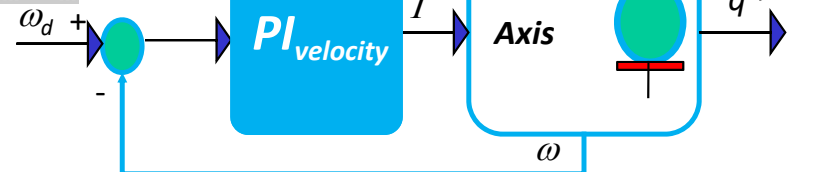
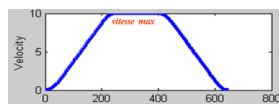
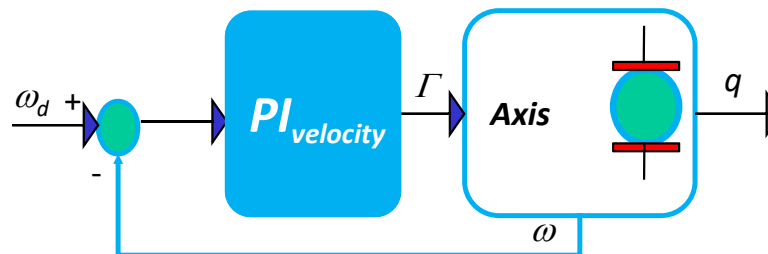
1-Velocity loop



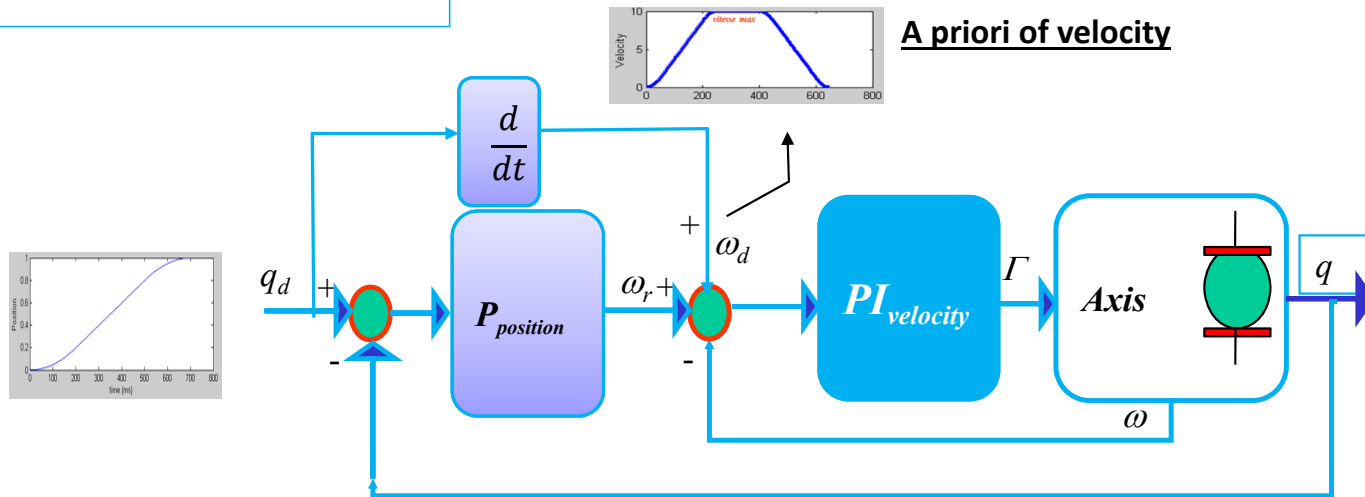
2-Velocity loop Or Position open loop



3- How to close the position control loop



Cascaded controllers, Common in industrial drives



Advantages of the double loop (cascaded)

1. Decoupling of objectives (position/speed)
2. Easy to set control parameters
3. Dual time scale (position / speed) and dual sampling periods
4. Robustness of control

Non linearities and dynamic compensation

Non linearities and compensation of known dynamics

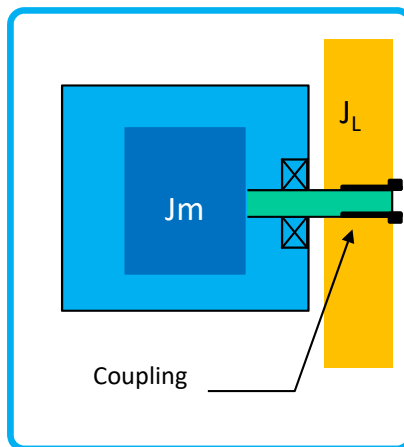
The dynamic model

Axis alone....

The dynamic model of an axis (**Motor + Transmission + Load**) is the mathematical equation of the physical (dynamic) behavior of this axis in relation to a torque action.

The worldwide simplest system

A motor with inertia J_m + turning load of inertia J_L (including coupling)



$$\sum M = \Gamma_m = (J_m + J_L)\ddot{\theta}^*$$

The a priori knowledge of the laws of motion (position, velocity and acceleration) implies the a priori knowledge of the torque necessary to achieve the desired motion. It is this torque that we call :

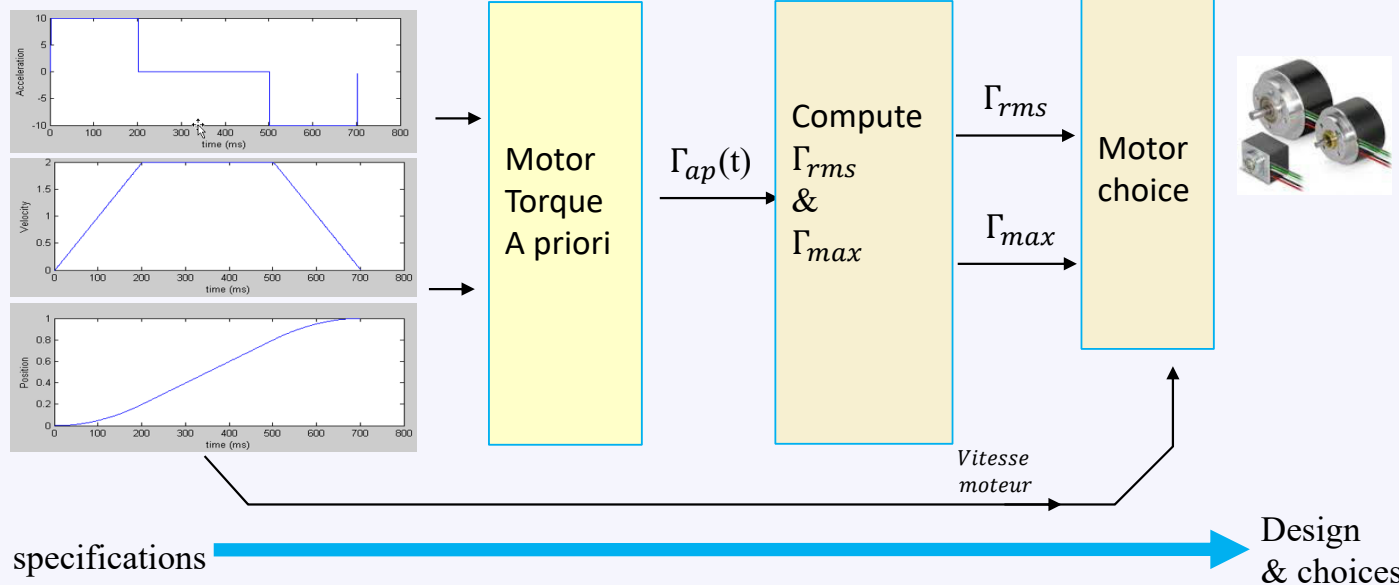
- **Inverse dynamic model** (Torque as a function of trajectories from laws of motion).
- **A priori dynamic model**

* This model assumes the system has no dry or viscous friction

Recap....Consider :

- θ_d the movement profile of the desired position
- $\dot{\theta}_d$ the movement profile of the desired velocity
- $\ddot{\theta}_d$ the movement profile of the desired acceleration

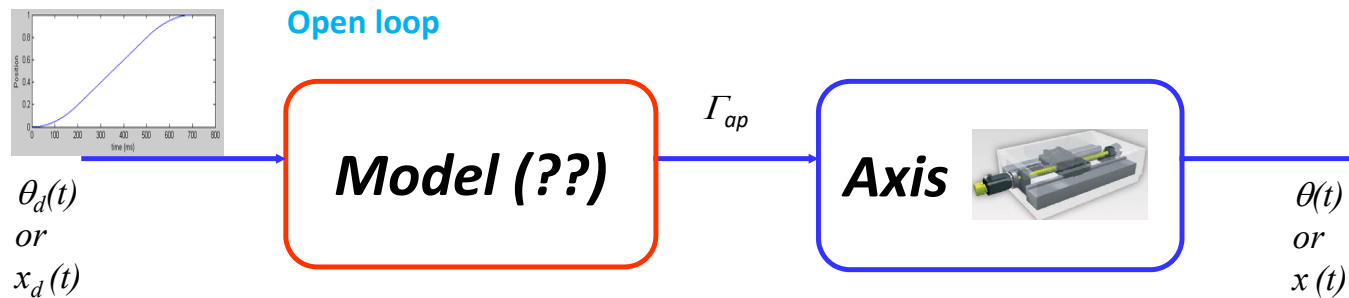
$$\Gamma_{ap} = \Gamma_m(\theta = \theta_d, \dot{\theta} = \dot{\theta}_d, \ddot{\theta} = \ddot{\theta}_d) = (J_m + J_{ch})\ddot{\theta}_d$$



The knowledge of this model a priori implies to exactly know the torque necessary to the realization of the desired trajectories (*for the moment it only concerns one axis*).

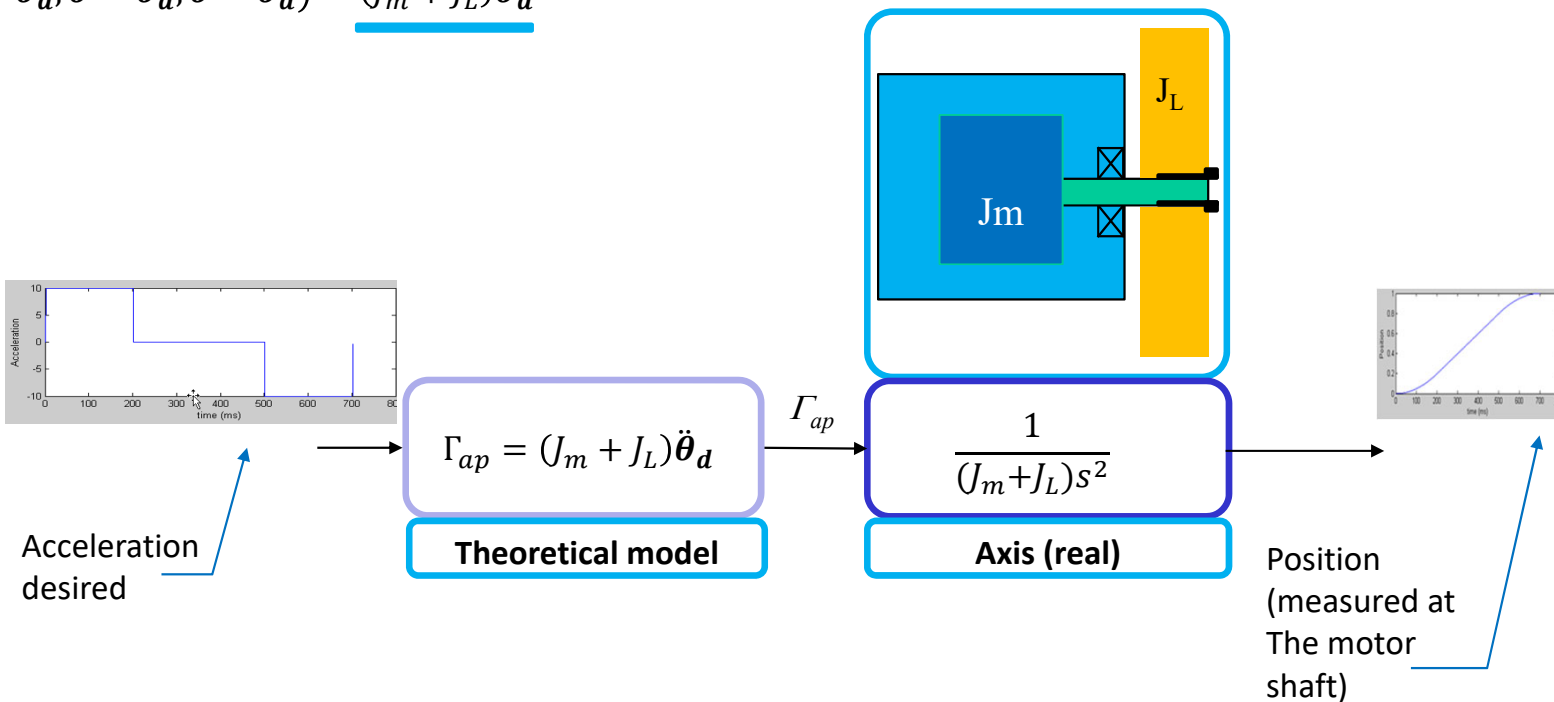
If the theoretical model obtained **corresponds exactly to the behavior of the physical (real) model**, then it would be sufficient to apply the a priori torque (from the laws of motion) to the axis motor so that the latter generates exactly the desired position, speed and acceleration.
[!] This is only a model inversion.

Principle



In the case of the previous example

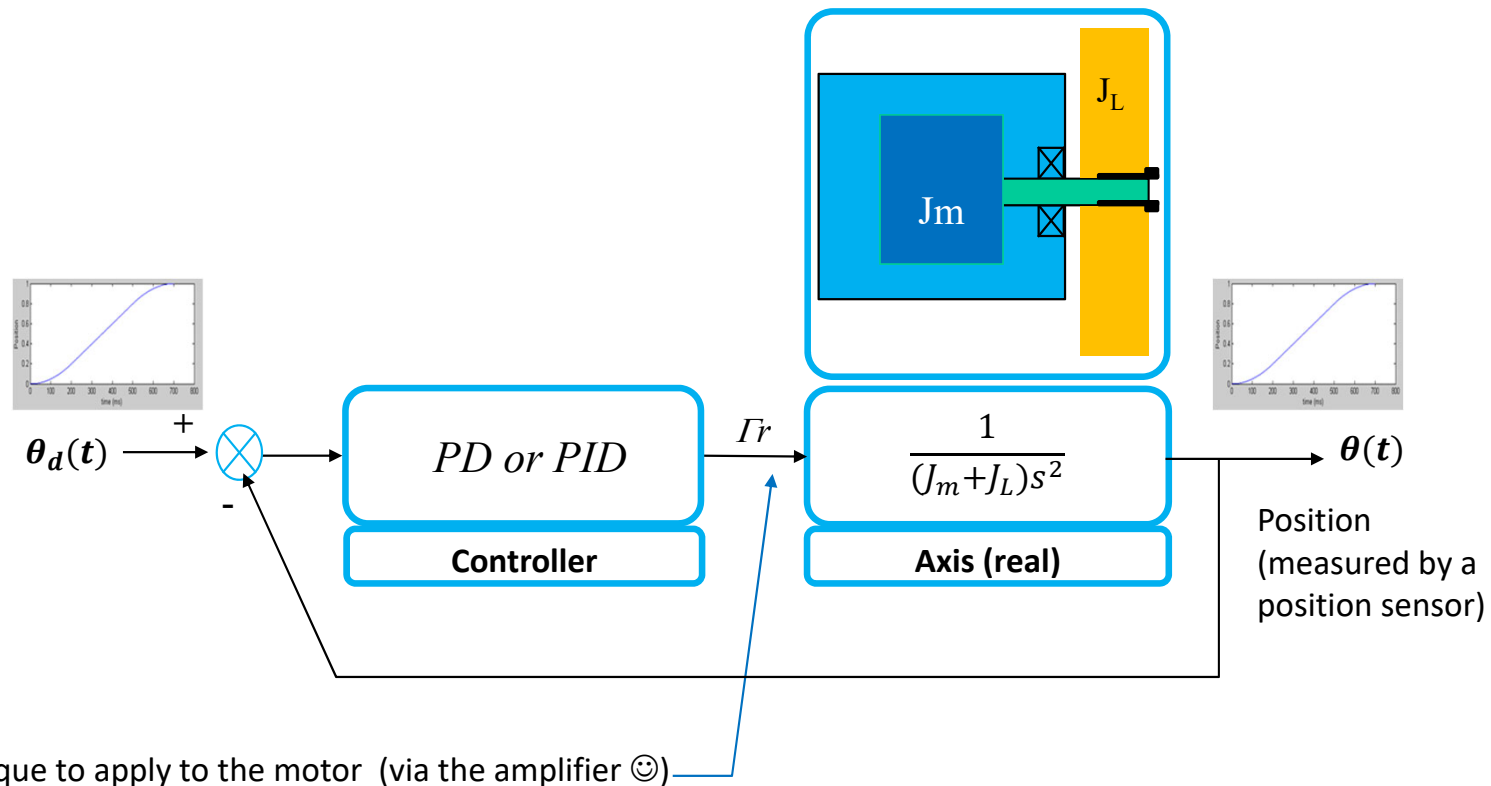
$$\Gamma_{ap} = \Gamma_m(\theta = \theta_d, \dot{\theta} = \dot{\theta}_d, \ddot{\theta} = \ddot{\theta}_d) = \underline{(J_m + J_L)\ddot{\theta}_d}$$



If the inertias used in the calculation of the a priori model **correspond exactly** to the inertias of the constructed system, we find at the output of our motor exactly the desired position (resulting from the double integration of the desired acceleration)

Reminder

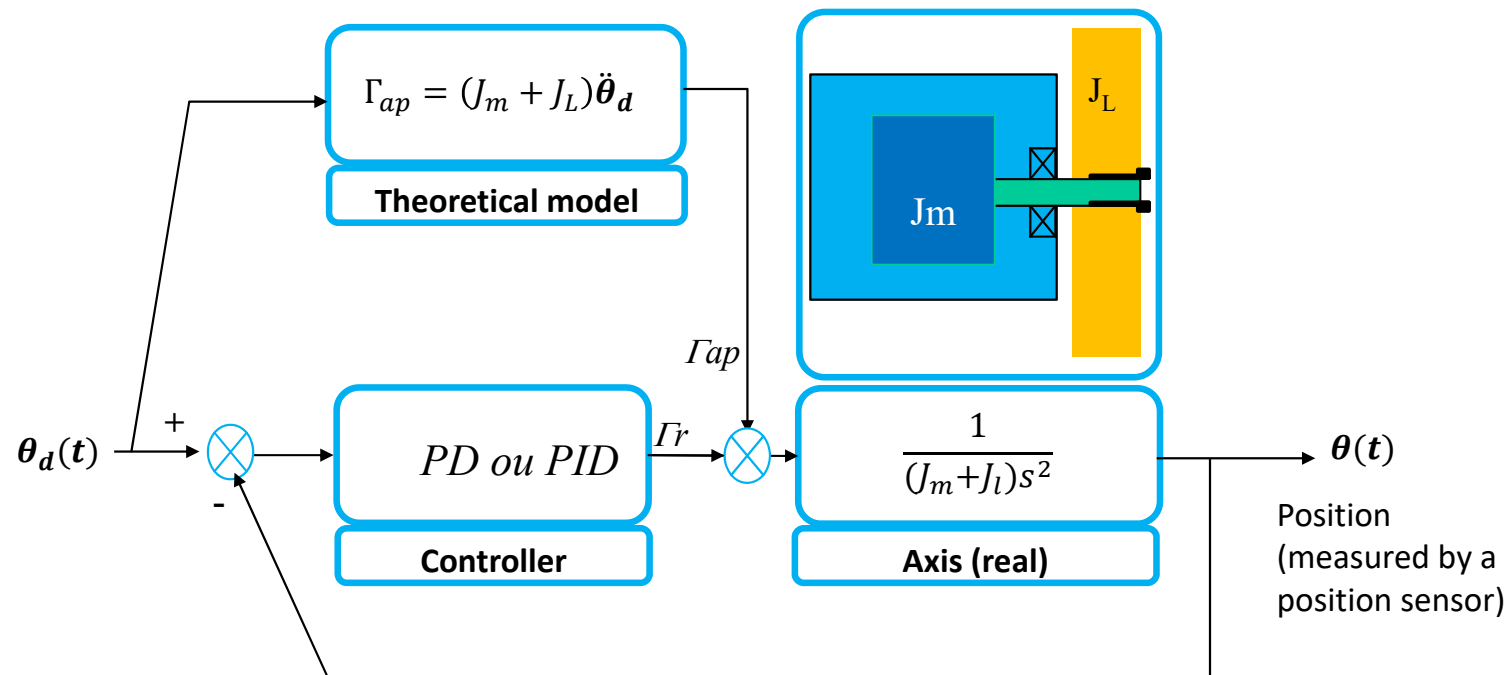
The role of a controller is to find the appropriate torque to be applied to the motor so that it performs the desired movement.

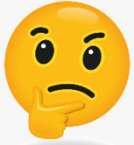


Control torque to apply to the motor (via the amplifier 😊)

The ideal is therefore to **combine these two instruments for the same objective**: to control the motor position as best as possible to the desired trajectory.

- The **a priori torque** will be used to quickly approach the torques required to achieve the movement.
- The **controller** to close the position loop.



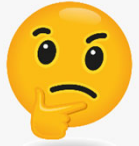


Very important :

In the case of the previous example the a priori torque contribution is zero in the static phase.



In which case the static contribution of the a priori dynamic model is not zero?

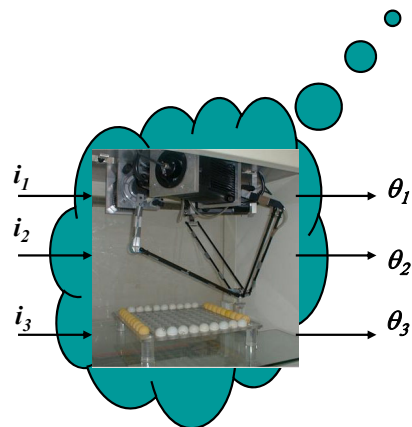
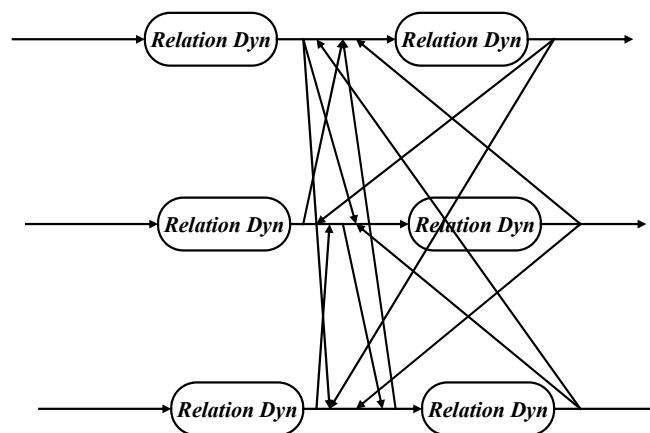


Very important :

The sources of errors between the physical (real) model and the theoretical model are mainly due to the knowledge of the following elements:

- The efficiency of the transmission (this can also vary according to speed and lubrication and also temperature).
- Friction in the transmission.
- The load to be moved (which may vary according to the customer's needs).
- The amplifier (gain and bandwidth).
- External forces from various sources.

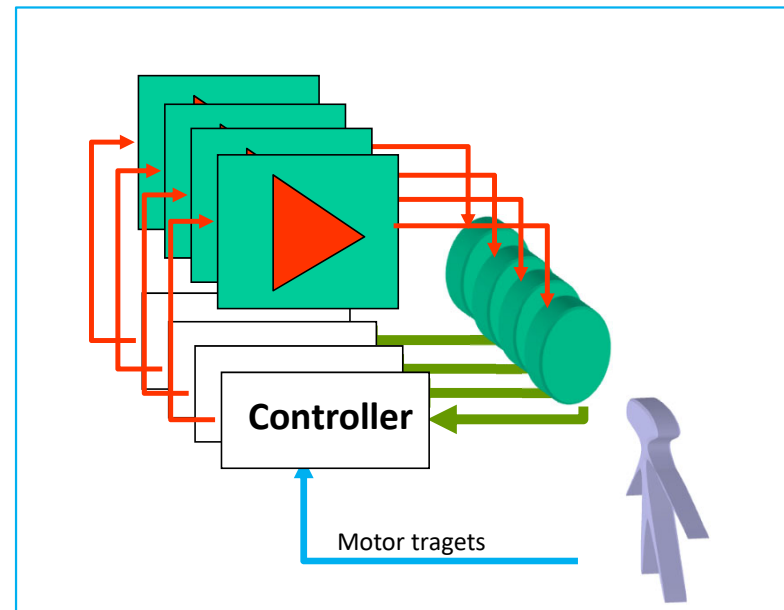
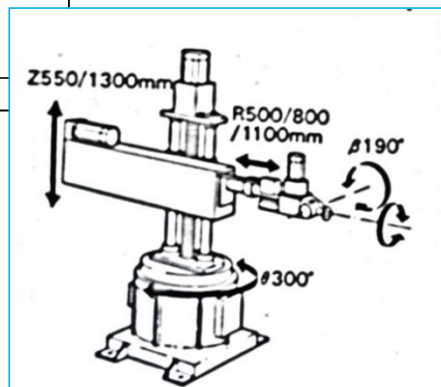
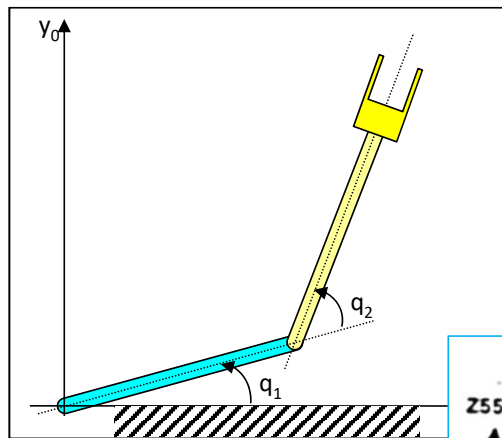
Couplings



Part 1

Objective CONTROL

Possibility 1 – (reminder)



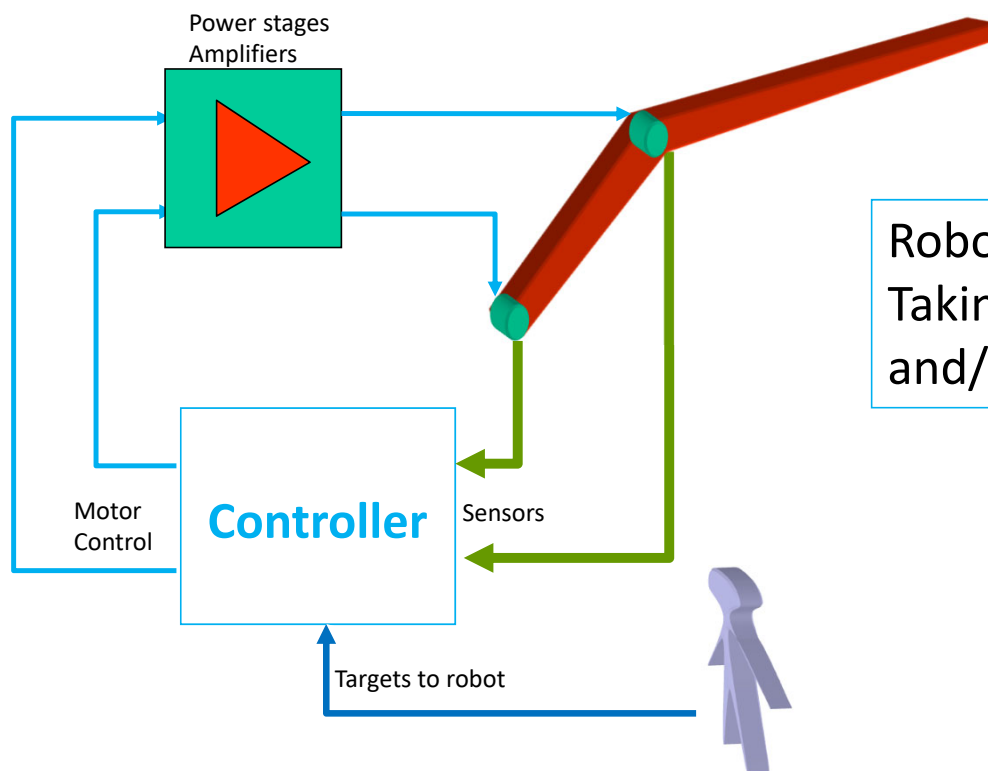
- Control of **several** motors
- **Decentralized** control – The controllers are independent from each others
- Control in the **joint space**

Simplest way to implement. Does not consider any coupling between the axis

Part 2

Objective CONTROL

Possibility 2 – Let us do better



Robot control –
Taking into account couplings
and/or non-linearities

Dynamic model of the robot

$$\Gamma = B(q) \cdot \ddot{q} + G(q) + C(q, \dot{q}) + F(q, \dot{q}) + K(q)$$

Vector of generalized torques
 Matrix of inertia
 Vector of gravity
 Centrifuge and Coriolis terms
 Friction terms
 Stiffness vector

That we put in the following form:

$$\Gamma = B(q) \cdot \ddot{q} + H(q, \dot{q})$$

$$\ddot{q} = (B(q))^{-1}(\Gamma - H(q, \dot{q}))$$

Direct dynamic model of the robot

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

State form of the dynamic model

Models of robots & Models for control

$$\ddot{q} = (B^{\text{mod}}(q))^{-1}(\Gamma - H^{\text{mod}}(q, \dot{q}))$$

Dynamic model of the robot obtained during the first modelling

$$\ddot{q} = (B^*(q))^{-1}(\Gamma - H^*(q, \dot{q}))$$

Dynamic model simplified

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

State model for simulation

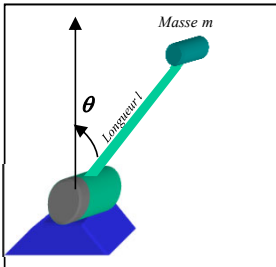
Models for control design

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

Simplified State model for control design

$$\ddot{q} = (B(q))^{-1}(\Gamma - H(q, \dot{q}))$$

2nd order Robot model for control



Model of
representation

Model simplified

State model
For simulation

Model for
control design

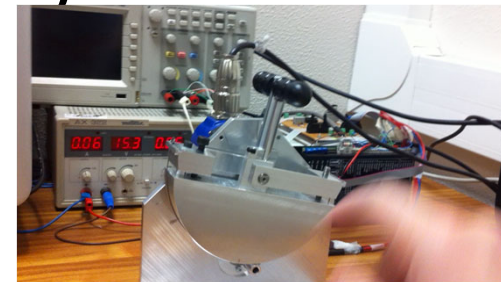
Example of 1 dof state model

$$\ddot{\theta} = \frac{k_c}{J} i - \frac{mgl}{J} \sin(\theta) - \frac{\alpha_{vis}(\omega, \theta)}{J} \omega - \frac{C_{dry}}{J} - \frac{C_{pert}(\text{play}, \text{Temp}, \text{wear}, \dots)}{J}$$

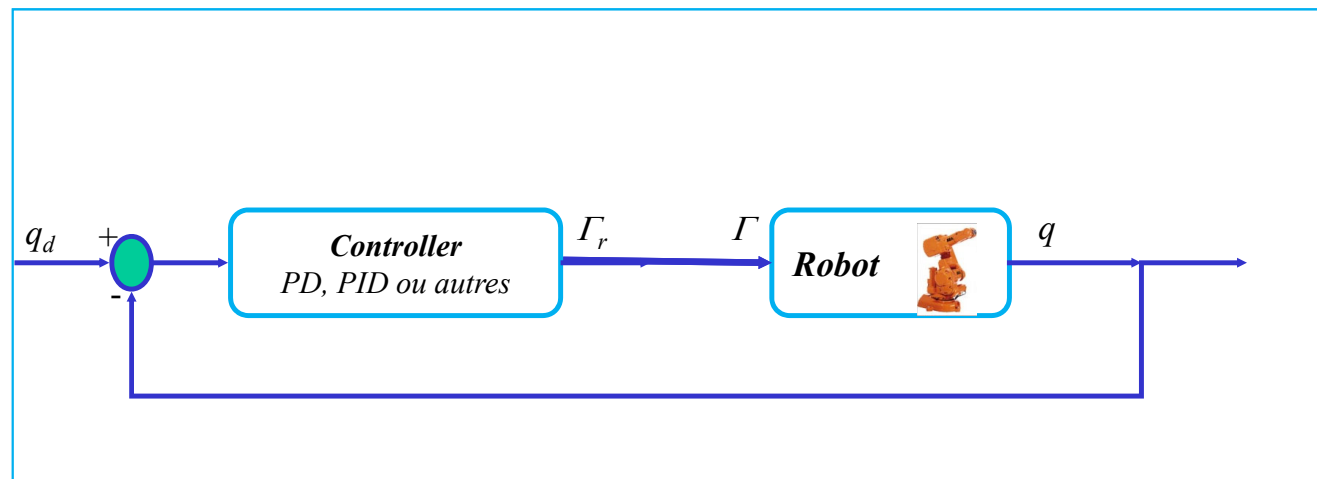
$$\ddot{\theta} = \frac{k_c}{J} i - \frac{mgl}{J} \sin(\theta) - \frac{\alpha_{vis}^*}{J} \omega - \frac{C_{dry}}{J}$$

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -\frac{mgl}{J} \sin(x_1) - \frac{\alpha_{vis}^*}{J} x_2 - \frac{C_{dry}}{J} + \frac{k_c}{J} u \end{aligned} \quad / \quad \underline{(x_1, x_2) = (\theta, \omega) \text{ et } u = i}$$

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -\frac{mgl}{J} \sin(x_1) - \frac{\alpha_{vis}^*}{J} x_2 + \frac{k_c}{J} u \end{aligned}$$



Simplest decentralized controller

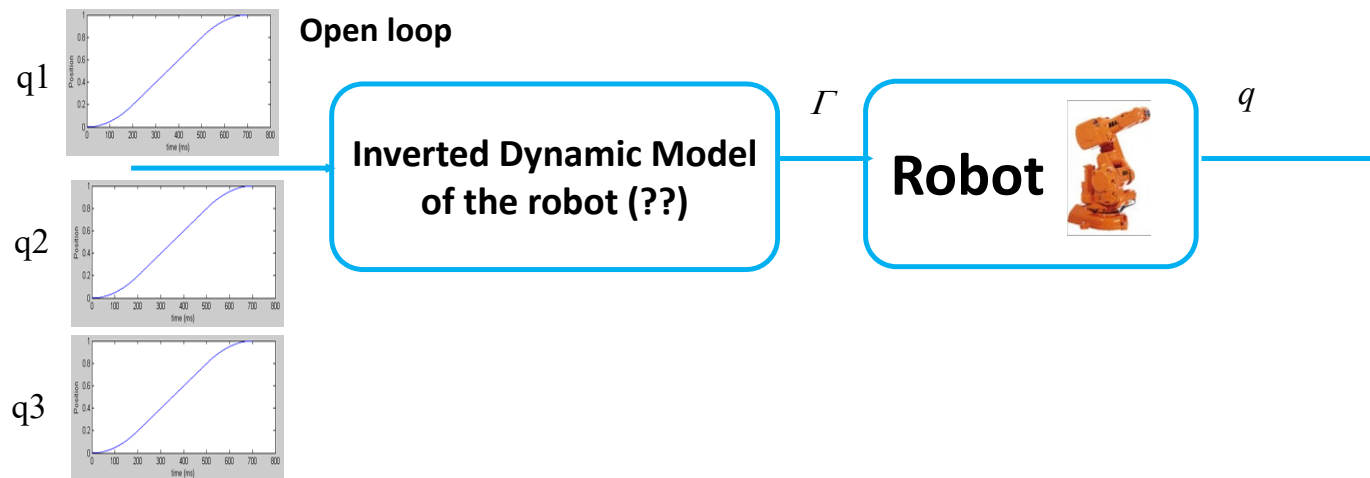


- 1 controller / axis
- All the controllers are independants

Centralized controller

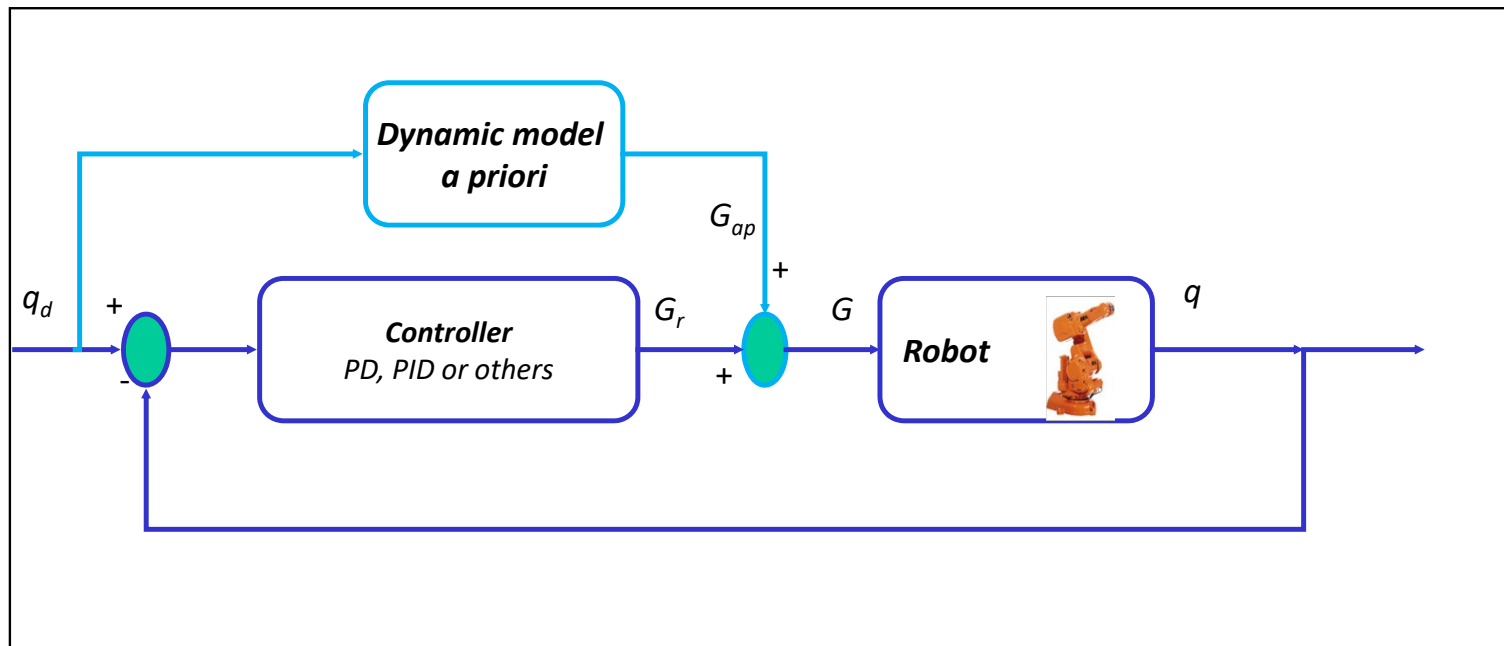
Controller a priori, to consider coupling

Principle



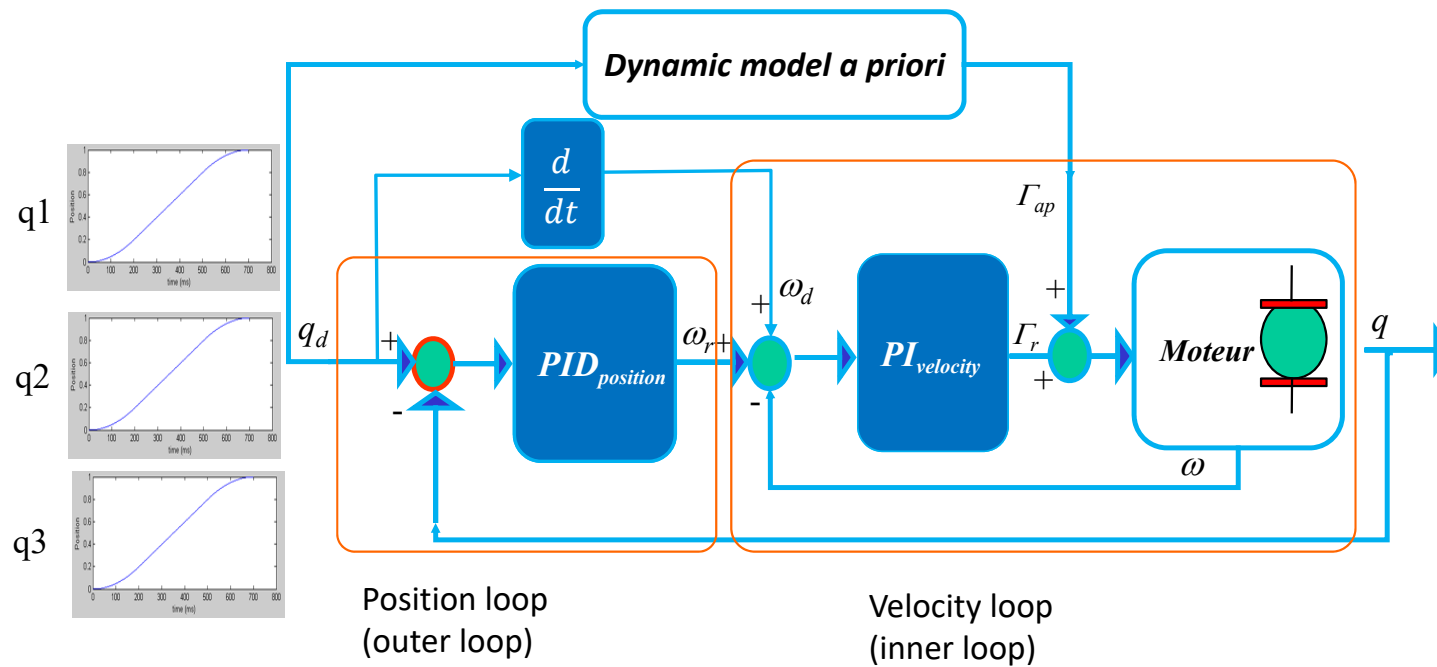
Centralized controller

Controller a priori, to consider coupling



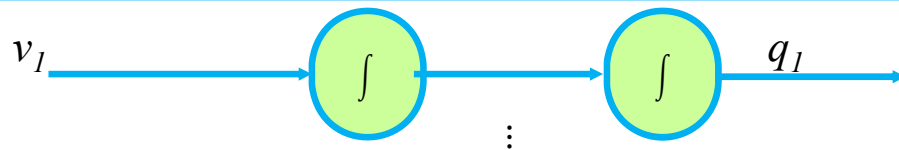
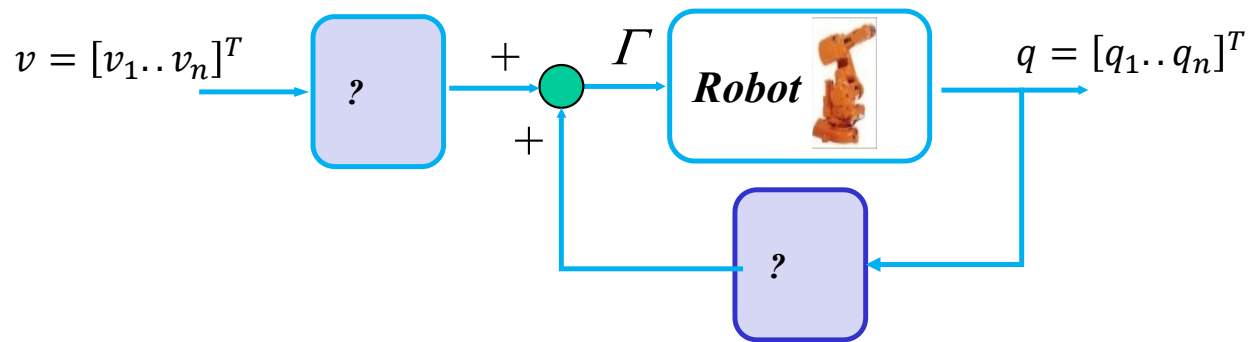
Centralized controller

Cascaded controller & a priori, to consider coupling

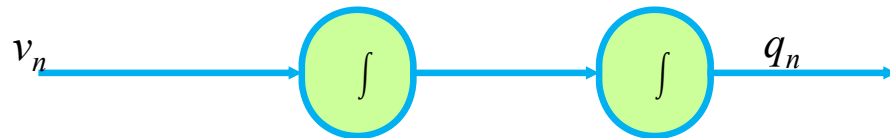


Centralized controller

Non linear compensation : Non linear linearizing controller

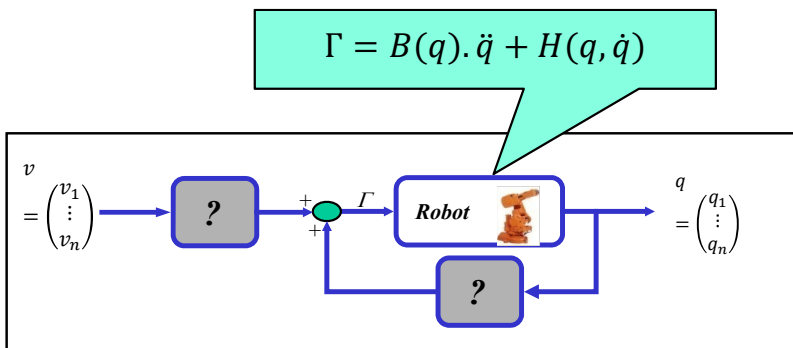


cascades of doubles integrators



Centralized controller

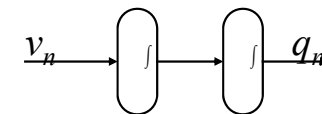
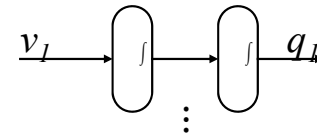
Non linear compensation : Non linear linearizing controller



Observe the following control law

$$\Gamma = B(q) \cdot v + H(q, \dot{q})$$

Objectives



cascades of doubles integrators

$$\ddot{q} = v$$

Calculation steps

From the nonlinear model

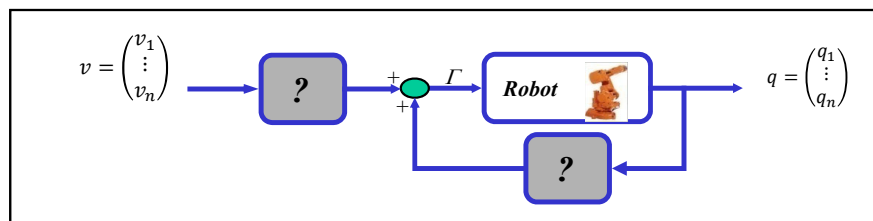
$$\ddot{q} = (B(q))^{-1}(\Gamma - H(q, \dot{q}))$$

By setting : $\ddot{q} = v$

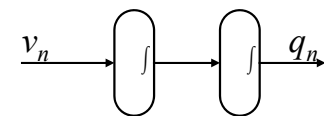
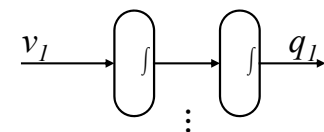
That leads to:

$$\Gamma = B(q) \cdot v + H(q, \dot{q})$$

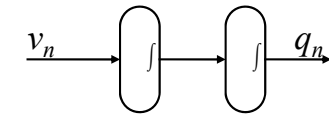
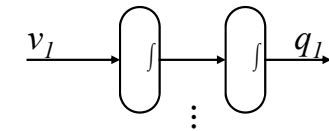
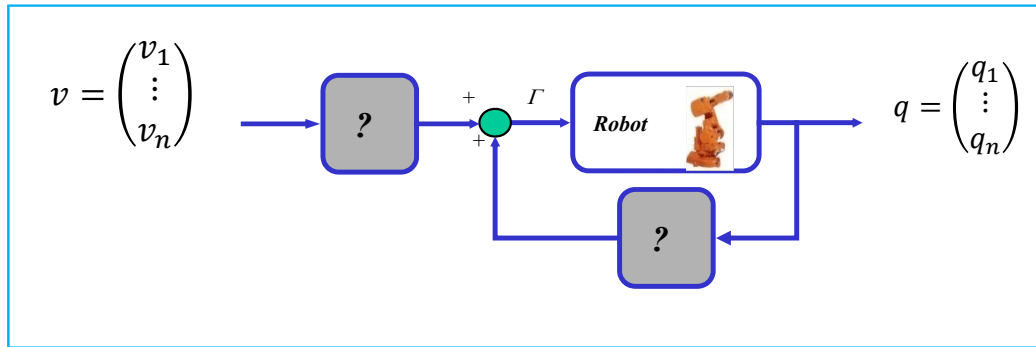
$$\Rightarrow \ddot{q} = (B(q))^{-1}(B(q) \cdot v + H(q, \dot{q}) - H(q, \dot{q})) = v$$



\Leftrightarrow



cascade of double integrators

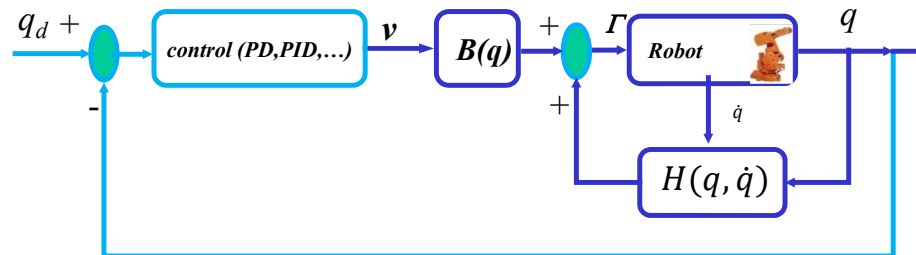


cascade de doubles intégrateurs

The double integrators must now be stabilized by looping:

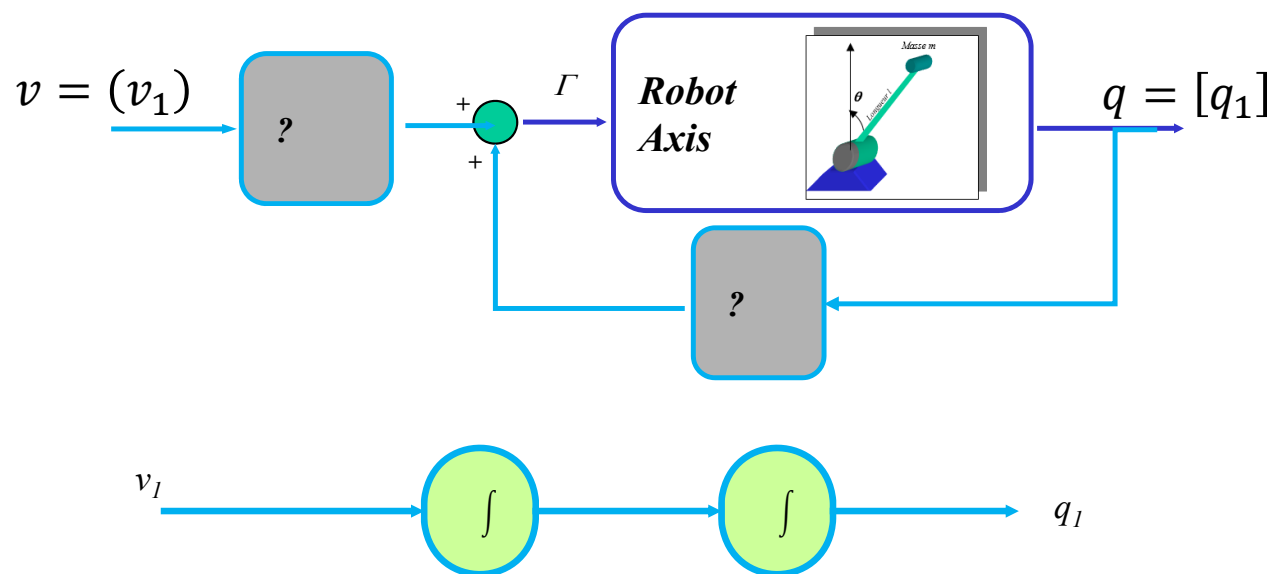
- PD,
- PID,
- or advanced controllers (adaptive ,sliding mode, GPC, MPC...)

$$\Gamma = B(q).v + H(q, \dot{q})$$



Example

$$\begin{aligned}\dot{x}_1 &= x_2 \\ \dot{x}_2 &= -\frac{mgl}{J} \sin(x_1) - \frac{\alpha_{vis}^*}{J} x_2 + \frac{k_c}{J} \Gamma\end{aligned}$$



Example

Position Control by Examples

1 Device description

Consider the following device (Figure 1). It is a cable driven disc steered by a Brushless Maxon¹ DC motor. It is equipped with two incremental encoders for position measurement. The first one is on the motor shaft and the second one is on the output shaft.

The device parameters are considered as follows:

- M_D and J_D are respectively the Mass and the Inertia of the disc relative to its rotation center.
- r_g is the distance of the center of mass of the disc to its rotation center.
- I_m is the inertia of the motor.
- The gear ratio of the cable based transmission is 15.

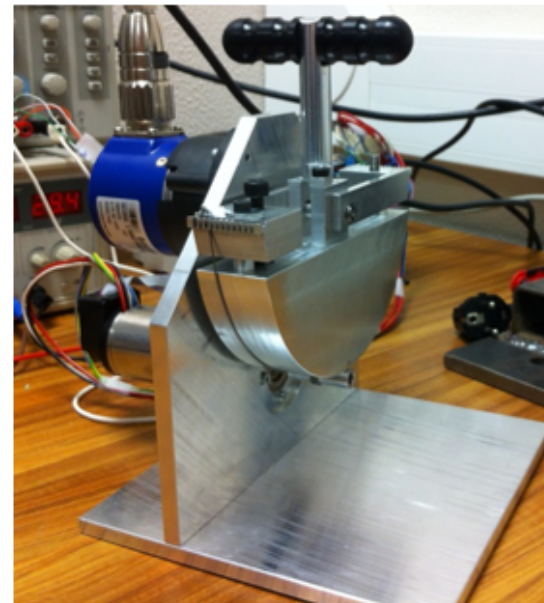


Figure 1-Haptic Device used for position control

Haptic Paddle with compensation of Dry and Viscous friction and Gravity

