Control of robots of manipulation

Ecole Polytechnique Fédérale de Lausanne

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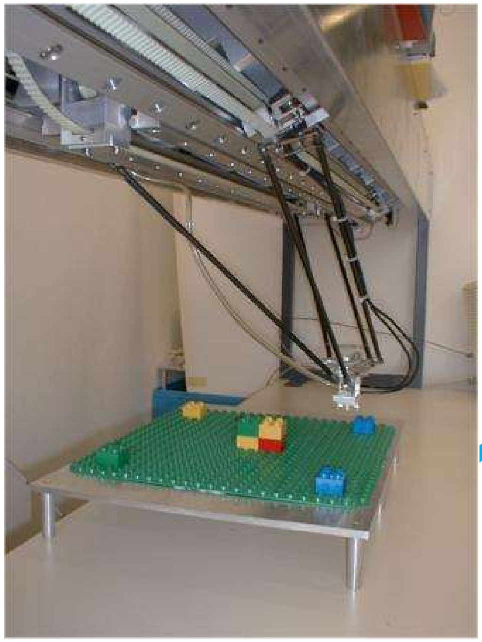
The robot and its numerical controller (NC)

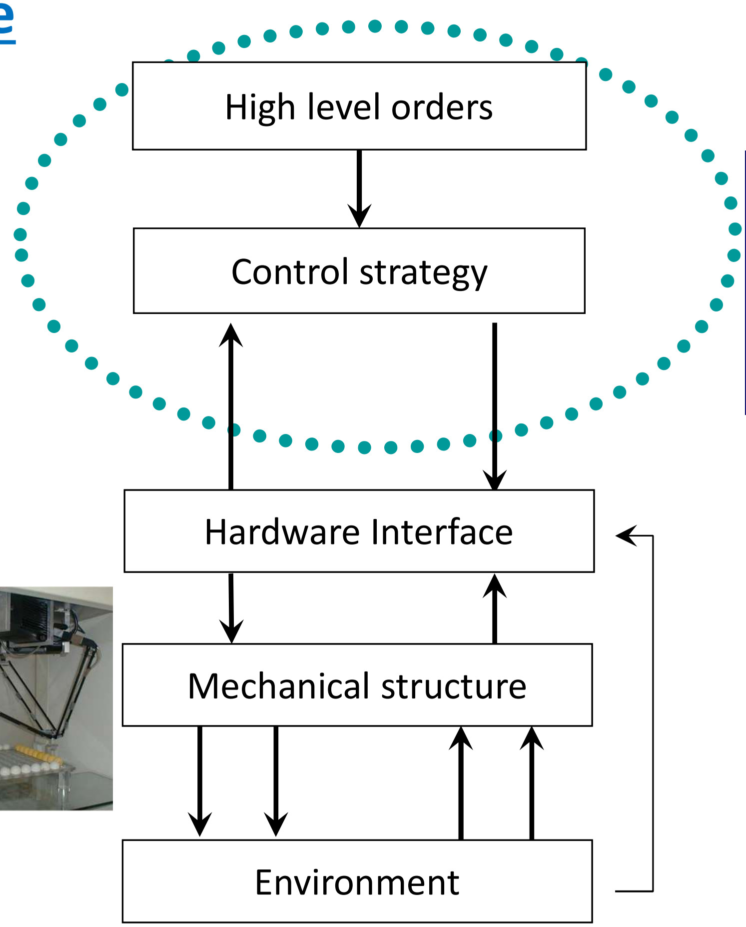


Robot:
- *Mechanical structure,*
- *motorization,*
- *instrumentation.*

Cabling:
- Power,
- Signals.

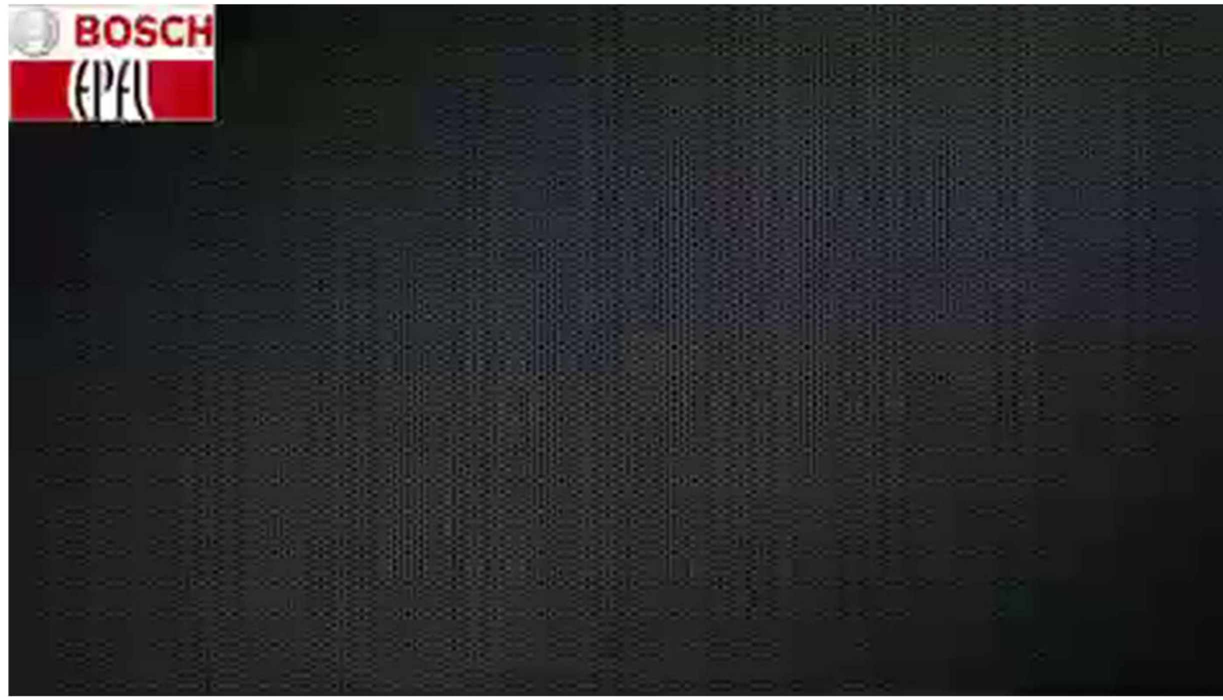
Control cabinet:
- *Intelligence*
- *I/O boards for the axes,*
- *I/O cards for safety,*
- *Power stage,*

Robot : general structure

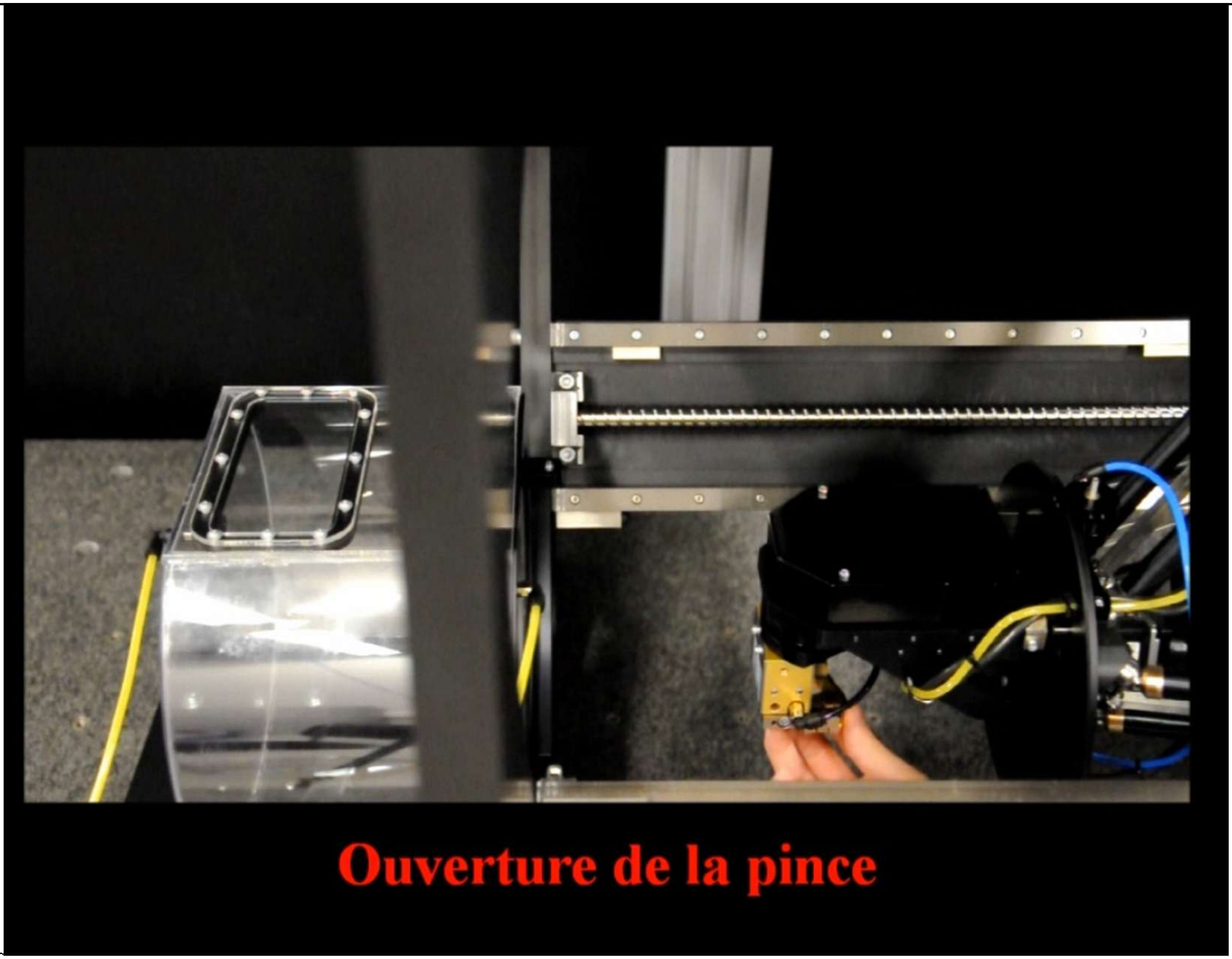


Direct Drive Actuated Delta realized for **BOSCH Packaging Technology**

BOSCH
Invented for life



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


Ouverture de la pince


EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE
MinAngle Concept
Flexure-based tilting platform
for high rotation amplitudes (±15°)
Laboratoire de Systèmes
Robotiques LSRO
http://lsro.epfl.ch

Learning objectives

1. Control aspects :

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

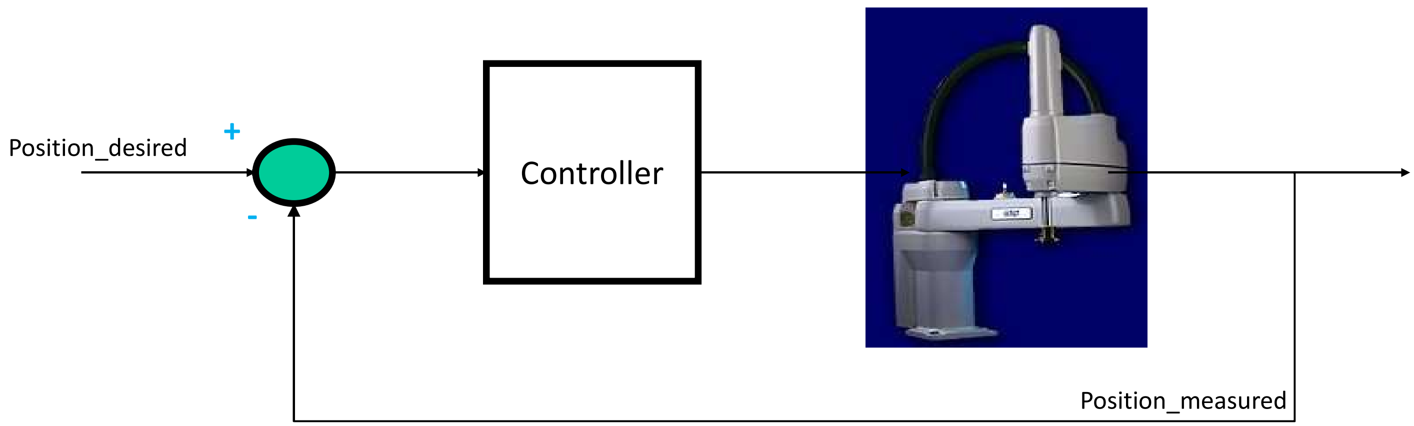
2. Hardware aspects:

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

3. Software aspects:

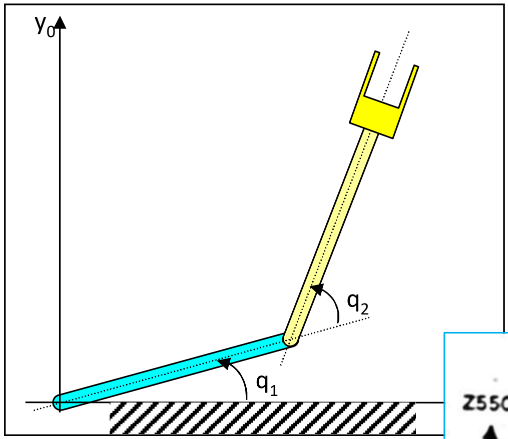
- Multitasking structure of a control software,
- Need for real time,
- Development tools

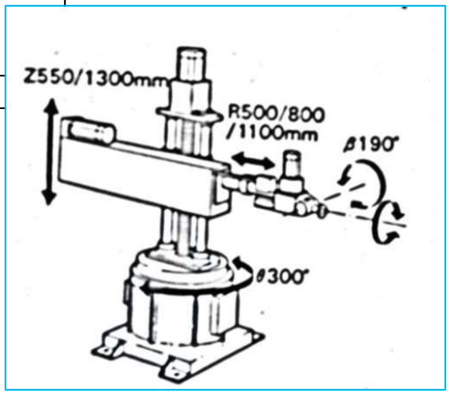
Part 1
Objective CONTROL

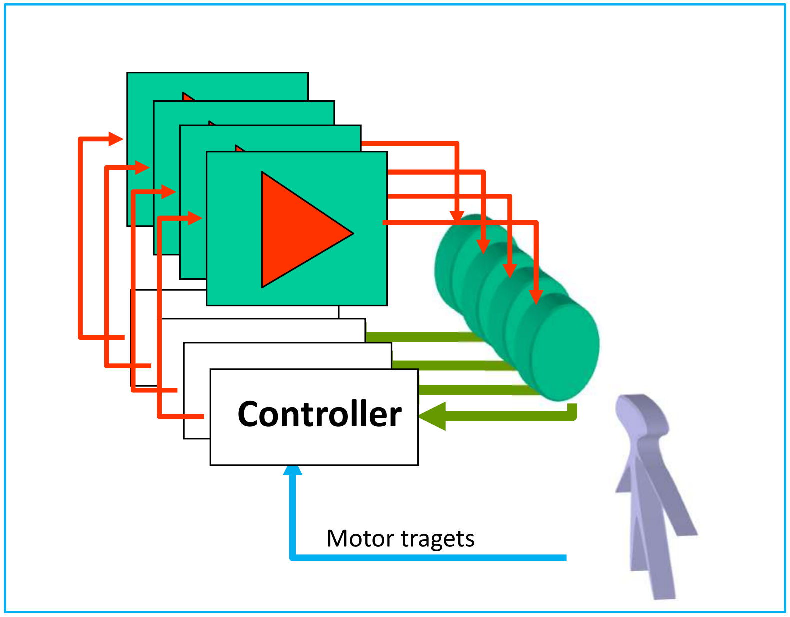


Part 1
Objective CONTROL

Possibility 1 -





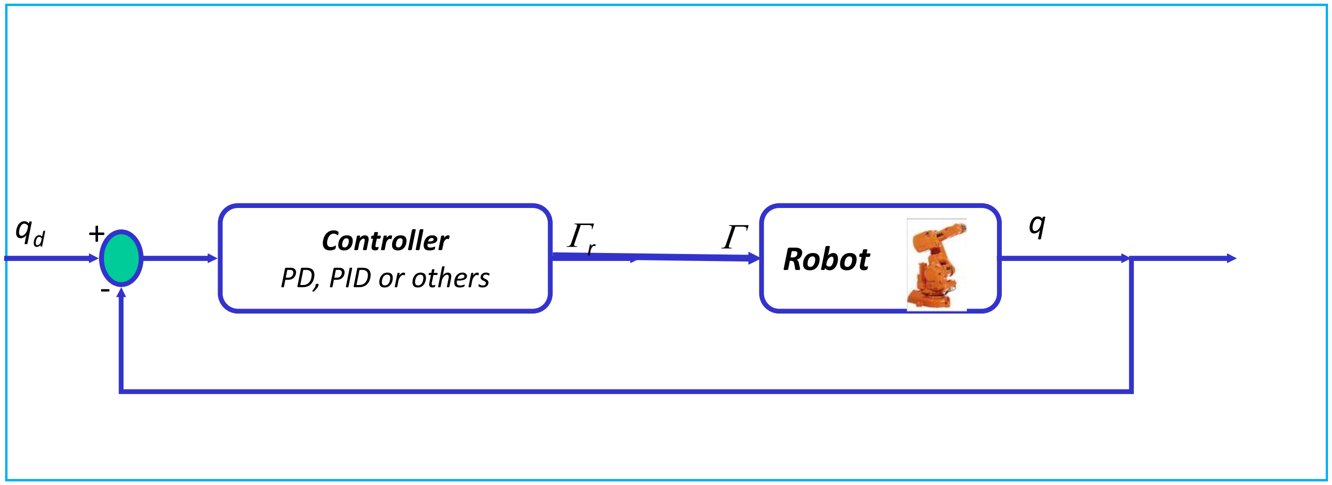


- **Control of several motors**
- **Decentralized control –** The controllers are independent from each others
- **Control in the joint space**

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

Decentralized controllers

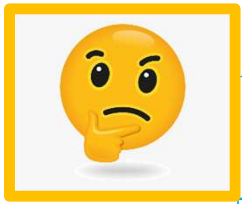
The simplest implementation



- **1 controller / axis**
- **All the controllers are independants**

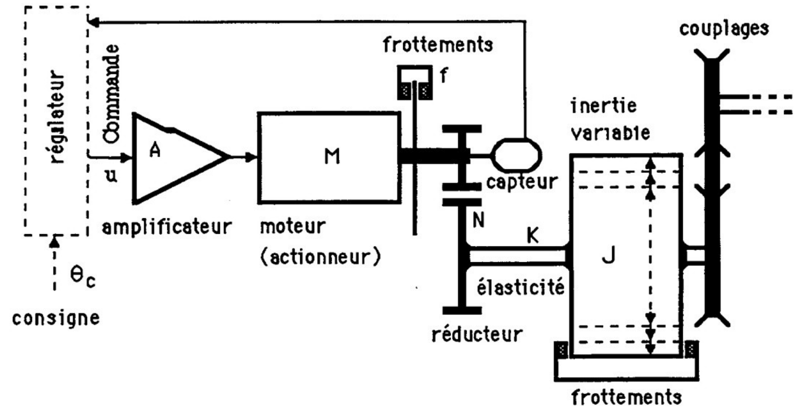
Decentralized controllers

Basics



Take Home

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

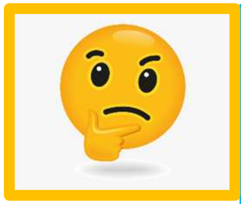


System parameters

- Loads
- Reduction ratio
- Efficiency
- Friction

Decentralized controllers

Second order systems



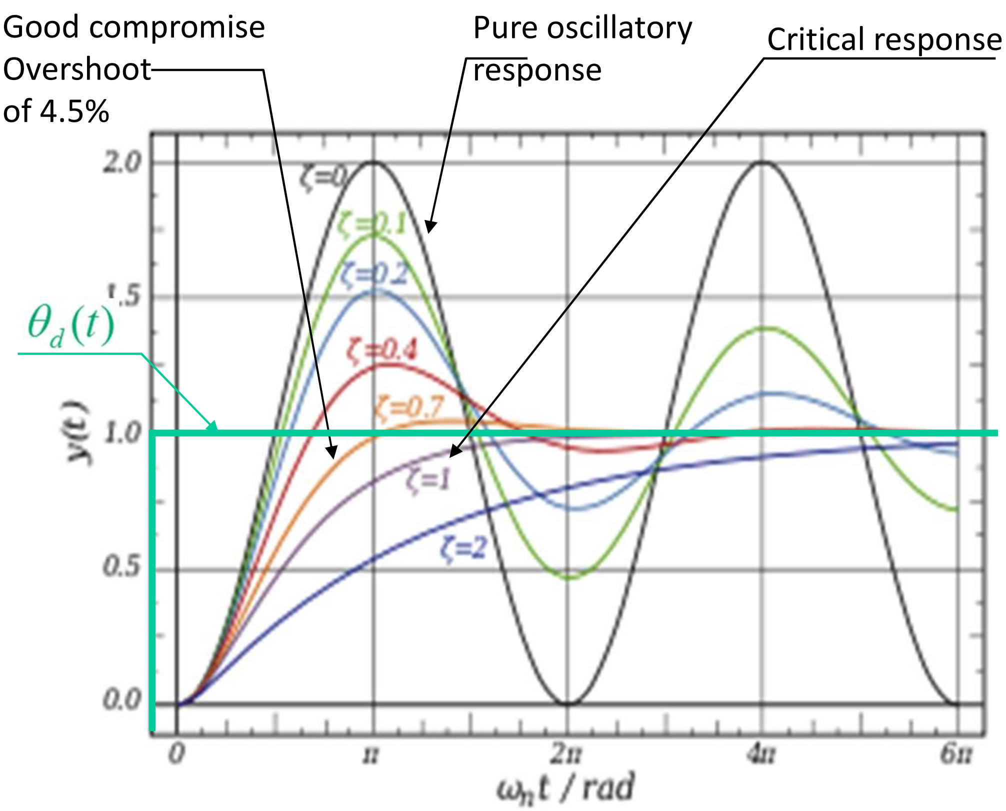
An electromechanical system (**Motor + Transmission + Load**) is **a second order system** with input $\boldsymbol{q_d}$ *and output* $\boldsymbol{q}$ ($\boldsymbol{q_d}$ is the position set point and $\boldsymbol{q}$ is the position to be controlled).
The transfer function (linear representation) of this electromechanical system corresponds to an asymptotically stable system, if it is in the following form:

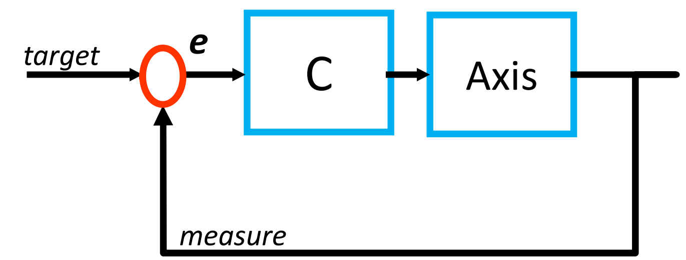
$$\frac{\theta}{\theta_d} = \frac{\omega_n^2}{s^2 + 2.z.\omega_n.s + \omega_n^2}$$

Damping coefficient (z)

Eigen pulsation (ω_n)

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





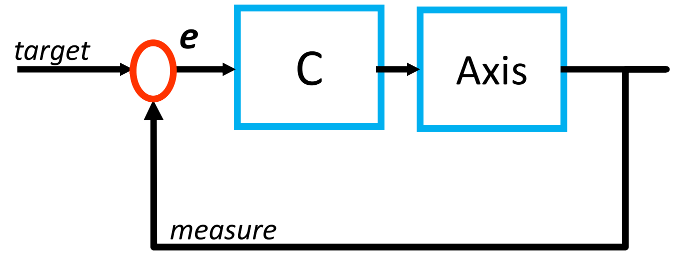
The objective of the controller is to lead to an **appropriate behavior of closed-loop response**

Please tell me about P, PD and PID controllers

P ⇒ $u = K_p . e$

D ⇒ $u = K_d . \left(\frac{de}{dt}\right)$

I ⇒ $u = K_i . \left(\int_0^t e(\tau) d\tau\right)$



The objective of the controller is to lead to an **appropriate behavior of closed-loop response**

EPFL

Understanding P, PD and PID controllers

P, PD, PI, & PID

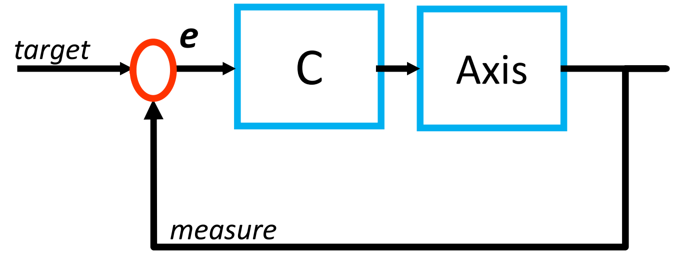
are the basic controllers to absolutely know !

P ⇒ $u = K_p . e$

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

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

PI ⇒ $u = K_p . \left(e + \frac{1}{T_i} \int_0^t e(\tau) d\tau \right)$



The objective of the controller is to lead to an **appropriate behavior of closed-loop response**

Roles of the P – D and I

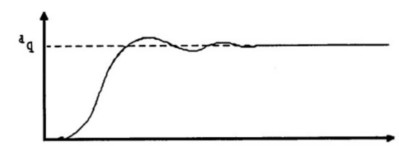
Together on the board

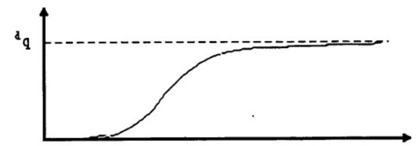
- Kp improves the time of response
- Td adds damping to avoid oscillations
- Ti improves the steady state response, cancels the steady state error

P $\Rightarrow$ $u = K_p . e$

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

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





Please remind me about the role of P, D and I parameters

Proportional gain (Kp)	**Derivative gain (Kd = Kp * Td)**	**Integrator gain (Ki = Kp / Ti)**
$\Gamma_p = K_p . e$, proportional to the position error e : It **acts as a spring**	$\Gamma_d = -K_d . \frac{d\theta}{dt}$, conversely proportional to the velocity : It **acts as a viscos friction**	$\Gamma_i = K_i . \int e \, dt$, **more and more effect** up t cancelling the error, estimation function.
Increases the stiffness of the control	Improves the damping in closed loop	Cancels the steady state error (sse) (completely eliminates the sse)
Increases the eigenfrequency in closed loop, $\omega_n \propto \sqrt{\frac{K_p}{J}}$,	Stabilizes the controlled system	Estimates the steady state disturbance at the origin of the sse,
Improves the response time (higher closed loop dynamics)		
Higher proportional gain increases the robustness of the control with respect to parameter and external disturbances		
Reduces (not cancels) the steady state error.		

EPFL

Please remind me about the **limits** of P, D and I parameters

Proportional gain (Kp)	Derivative gain (Kd = Kp * Td)	Integrator gain (Ki = Kp / Ti)
$\Gamma_p = K_p.e$, proportional to the position error e : It **acts as a spring**	$\Gamma_d = -K_d.\frac{d\theta}{dt}$, conversely proportional to the velocity : It **acts as a viscos friction**	$\Gamma_i = K_i.\int e\ dt$, **more and more effect** up t cancelling the error, estimation function.
Higher gains saturate the control torque, • the system gets into a non linear area, because of the control saturation. • It may make the position oscillate, notice that we are in an open loop during saturation,	Differentiation is know to amplify the noise, • which increases the noise at the torque control, • Which may excite mechanical resonant frequencies	The integrator affects the convergence time to a complete cancelation of the steady state error.
Higher gains may destabilize the closed loop system (demonstrated with a root locus and Nyquist linear representations)	The viscous effect may induce to slower behaviours.	Increasing the integrator gain, to make the system faster, may create overshoots when loading/unloading the integrator.
	In some cases, we may be motivated by adding filters, or derivate at higher sampling periods, this induces delays that consequently may destabilize the system.	<u>**Advice**</u>, limit the contribution of the integrator to a maximum of 25-30% of the maximum applied torque (use an anti reset windup ARW)

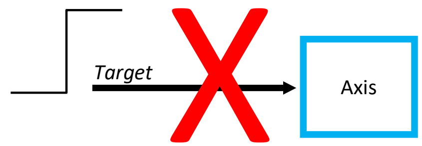
P / PD and PID position control of a DC motor

Details and claculations ☺

Document Moodle
CommandePID_DC_motor.pdf

Tuning of PID parameters

Ziegler-Nichols Open loop



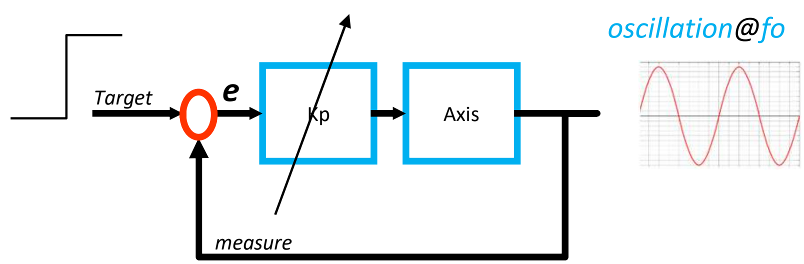
To be avoided as the system will run away without damping!

Ziegler-Nichols, closed loop

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

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

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

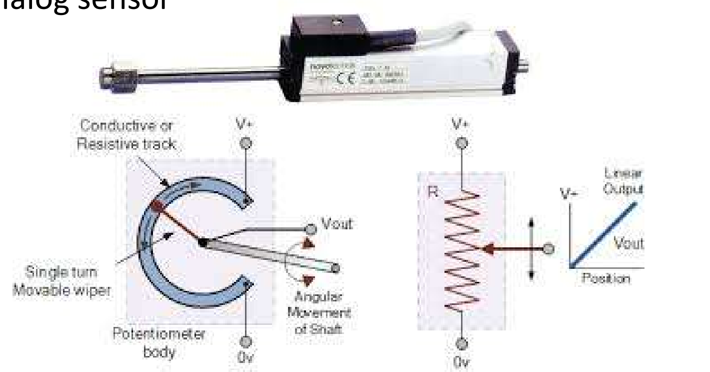


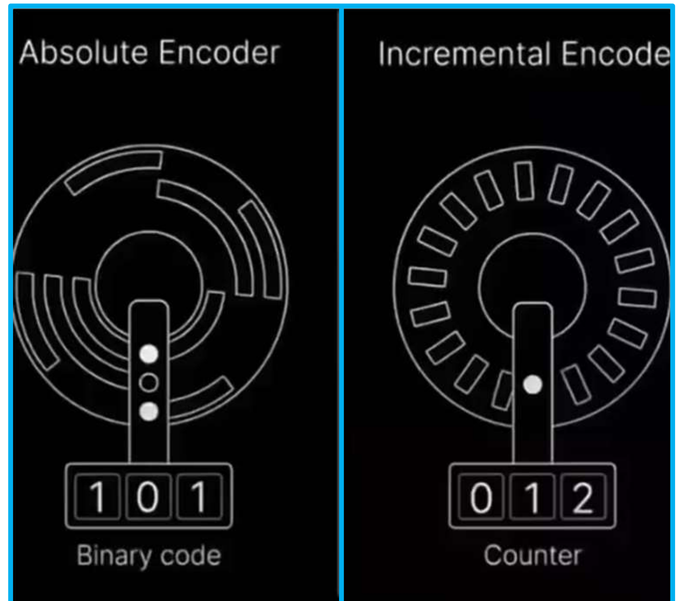
Other methods ????

Control
Discuss resolutions

Position sensors:
- Analog
- Incremental encoders
- Absolute encoders

Analog sensor





Codes the positions in an absolute way.
No need of referencing

Codes the positions in an absolute way.
No need of referencing

Generates pulses for each increement of position defined by the number of physical wholes (marks) .
Need of referencing

Control
Discuss resolutions

Position sensors:
- Analog
- Incremental encoders

Velocity sensors:
- Tachymeters
- Numerical derivation

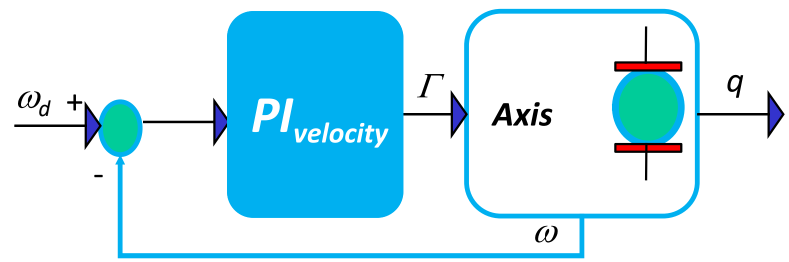
Numerical derivation $\omega(k) = \frac{\theta(k) - \theta(k-1)}{T_s}$ ***or*** $\omega(k) = \frac{\theta(k) - \theta(k-2)}{2.T_s}$

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

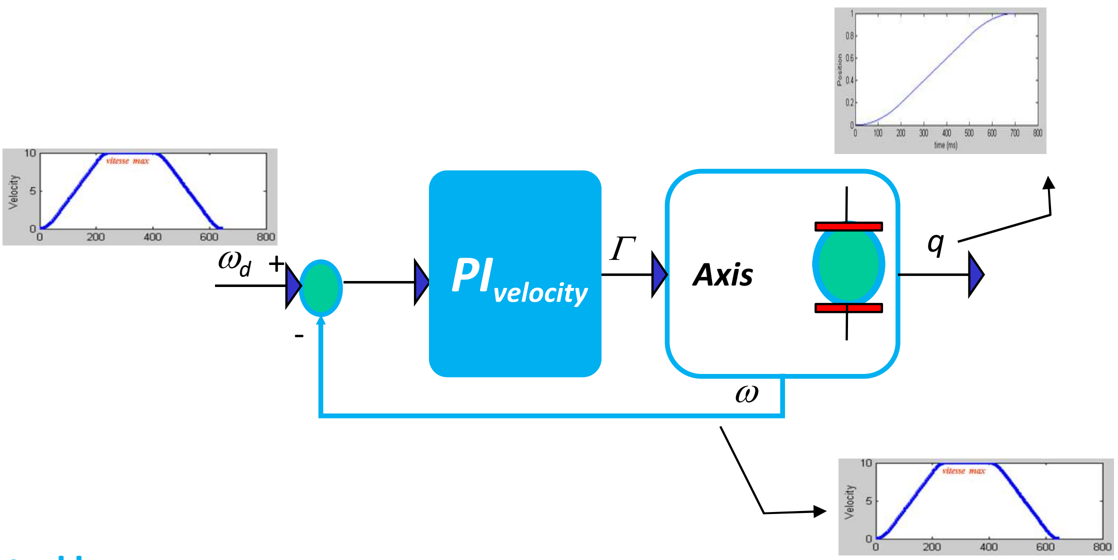
T_s : sampling period
R():Resolution

Cascaded controllers,
Common in industrial drives

1-Velocity loop

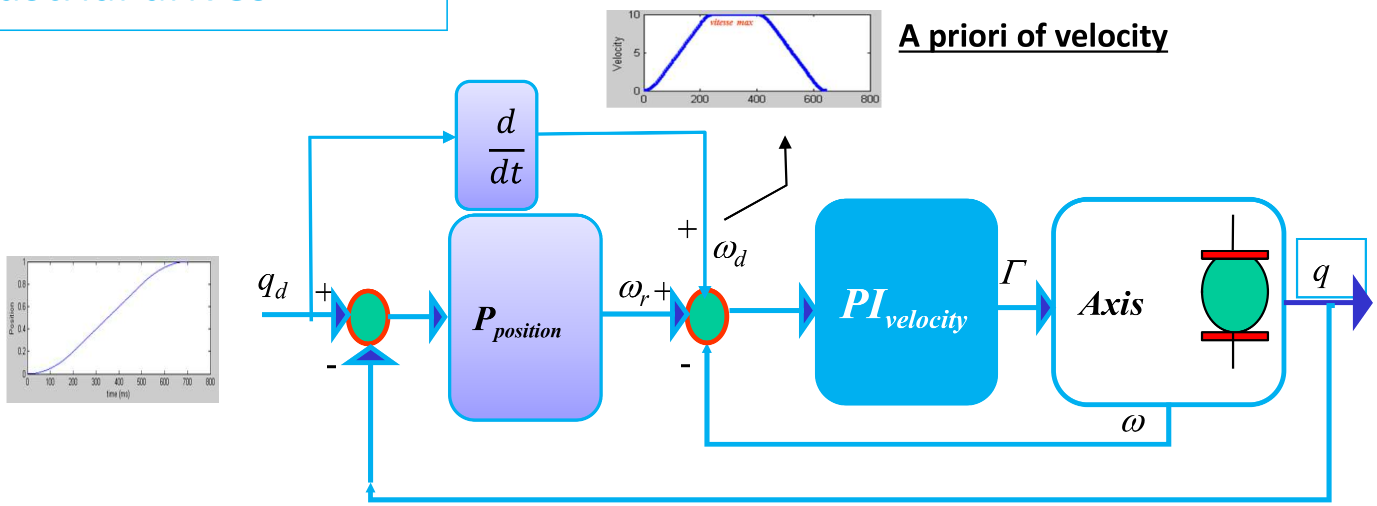


2-Velocity loop
Or
Position open loop



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

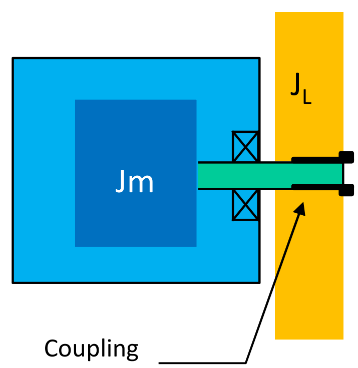
The dynamic model

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)**



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

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 :

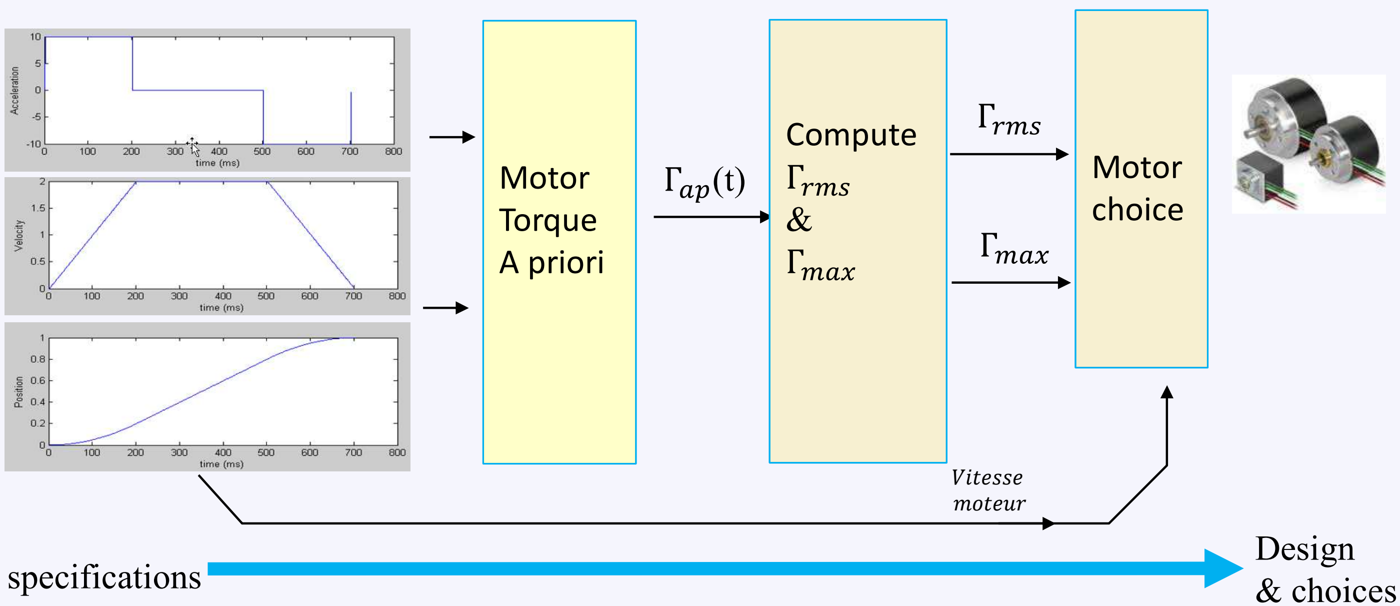
- **Inverse dynamic model (Torque as a function of trajectories from laws of motion).**
- **A priori dynamic model**

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

Recap….Consider :

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

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

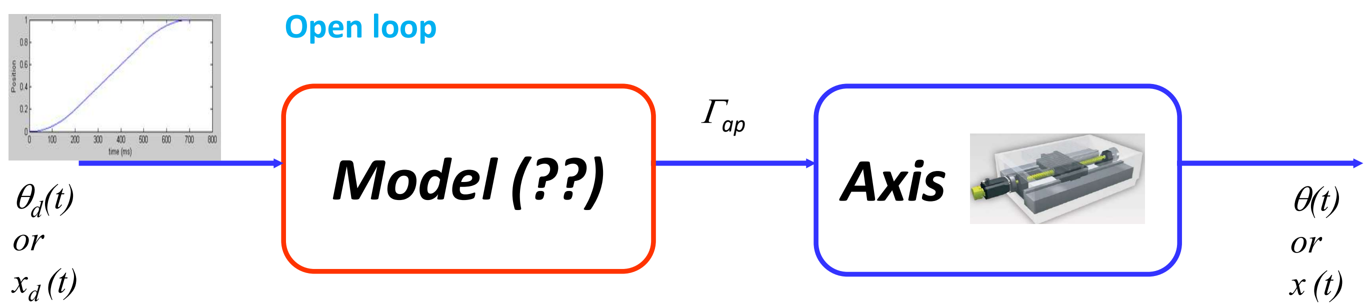


The knowledge of this model a priori implies to exactly know the torque necessary to the realization of the desired trajectories (*for the moment it only concerns one axis*).

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.

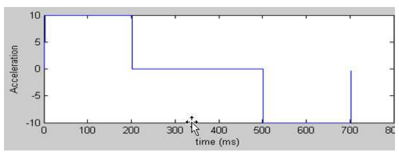
[!] This is only a model inversion.

Principle

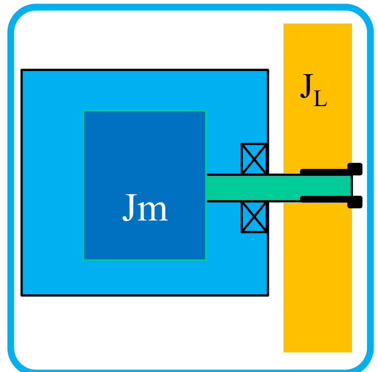


In the case of the previous example

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

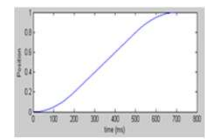


Acceleration desired



$\Gamma_{ap} = (J_m + J_L)\ddot{\boldsymbol{\theta}}_{\boldsymbol{d}}$ → Γ_{ap} → $\frac{1}{(J_m+J_L)s^2}$ →

Theoretical model | **Axis (real)**

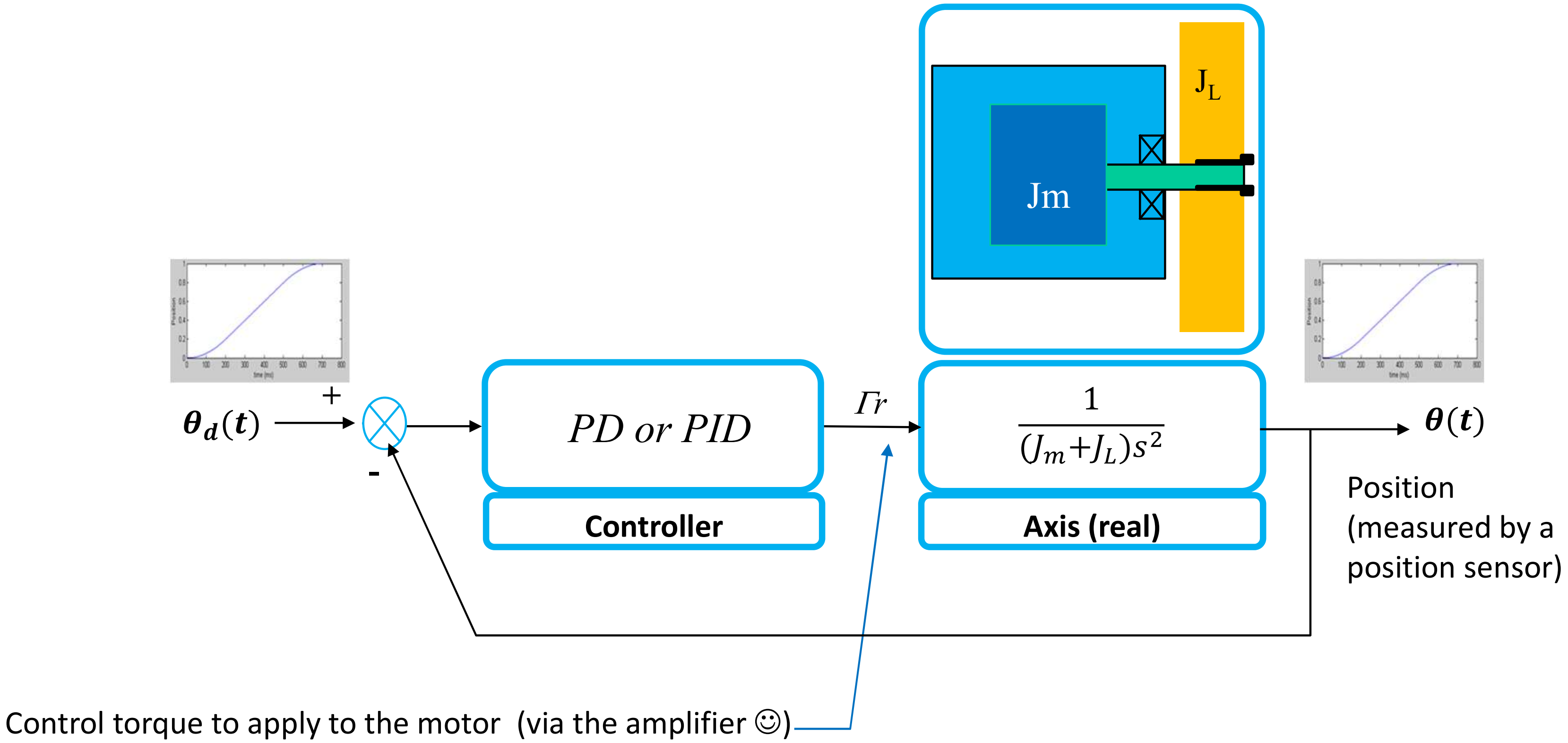


Position (measured at The motor shaft)

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)

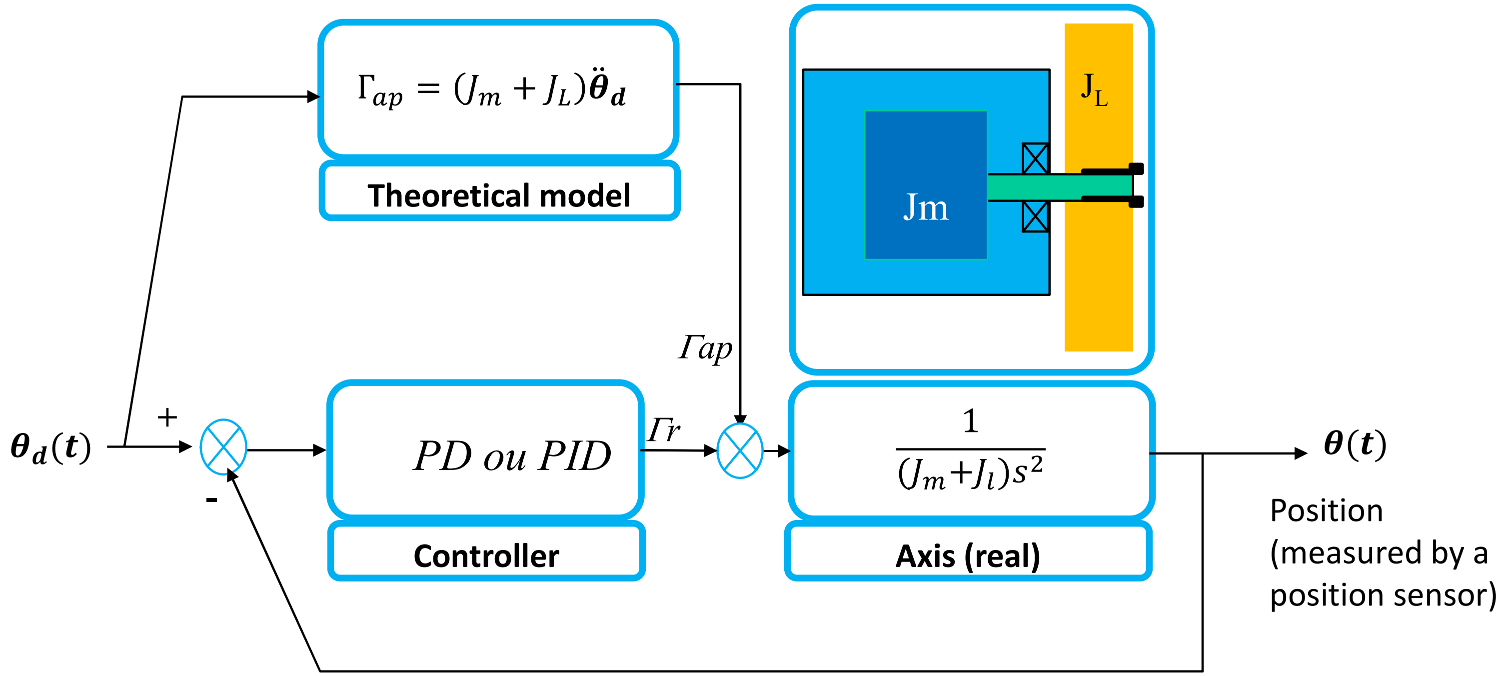
Reminder

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



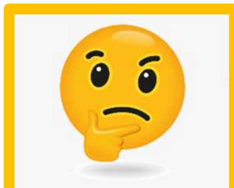
The ideal is therefore to **combine these two instruments for the same objective**: to control the motor position as best as possible to the desired trajectory.

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

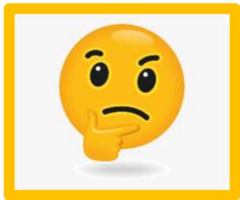


Very important :

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?

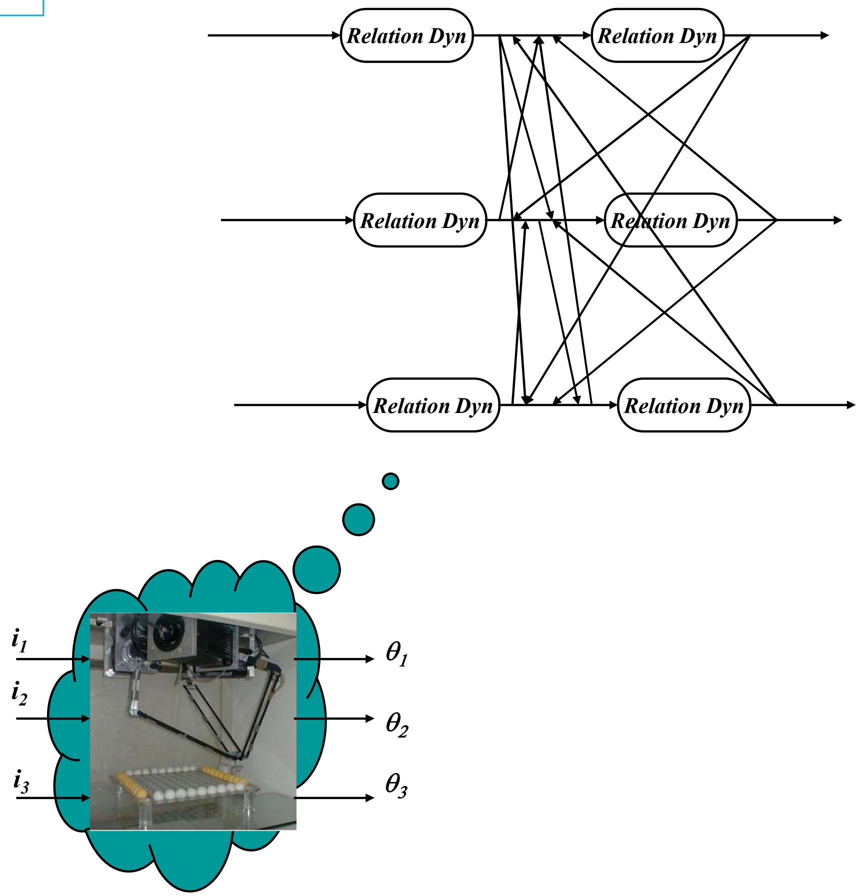


Very important :

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

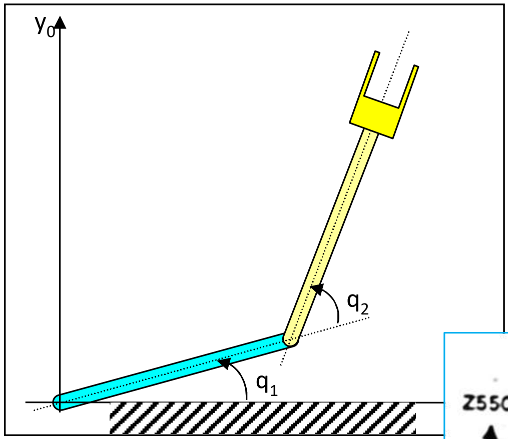
- The efficiency of the transmission (this can also vary according to speed and lubrication and also temperature).
- Friction in the transmission.
- The load to be moved (which may vary according to the customer's needs).
- The amplifier (gain and bandwidth).
- External forces from various sources.

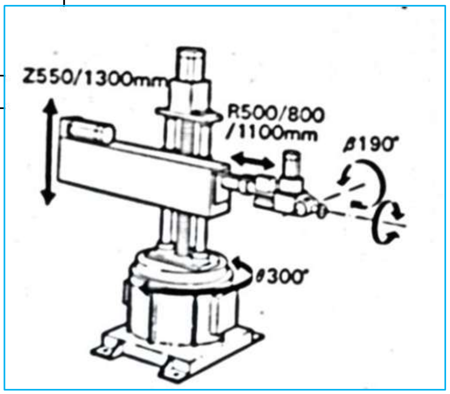
Couplings

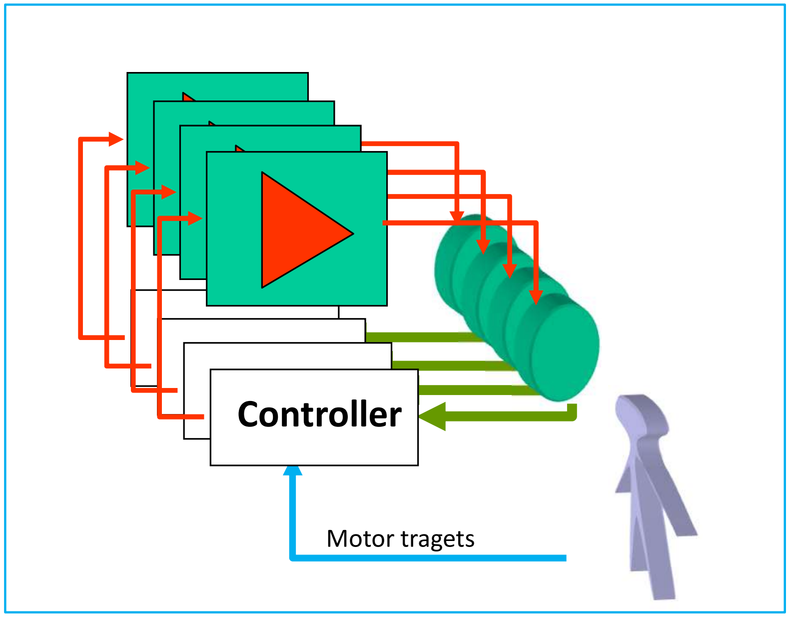

Relation Dyn
Relation Dyn
Relation Dyn
Relation Dyn
Relation Dyn
Relation Dyn
i_1
i_2
i_3
θ_1
θ_2
θ_3

Part 1
Objective CONTROL

Possibility 1 – (reminder)





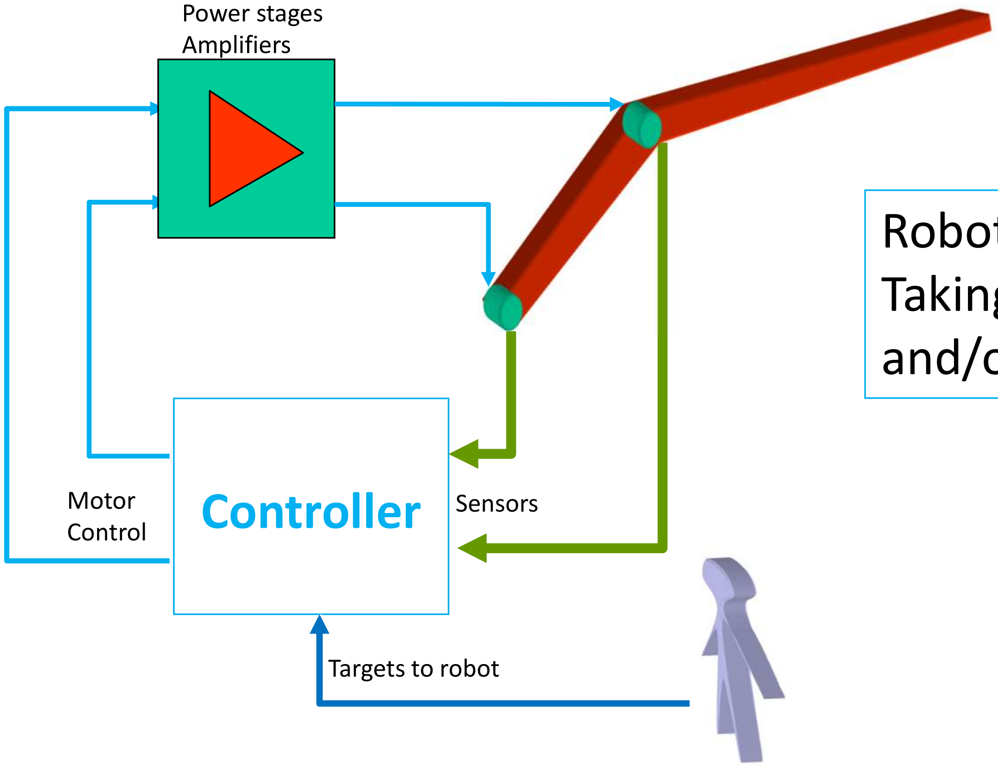


- **Control of several motors**
- **Decentralized control –** The controllers are independent from each others
- **Control in the joint space**

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

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

- Γ: Vector of generalized torques
- $B(q)$: Matrix of inertia
- $G(q)$: Vector of gravity
- $C(q,\dot{q})$: Centrifuge and Coriolis terms
- $F(q,\dot{q})$: Friction terms
- $K(q)$: Stiffness vector

That we put in the following form:

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

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

Direct dynamic model of the robot

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

State form of the dynamic model

Models of robots & Models for control

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

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

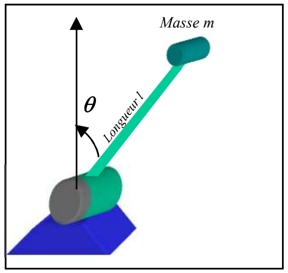
Models for control design

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

Simplified State model for control design

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

2nd order Robot model for control



Example of of 1 dof state model

Model of representation

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

Model simplified

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

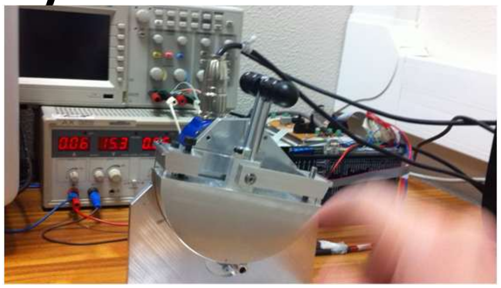
State model For simulation

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -\frac{mgl}{J}\sin(x_1) - \frac{\alpha^*_{vis}}{J}x_2 - \frac{C_{dry}}{J} + \frac{k_c}{J}u$$

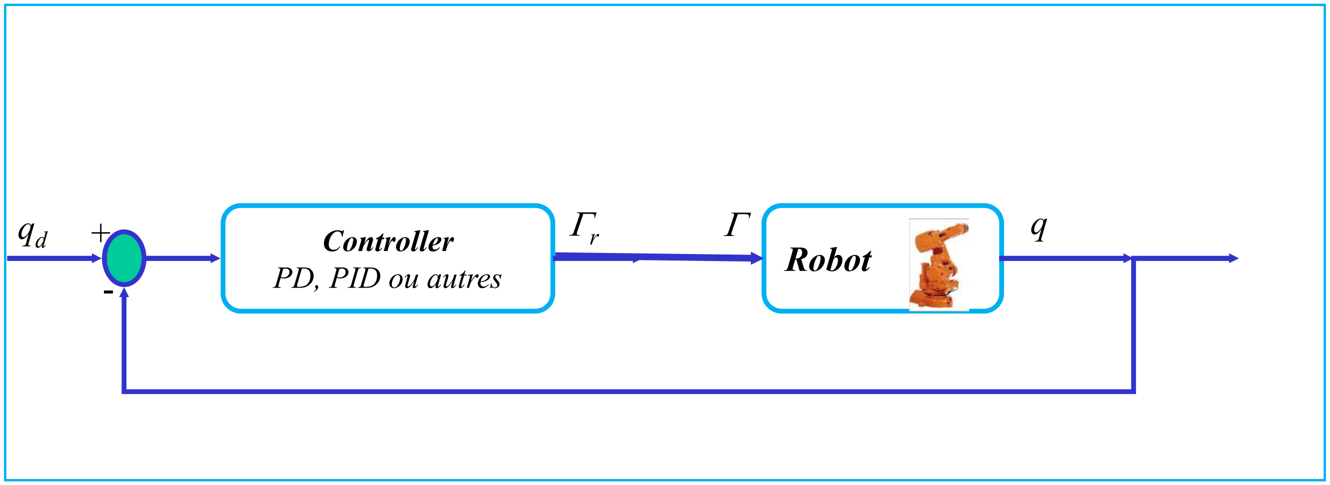
$$(x_1, x_2) = (\theta, \omega)\ et\ u = i$$

Model for control design

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -\frac{mgl}{J}\sin(x_1) - \frac{\alpha^*_{vis}}{J}x_2 + \frac{k_c}{J}u$$



Simplest decentralized controller

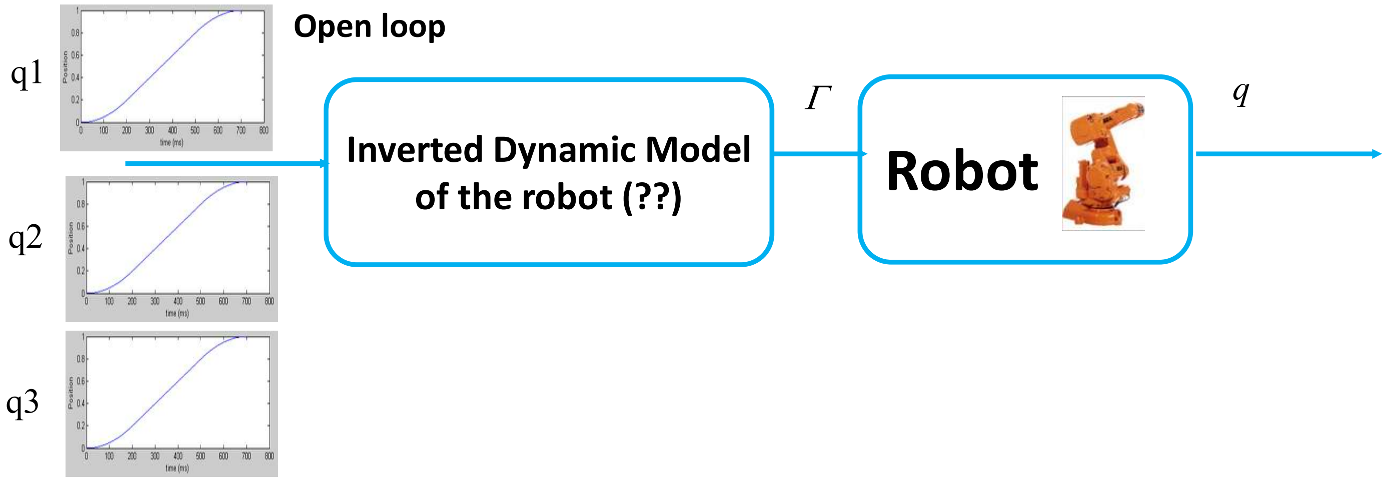


- 1 controller / axis
- All the controllers are independants

Centralized controller

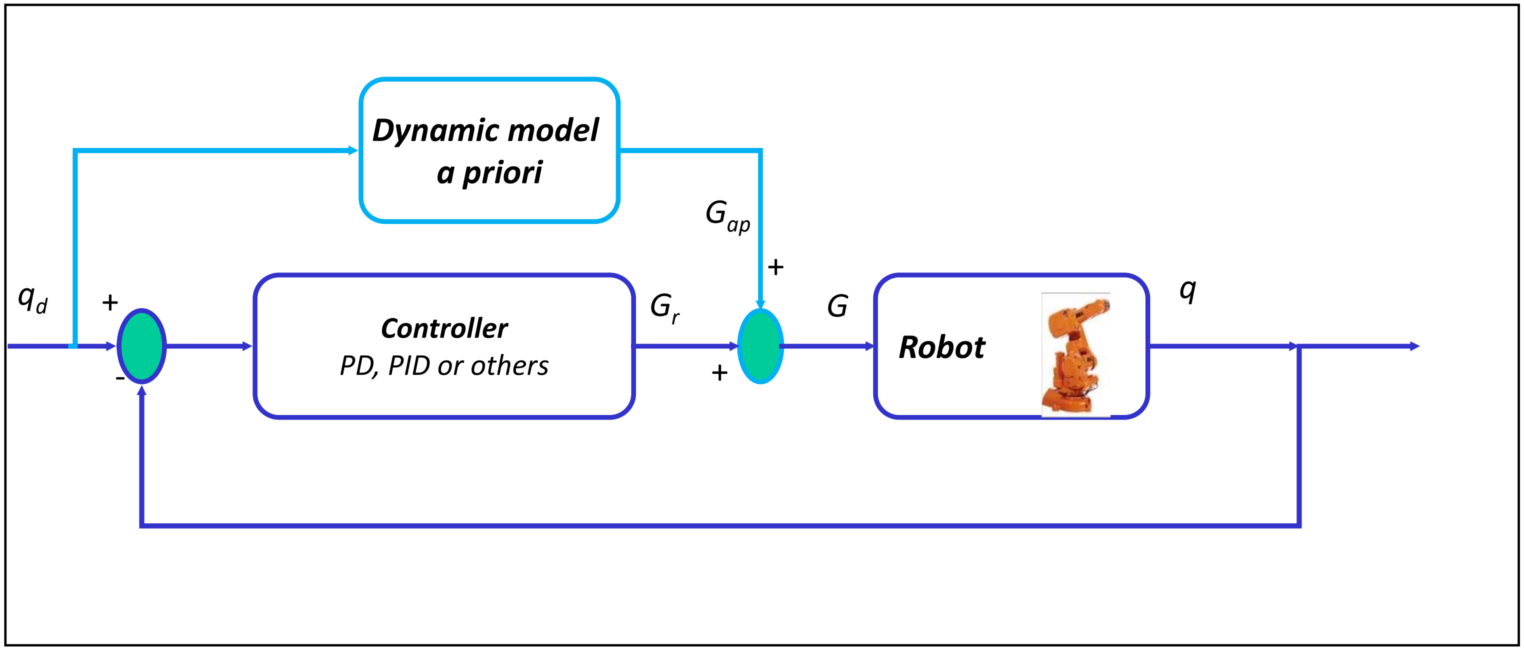
Controller a priori, to consider coupling

Principle



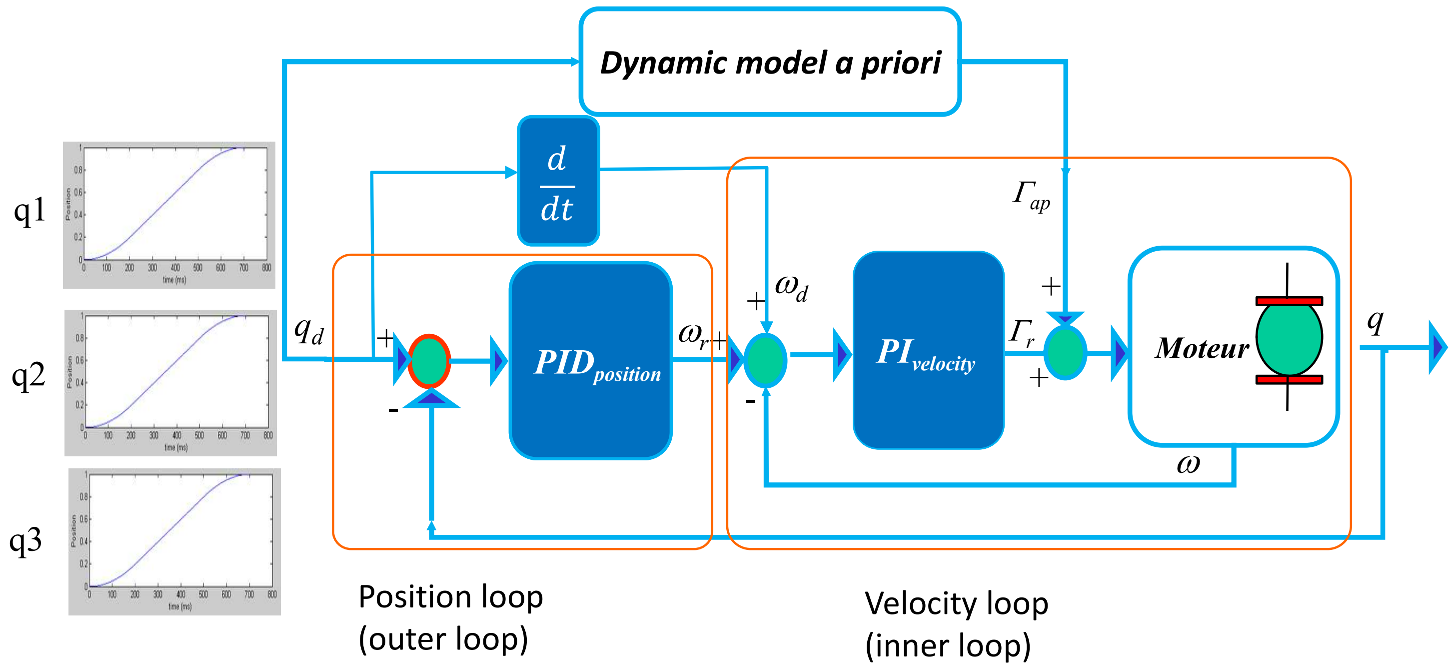
Centralized controller

Controller a priori, to consider coupling



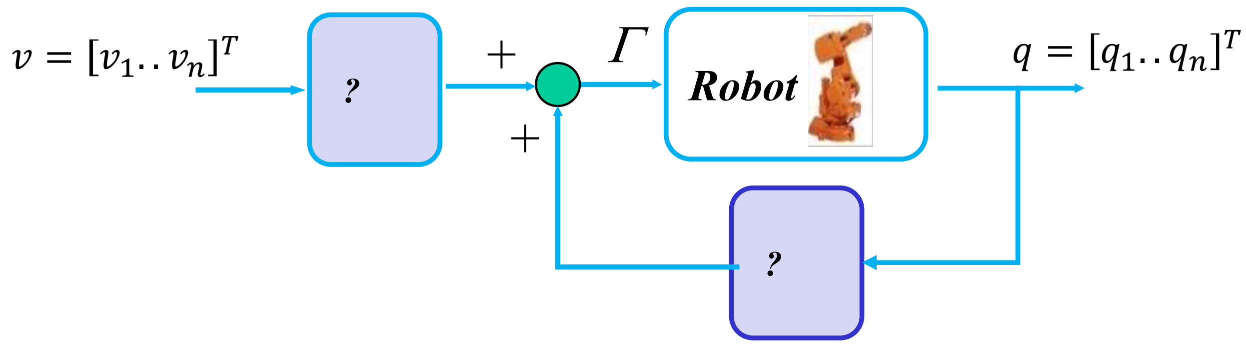
Centralized controller

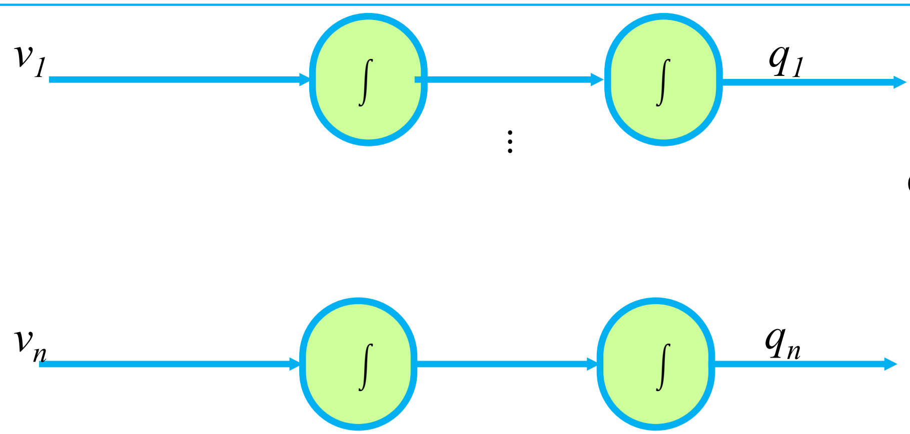
Cascaded controller & a priori, to consider coupling



Centralized controller

Non linear compensation : Non linear linearizing controller





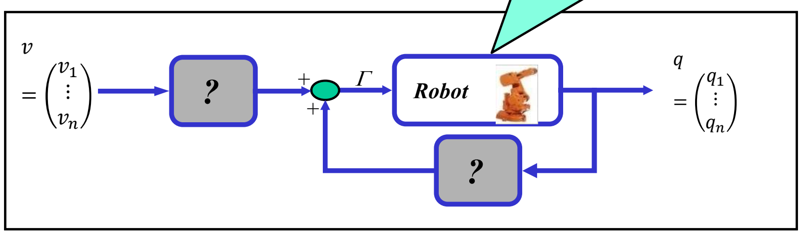
cascades of doubles integrators

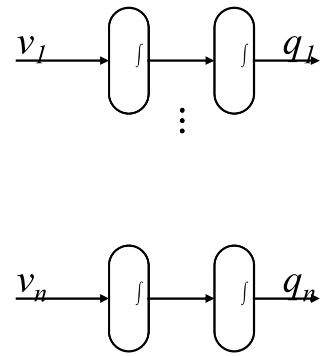
Centralized controller

Non linear compensation : Non linear linearizing controller

Objectives

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





cascades of doubles intrgrators

Observ the following control law

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

$$\ddot{q} = v$$

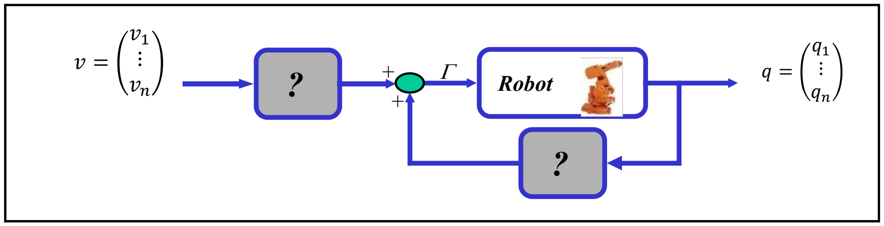
Calculation steps From the nonlinear model

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

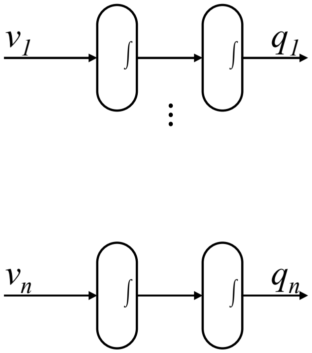
By setting : $\ddot{q} = v$

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

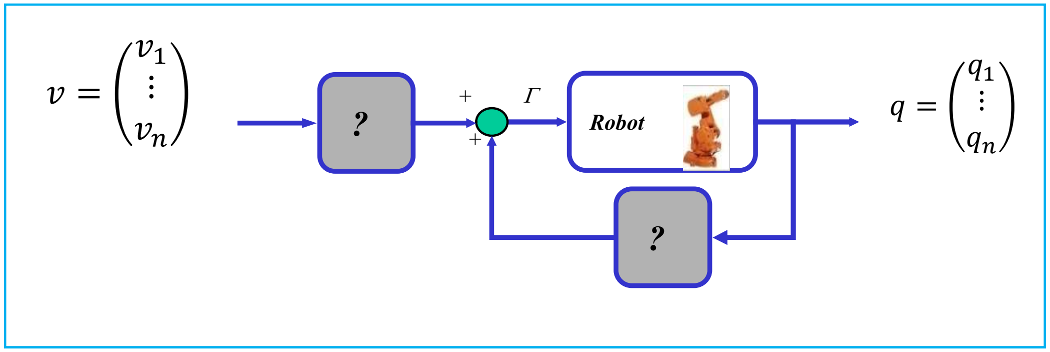
$$\ddot{q} = (B(q))^{-1}(B(q).v + H(q,\dot{q}) - H(q,\dot{q})) = v$$

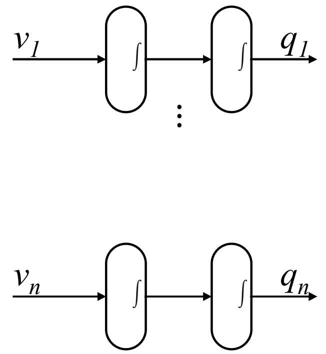


$\Leftrightarrow$



cascade of double integrators



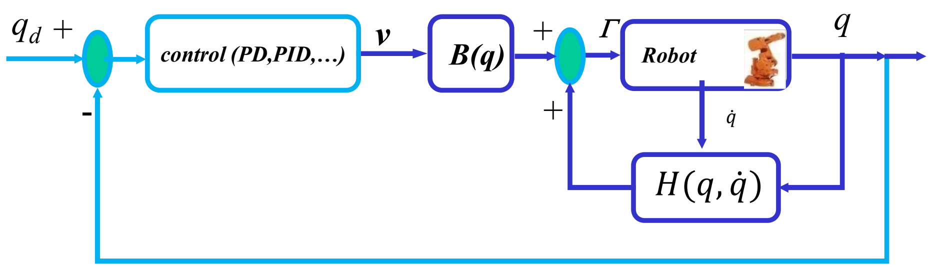


cascade de doubles intégrateurs

The double integrators must now be stabilized by looping:

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

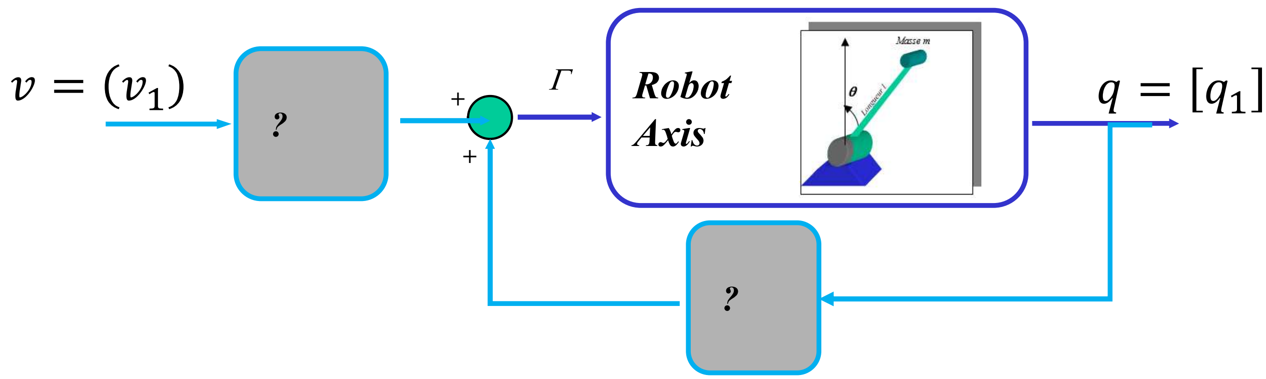
$$\Gamma = B(q).v + H(q, \dot{q})$$

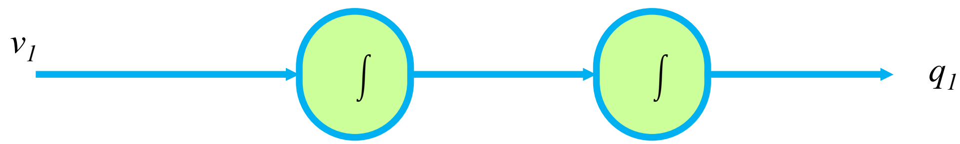


Example

$$\dot{x}_1 = x_2$$

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





Example

Position Control by Examples

1 Device description

Consider the following device (Figure 1). It is a cable driven disc steered by a Brushless Maxon[1] 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.

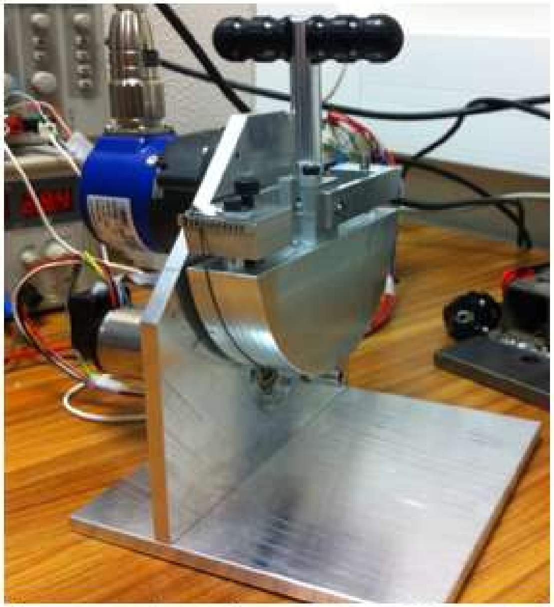


Figure 1-Haptic Device used for position control

Haptic Paddle with compensation of Dry and Viscous friction and Gravity