Human-Robot Interaction

Advanced Control – Control Schemes for a Haptic Interface

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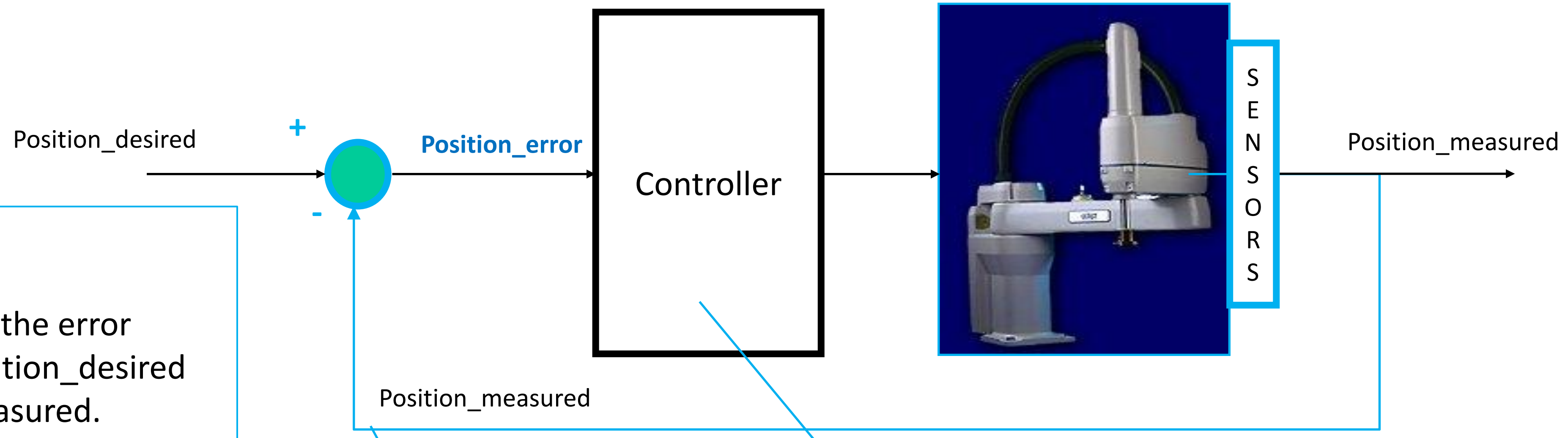
Reminders – prerequisites

Open loop versus Closed loop CONTROL

Closed loop



Sensors are used

Position_error is the error between the position_desired and position_measured.

Closing the loop also called feedback

The controller adapts the control value as a function of the position_error.

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Please tell me about P, PD and PID controllers

u is the control input (action)

P ⇒ $\Gamma_p = K_p . e$

Spring effect : provides stiffness of the control, robustness to disturbances

D ⇒ $\Gamma_d = K_d . \frac{de}{dt}$

Damping effect : improves stability of the control and reduces overshoots

I ⇒ $\Gamma_i = K_i \int_0^t e(\tau)d\tau$

"More and more" effect : Increases the control value to cancel the steady state error.

PID

$$u = K_p . e + K_d . \frac{de}{dt} + K_i \int_0^t e(\tau)d\tau$$

How to implement friction and gravity compensation in position control?

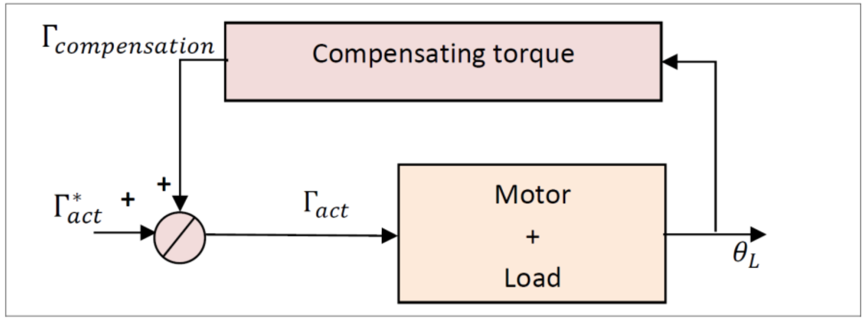
1. Use the integrator term of the PID. → **Does not apply for haptic feedback and for compliant control since it provides an infinite (very high) impedance**

$$\Gamma_{PID} = k_p\varepsilon \quad - k_D\dot{\theta}_L + k_I\int_0^t \varepsilon(\tau)d\tau$$

2. Implement an exact compensation

That means that the compensating torque is given by:

$$\Gamma_{compensation} = M_D g\, r_g \sin(\theta_L) + \Gamma_{dry} + k_{vis}\,\dot{\theta}_L$$



The integrator of the PID controller is an estimator for steady-state unknown efforts (disturbances)

Case 1: PID to compensate for gravity

$$J_{RL}\ddot{\theta}_L = \boldsymbol{k_p \varepsilon} \quad \boldsymbol{- k_D \dot{\theta}_L + k_I \int_0^t \varepsilon(\tau) d\tau} - M.g.l.\sin(\theta_L)$$

In the static phase, $\dot{\theta}_L = \ddot{\theta}_L = \dot{\theta}_d = \ddot{\theta}_d = 0.$

@ constant desired position θ_d, this leads to the following **very important** equality:

$$\boldsymbol{k_I \int_0^t \varepsilon(\tau) d\tau} = M.g.l.\sin(\theta_L) = M.g.l.\sin(\theta_d)$$

because the static error ε = 0

Case 2: PID to compensate for gravity and friction

$$J_{RL}\ddot{\theta}_L = k_p \varepsilon \quad - k_D \dot{\theta}_L + k_I \int_0^t \varepsilon(\tau) d\tau - \boldsymbol{\Gamma_{dry}} - M.g.l.\sin(\theta_L)$$

$$\boldsymbol{k_I \int_0^t \varepsilon(\tau) d\tau} = \boldsymbol{\Gamma_{dry}} + M.g.l.\sin(\theta_L)$$ **(at the static phase)**

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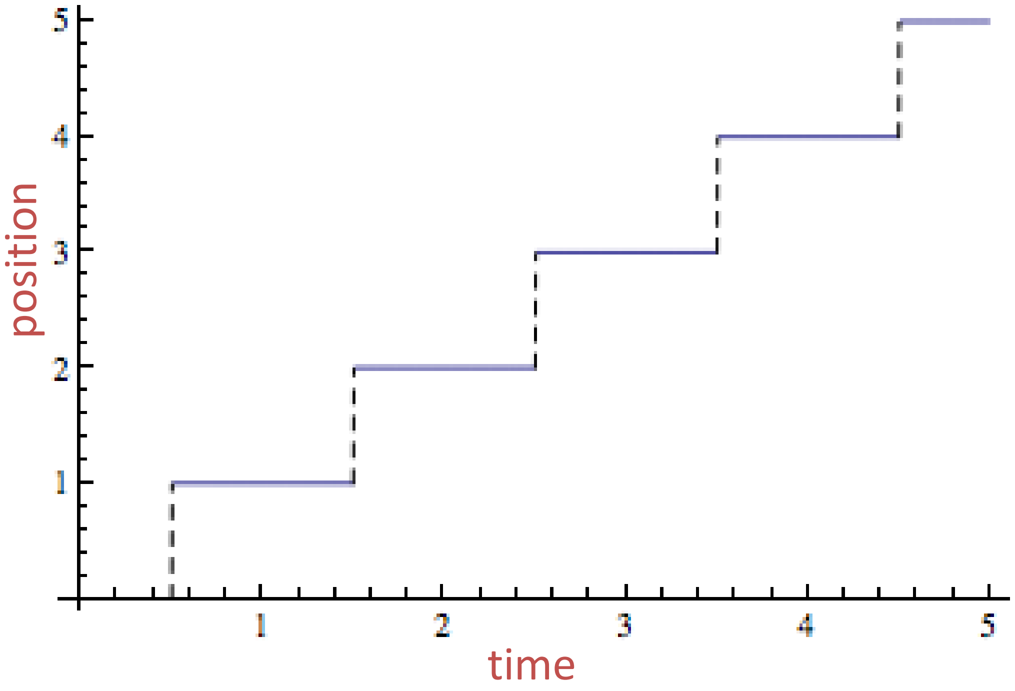
PID – Quasi static torque compensation

$$J_{RL}\ddot{\theta}_L = k_p\varepsilon \quad - k_D\dot{\theta}_L + k_I\int_0^t \varepsilon(\tau)d\tau - \boldsymbol{\Gamma_g}(\boldsymbol{\theta_L})$$

In the static phase, $\dot{\theta}_L = \ddot{\theta}_L = \dot{\theta}_d = \ddot{\theta}_d = 0$.

$$\boldsymbol{k_I\int_0^t \varepsilon(\tau)d\tau} = \boldsymbol{\Gamma_g}(\theta_L) = \boldsymbol{\Gamma_g}(\theta_d)$$

The experiment may be implemented **for different desired positions scanning the entire workspace of the robot**. The integrator compensates for the quasi static disturbance torque at each desired position.
The compensation torque may then be interpolated and fitted with a known polynomial function.



PID – multi-variable Quasi-static torque compensation

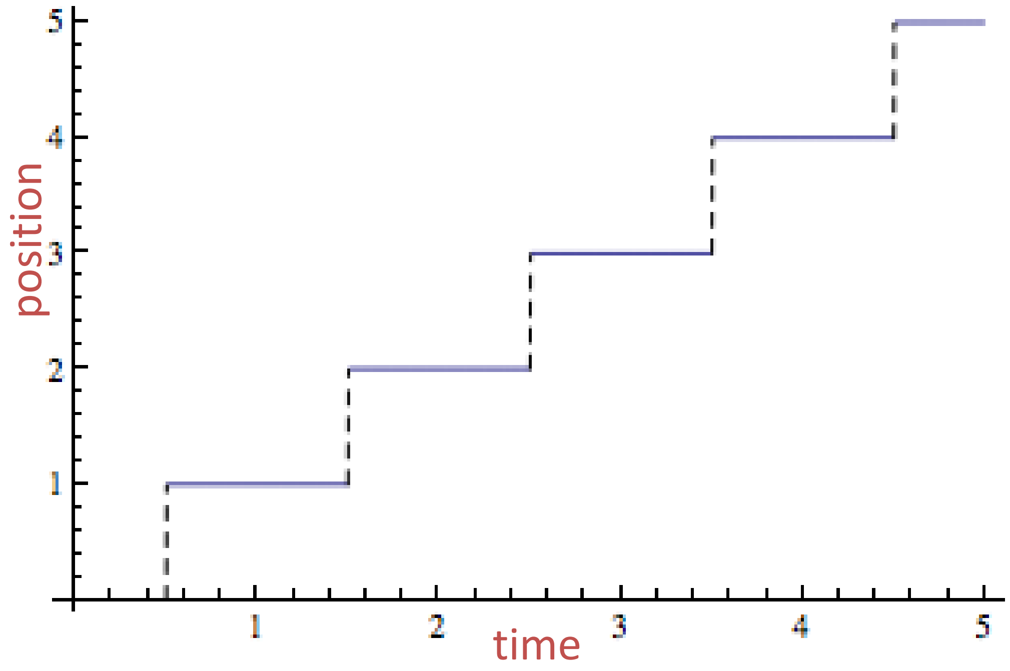
$$J_{RL}\ddot{q}_{i,L} = k_p\varepsilon_i - k_D\dot{\theta}_{i,L} + k_I\int_0^t \varepsilon_i(\tau)d\tau - \boldsymbol{\Gamma}_{\boldsymbol{g}}(\boldsymbol{q_1}, \boldsymbol{q_2}, \boldsymbol{q_3}) \qquad \boldsymbol{i = 1, 2 \text{ or } 3}$$

In the static phase, $\dot{q}_L = \ddot{q}_L = \dot{q}_d = \ddot{q}_d = 0.$

$$\boldsymbol{k_I \int_0^t \varepsilon_i(\tau)d\tau = \Gamma_g(q_1, q_2, q_3)}$$

The experiment may be implemented **for different desired positions**. The integrator compensates for the quasi static disturbance torque at each desired position.

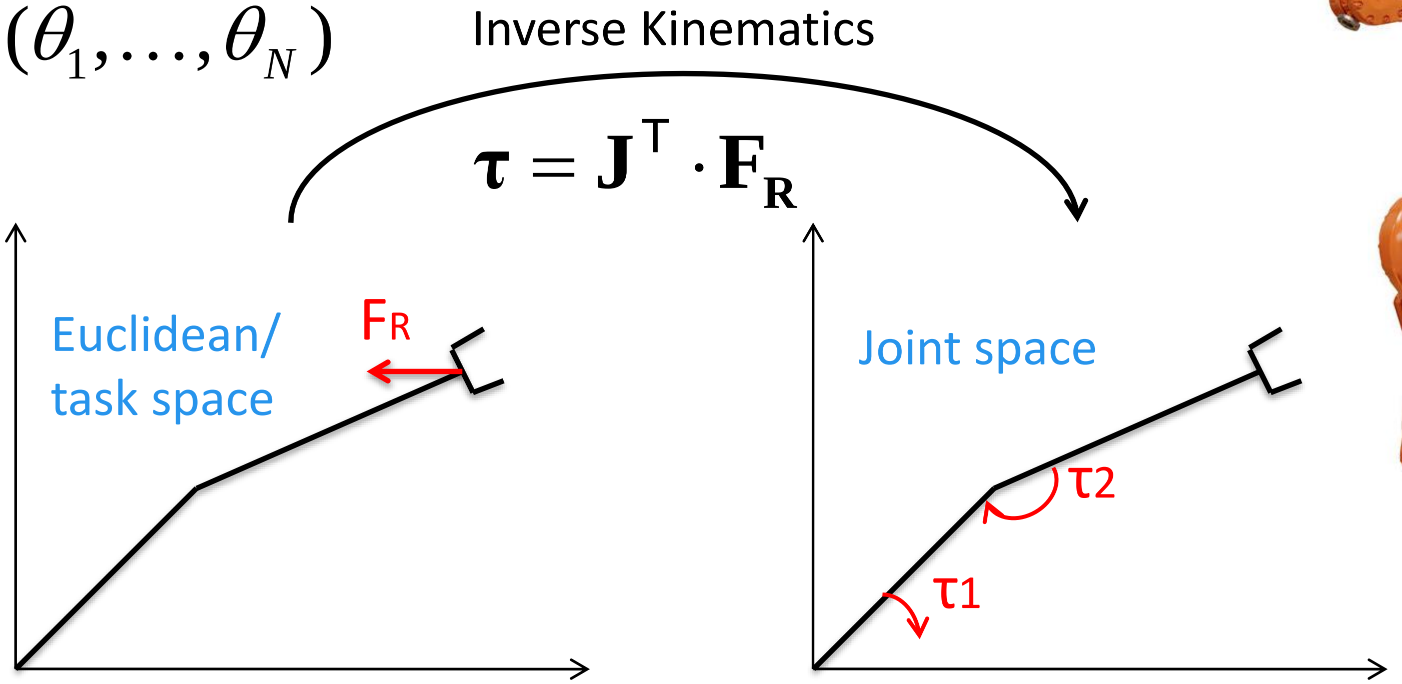
The compensation torque may then be interpolated and fitted with a known multivariable polynomial function.



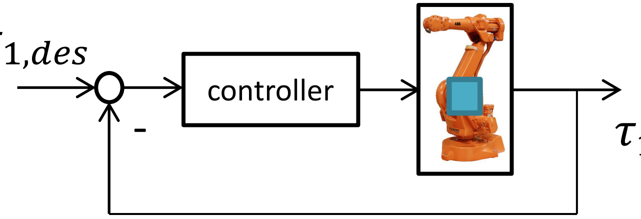
End of reminders

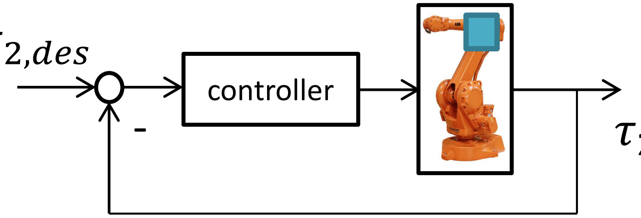
Forces and **Torques**
Tool coordinates versus Joint coordinates

$$J = f(\theta_1, \ldots, \theta_N)$$



$$\boldsymbol{\tau} = \mathbf{J}^{\mathsf{T}} \cdot \mathbf{F_R}$$

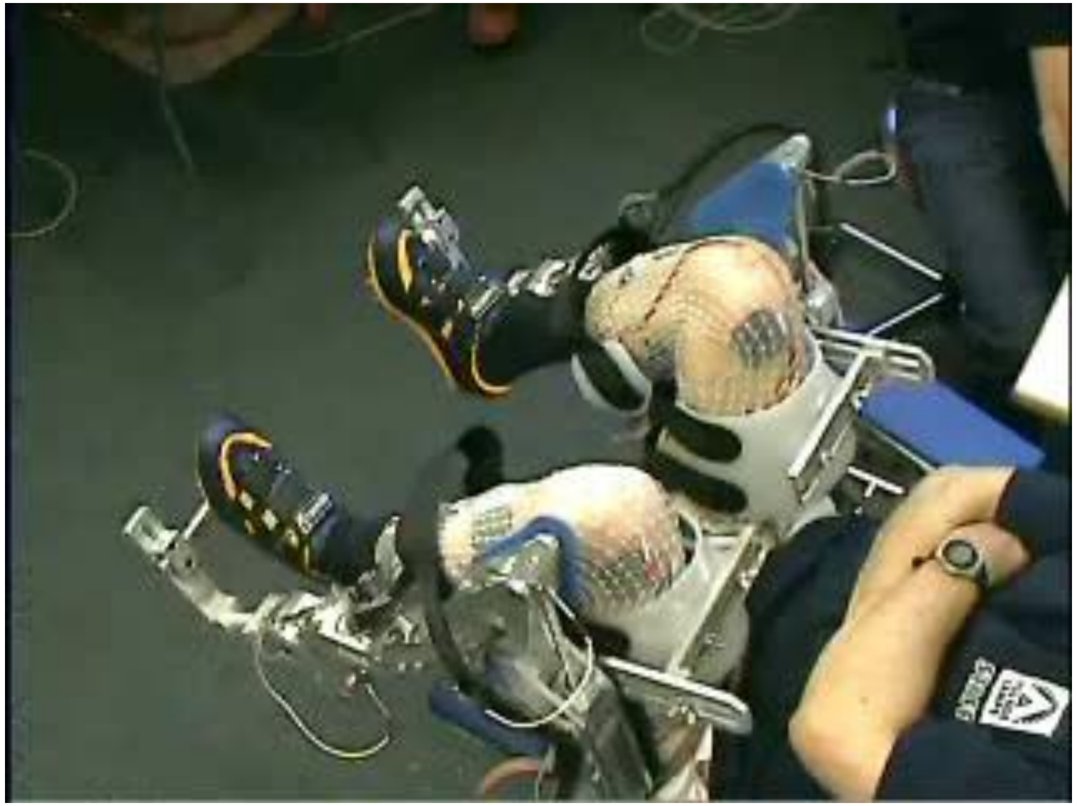


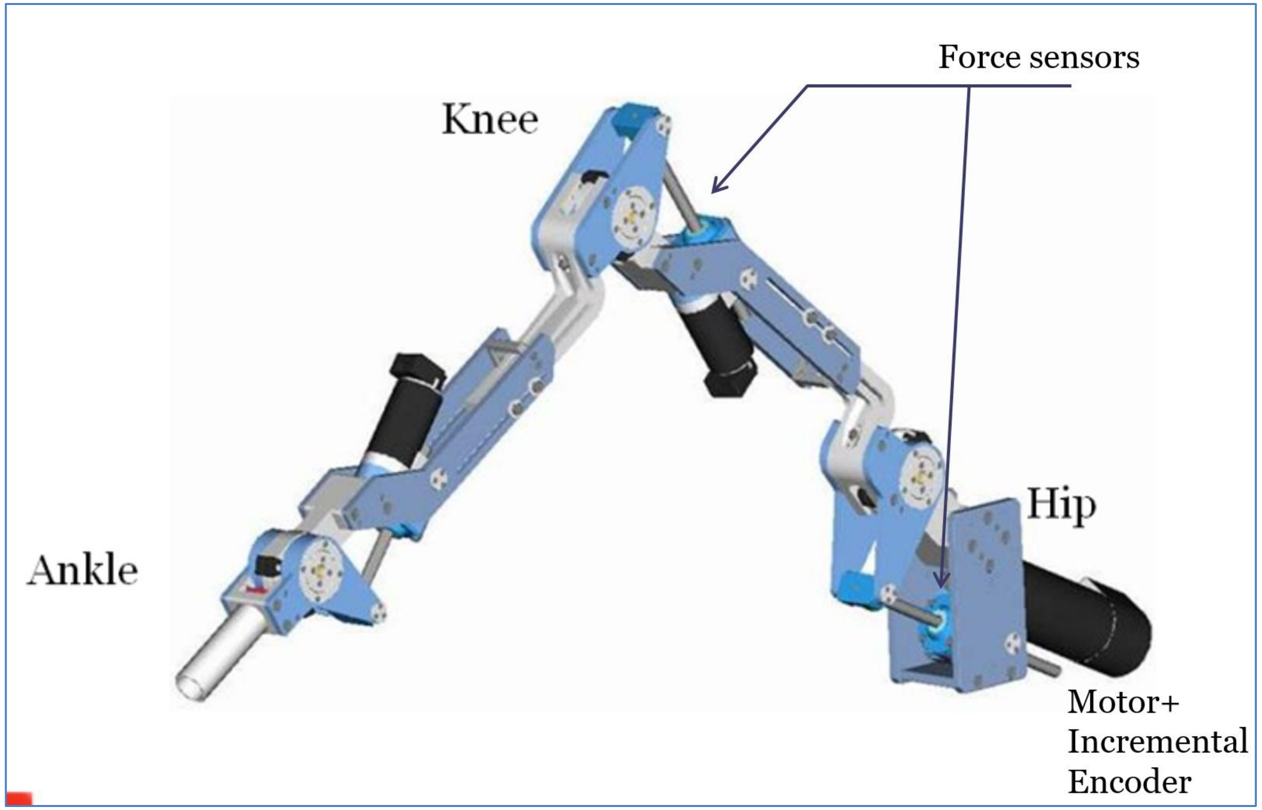


Example
Closed loop force control through Muscle Electrostimulation

Flexion extension desired force ----

Torques measured at the joints ----

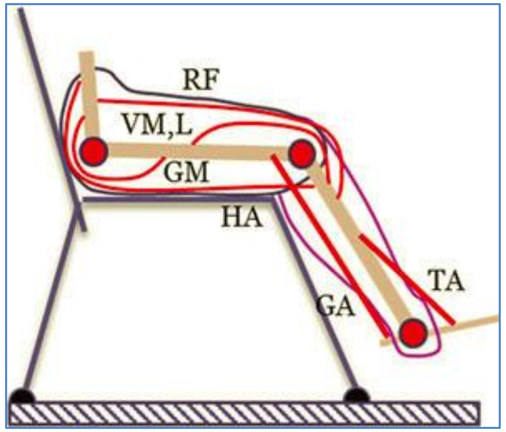


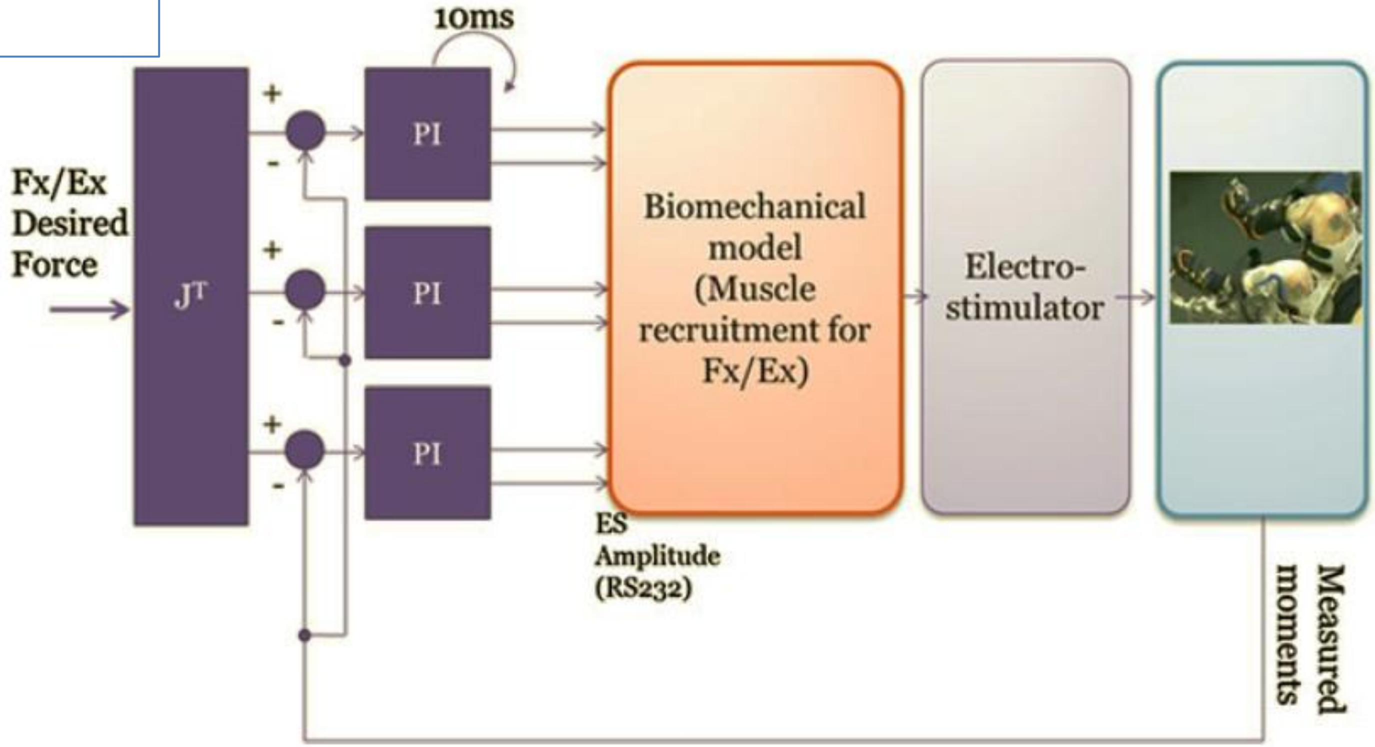


Example
Closed loop force control through Muscle Electrostimulation

Total of **7 muscles have been used** in the loop:

- RF Rectus Femoris,
- VM, L Vastus Medialis and Lateralis, GM Gluteus maximus.
- HA Hamstring,
- GA Gastrocnemius,
- TA Tibialis Anterior



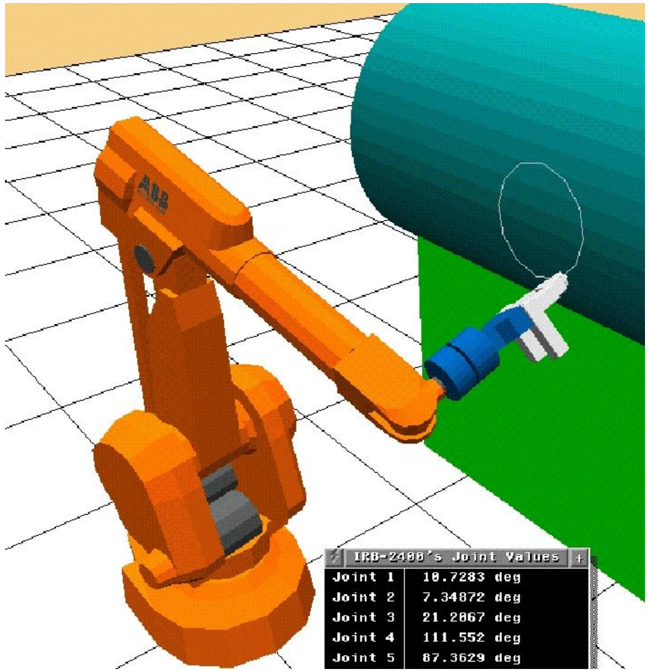


The Electrostimulation Control loop

Position Control vs. Force Control

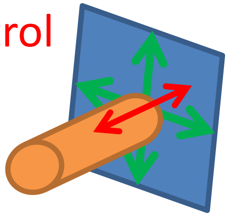
Application	Control mode
Pick and place application	Position
Tool machining	Position- stiff control
Laser cutting	position
Sanding	
Polishing	

Position Control vs. Force Control



Hybrid position and force control

Force control (normal)



Position control (tangential)

Force/Impedance control for robotic manipulators, Nagarkatti and Dawson, 2005

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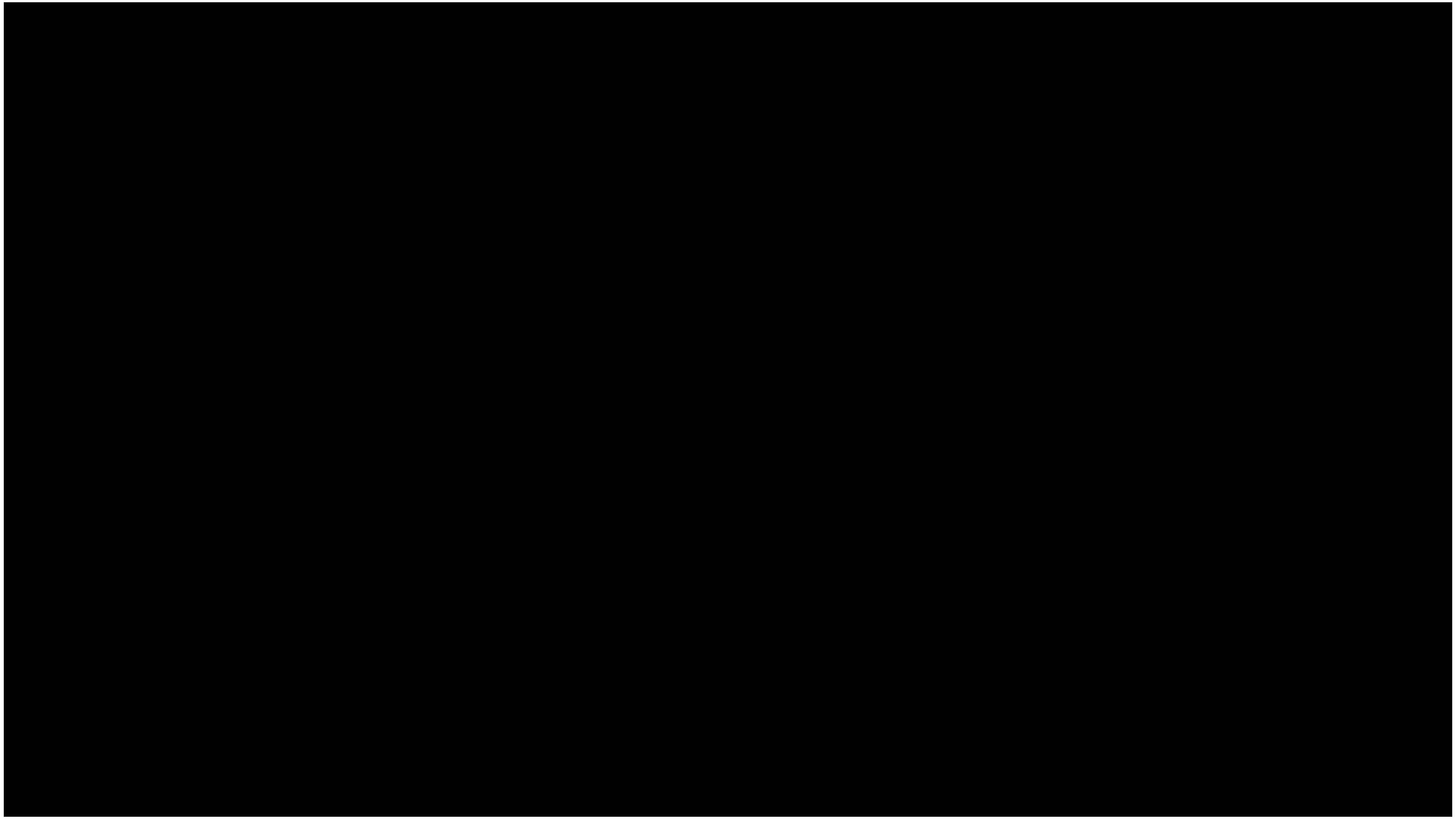
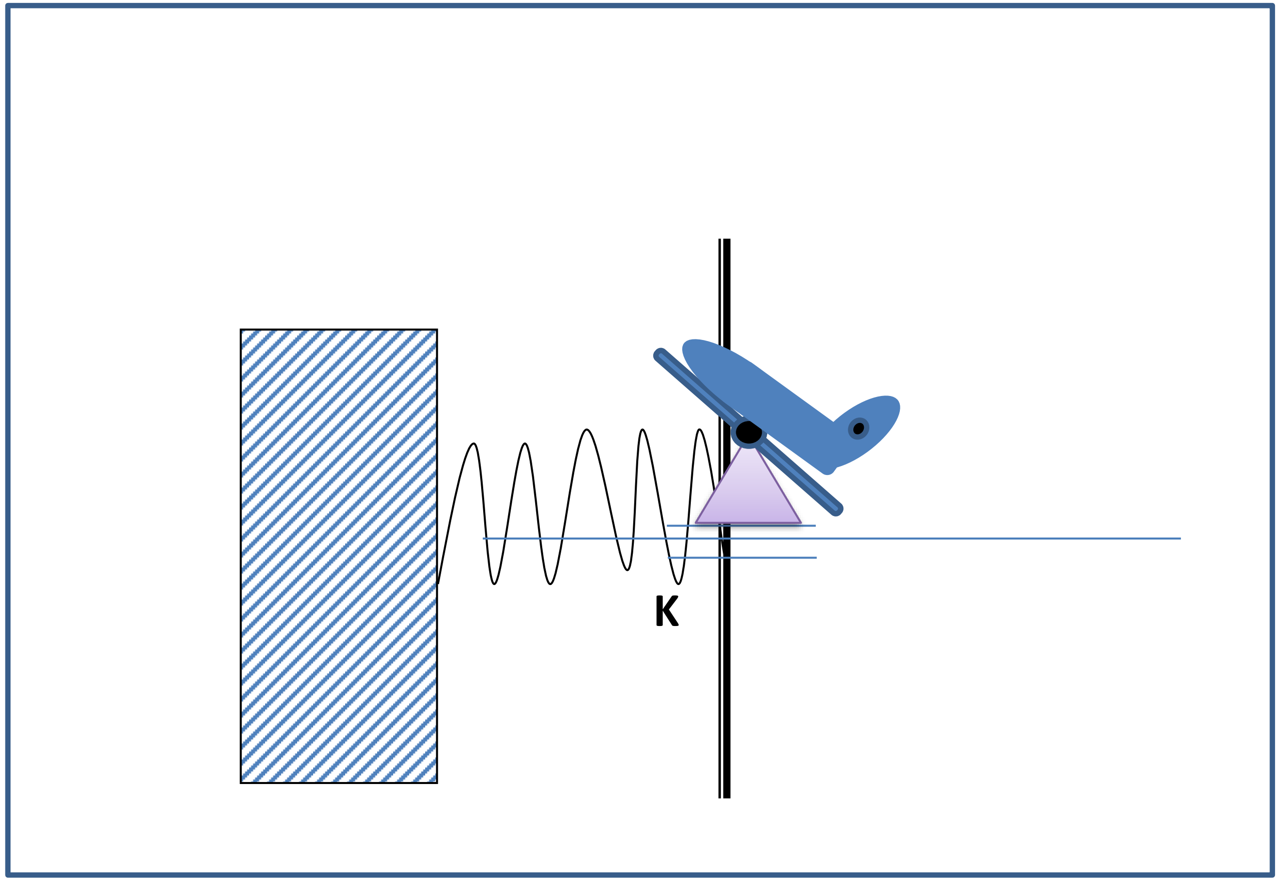
Which kind of control is it ?



Human Robot Interaction

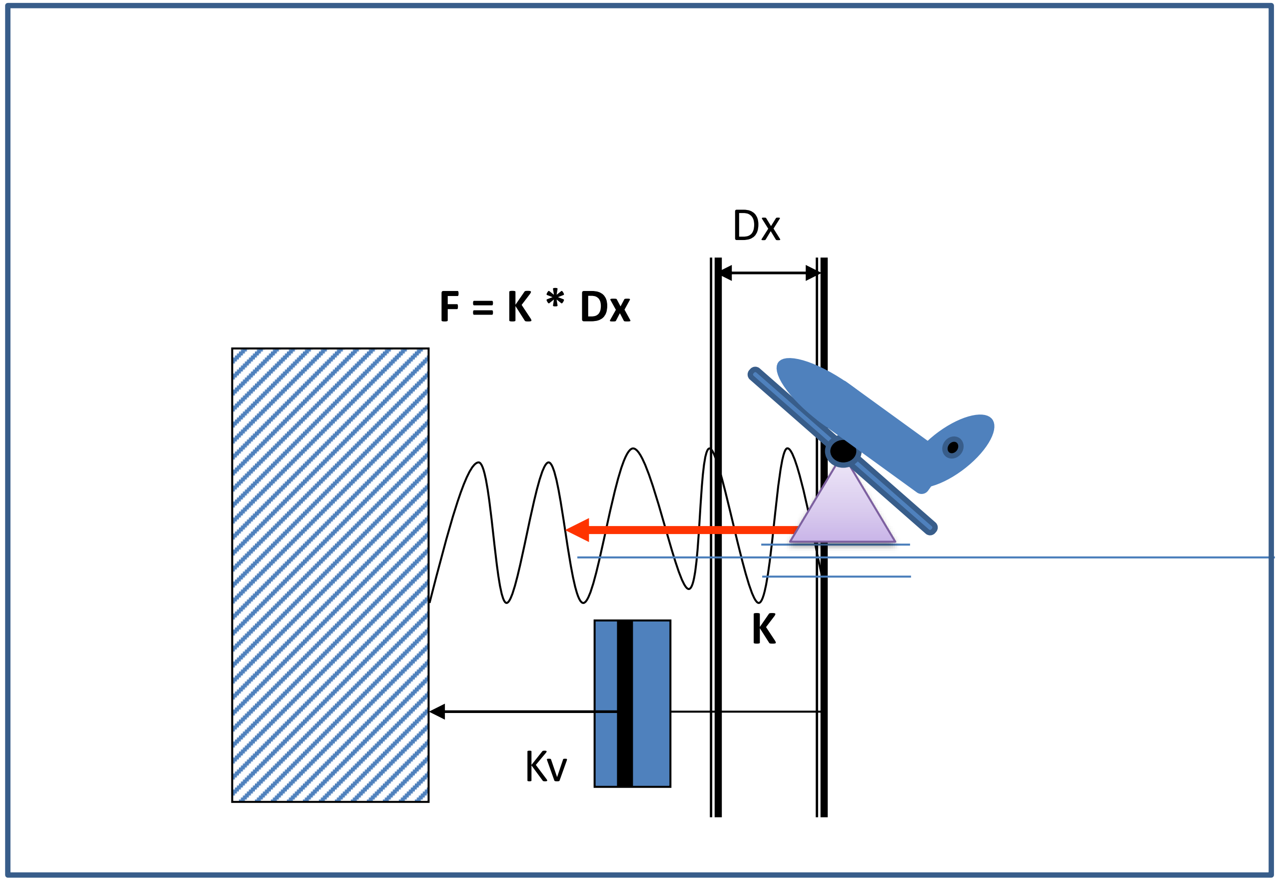
What is mechanical impedance ?



Mechanical impedance concerns **INTERACTION**.

The simplest way to feel/implement interaction is a **SPRING**.

What is mechanical impedance ?

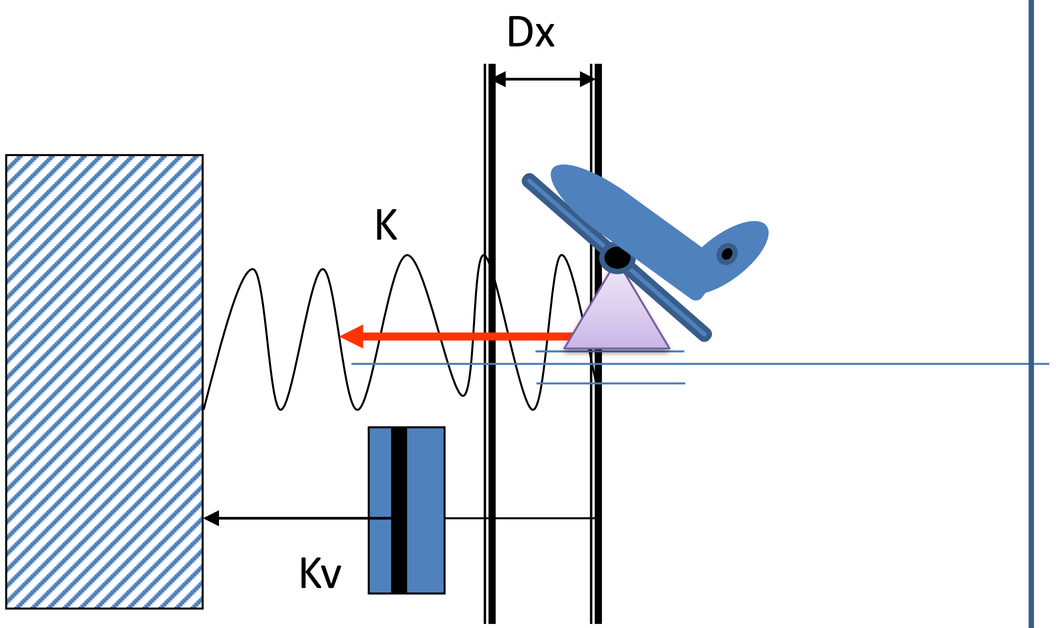


a **SPRING** ⊕ a **DAMPER**

F = K * Dx + Kv * d(Dx)/dt

What is mechanical impedance ?

Fmot = Kp * Dx + Kd * d(Dx)/dt



Mechanical Impedance denotes
the quality of compliance : stiffness of the interaction (Kp, Kd)

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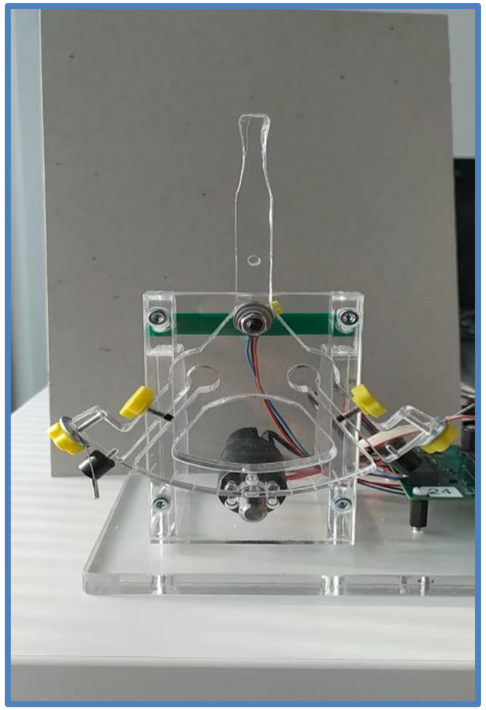
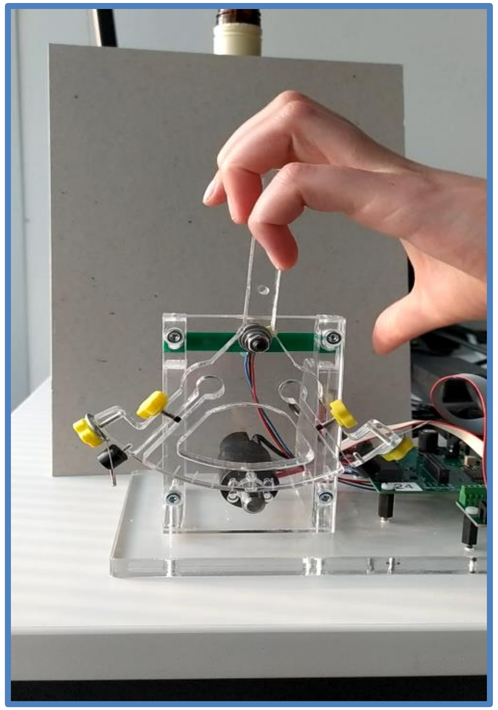
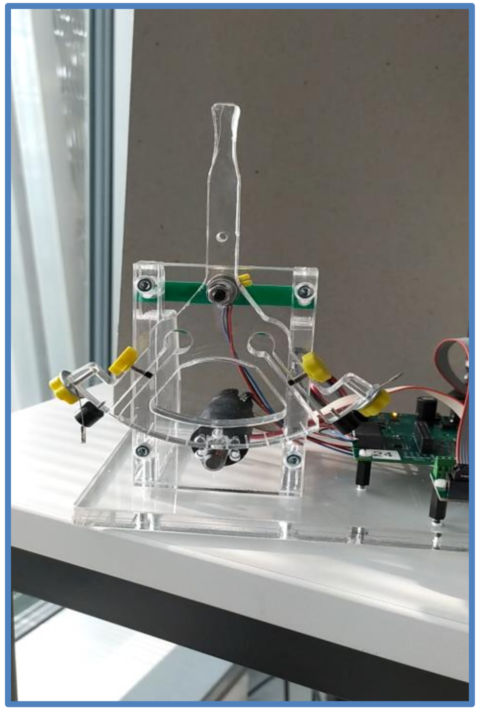
Examples of behaviors



Stiff
(kp is high)



Compliant
(kp is low)



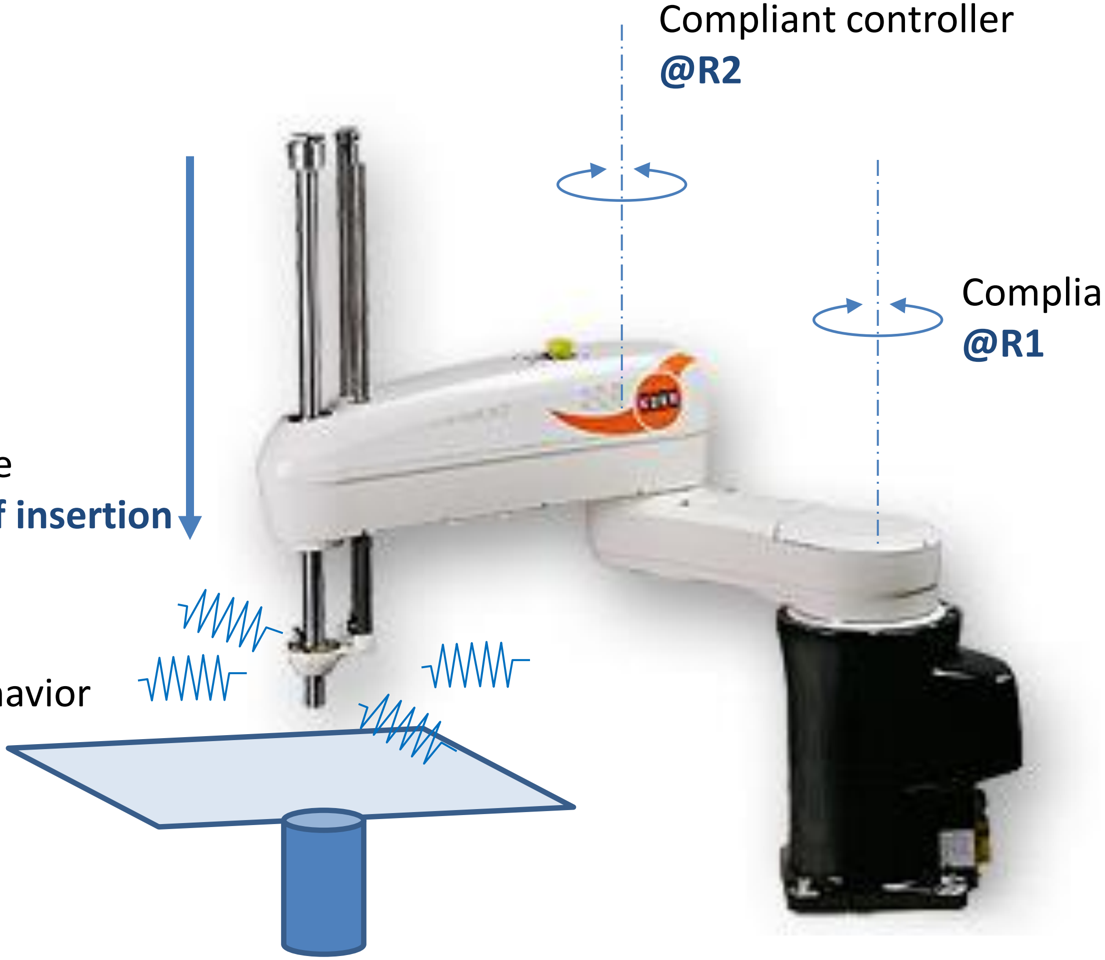
Damped
(kp is low, kd is high enough to damp)

Higher is the impedance, **stiffer** is the interaction

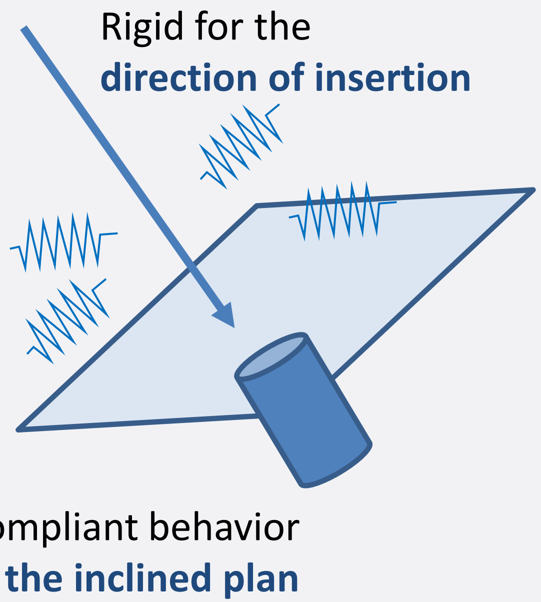
Lower is the impedance, higher is the compliance

What is “Selective Compliance” ?

The SCARA, a mechanically **selective compliant** robot



6 Dof selective compliance…

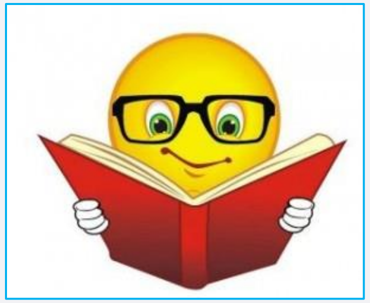


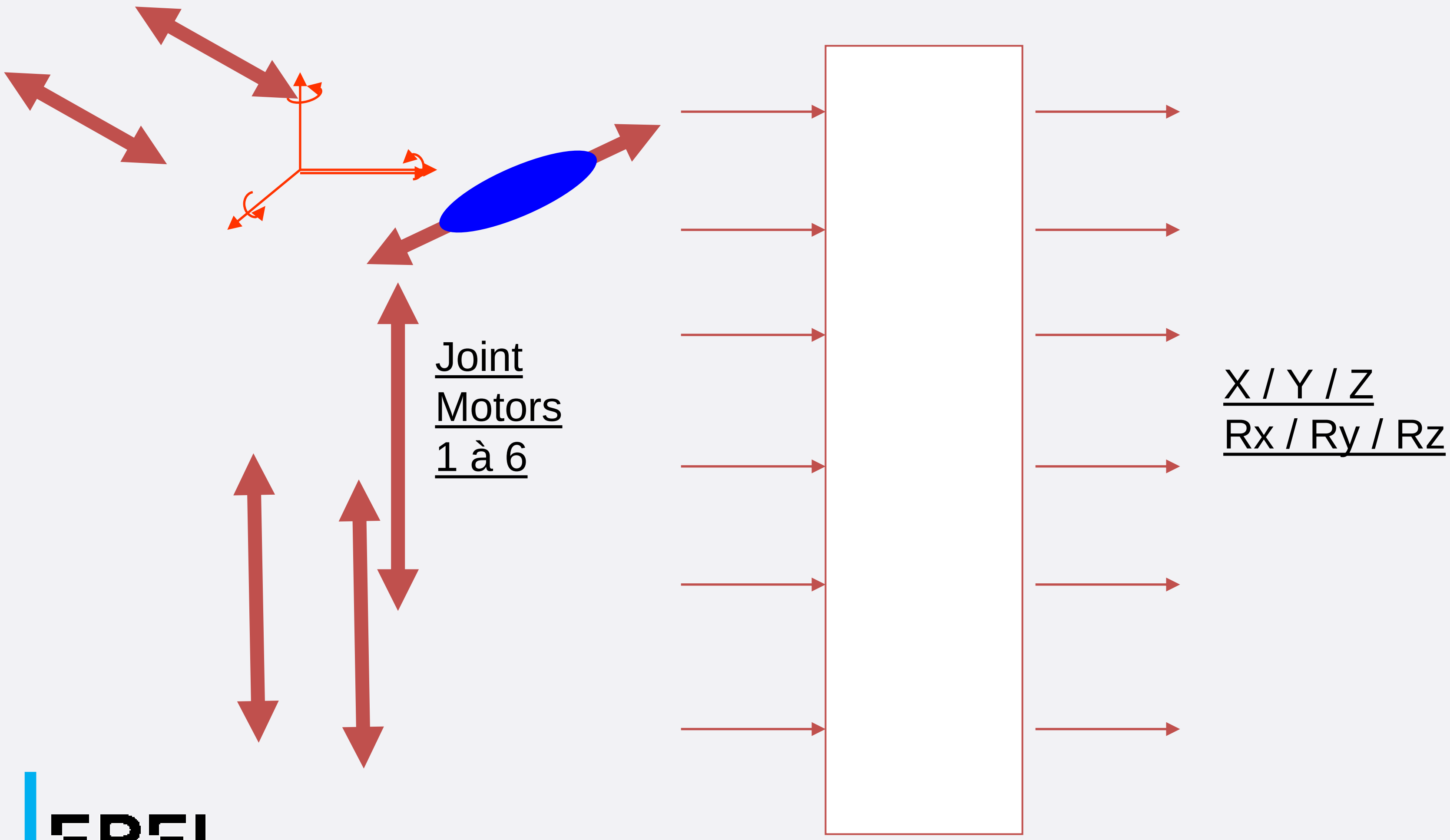
Control strategies may implement selective compliance for any single or combined directions (dofs)

23

6 Dof selective compliance…

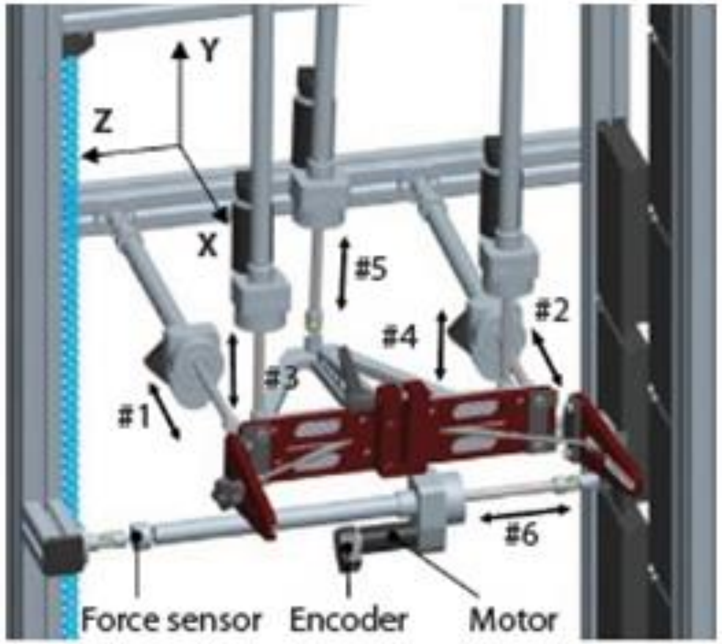
How to implement a selective compliance in one or multiple directions, either a parallel or serial structure?

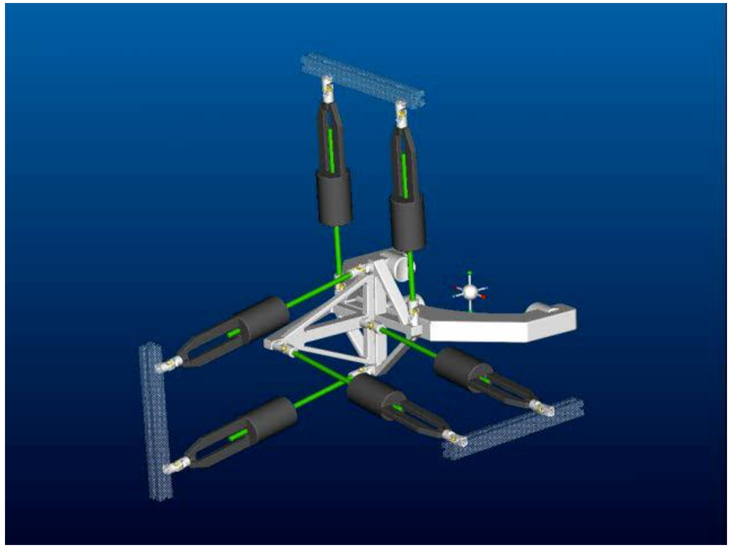


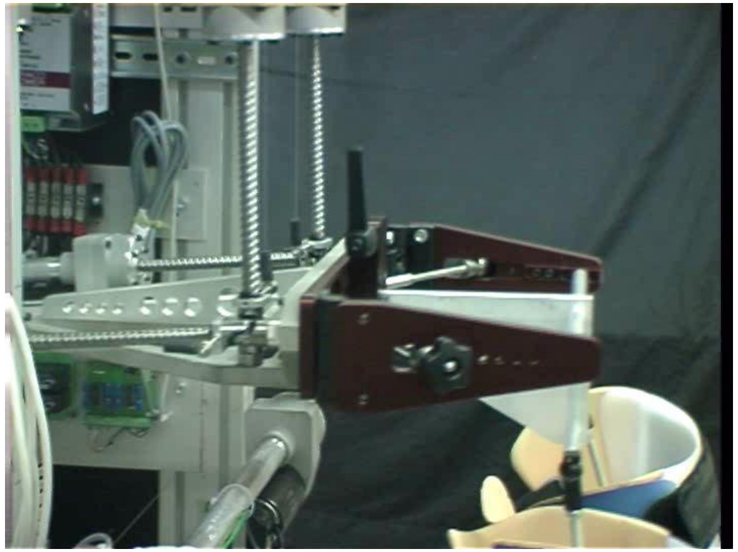


Use case….

Make compliant selected axes, on the following pelvic orthosis







2 x 2 x 2 Kinematics

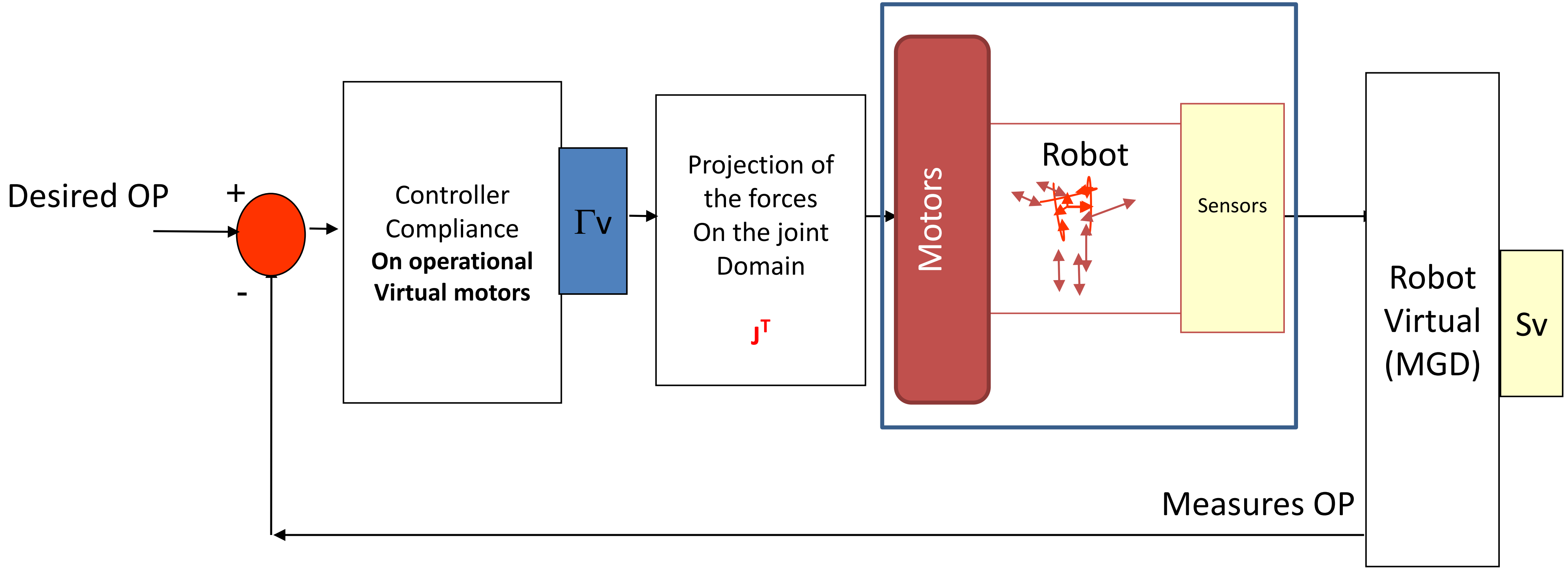
3 x 2 x 1 Kinematics

Use case….

Make compliant selected axes,
on the following pelvic orthosis

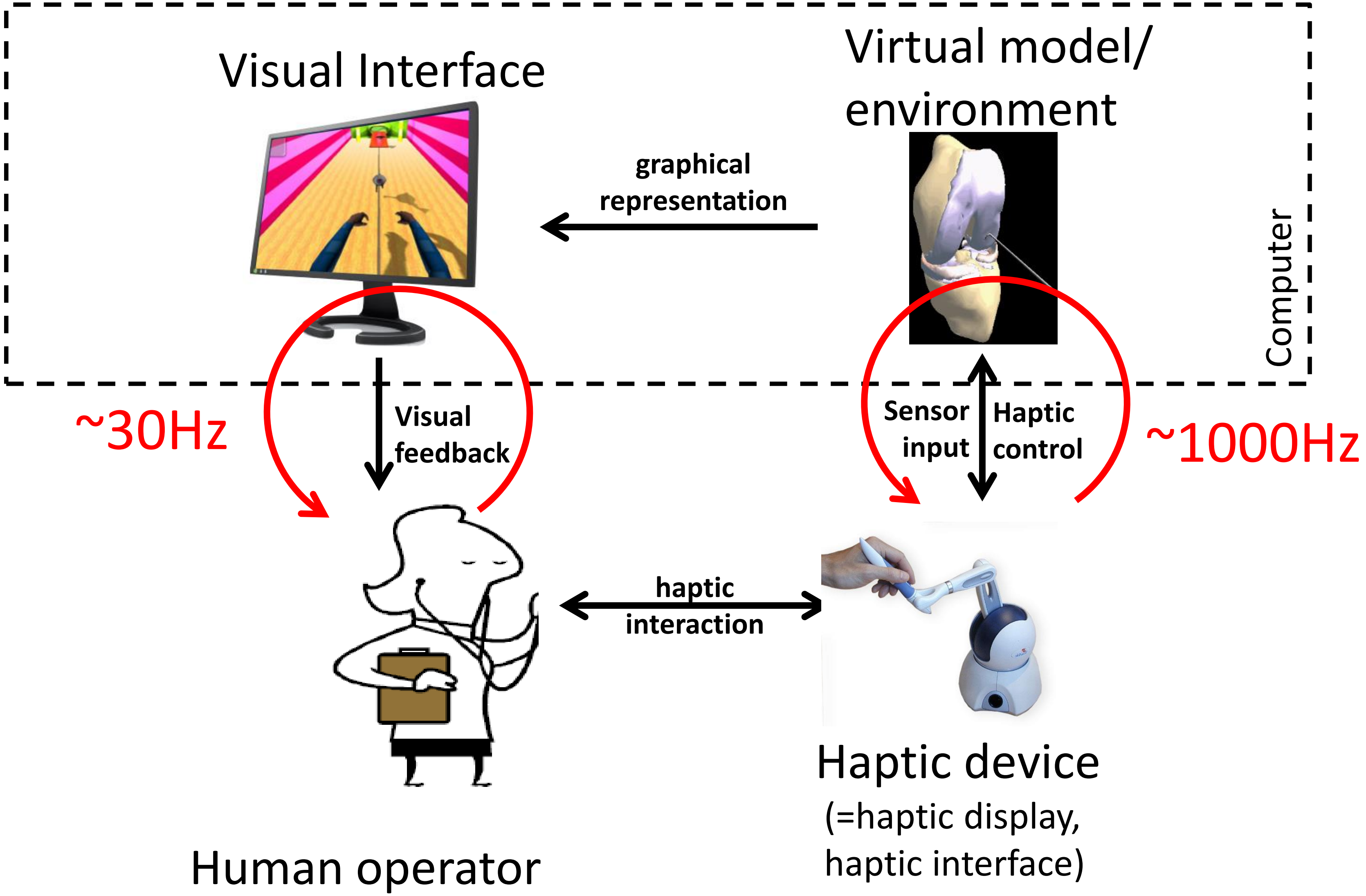
WalkTrainer

Principle of a Tool Selective Compliance Control

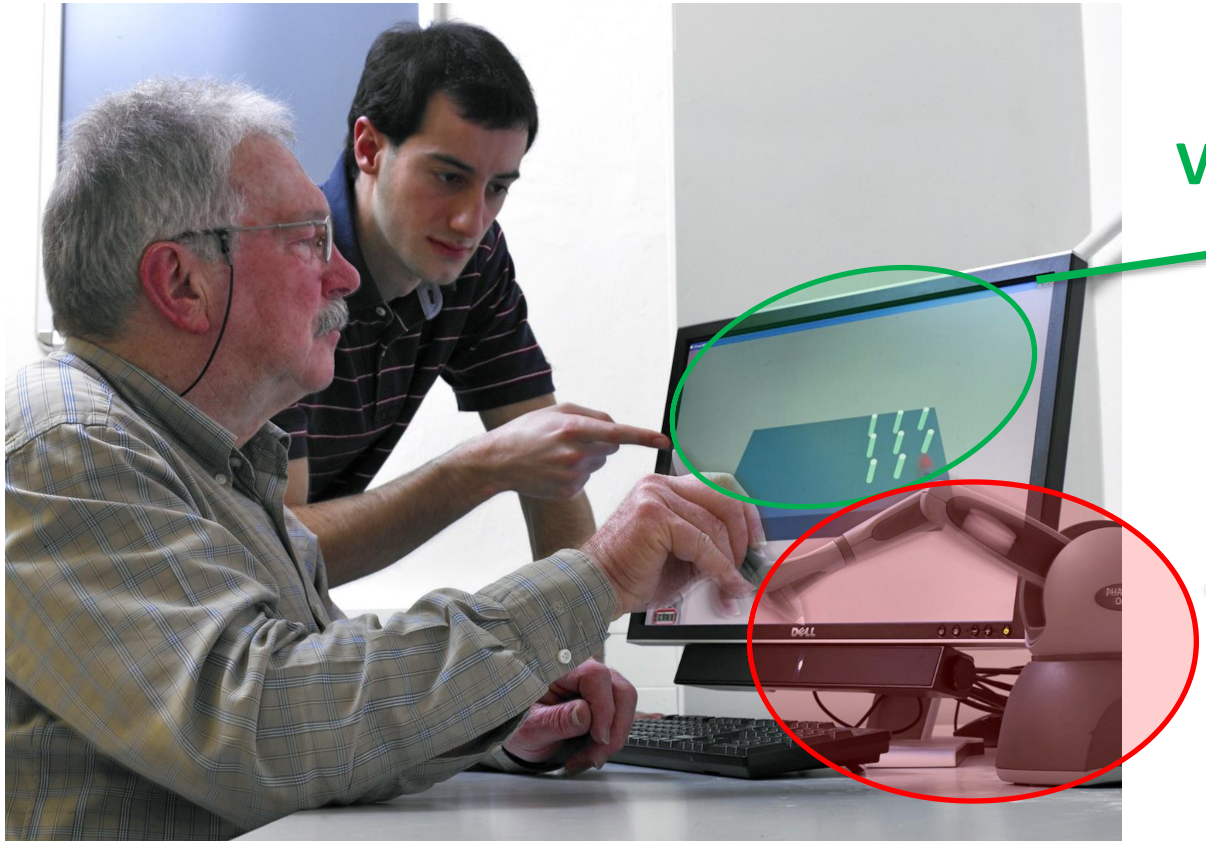


Haptic control and Virtual Environment

Haptic control and a VE



What Would We Like to Feel at a Haptic Device?
What Do We Feel at a Haptic Device?



Virtual Environment

+

Device

(Inertia, friction)

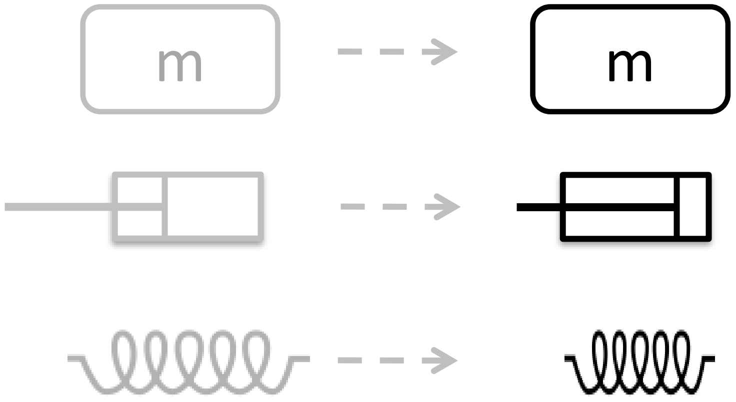
A *haptic interface* let a human operator **touch**, **manipulate** and **feel** a virtual environment

Mechanical Impedance - Z

- *Dynamic* relationship between velocity and force
- Frequency-dependent resistance

$$\mathbf{f}(\omega) = \mathbf{Z}(\omega) \cdot \mathbf{v}(\omega)$$

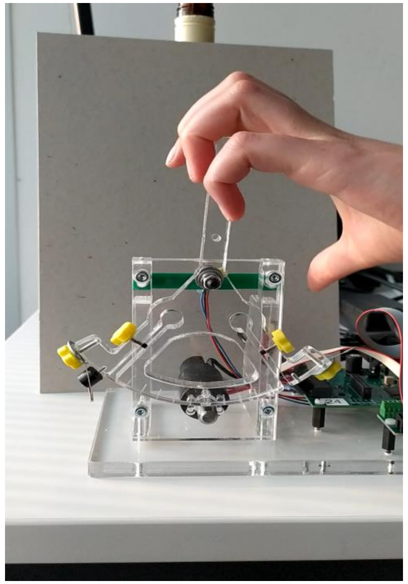
force **velocity**



$$F \sim \ddot{x}$$

$$F \sim \dot{x}$$

$$F \sim \Delta x$$

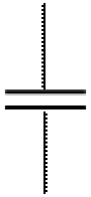


Mechanical admittance: $Y = Z^{-1}$ → $v(\omega) = Z^{-1} \cdot f(\omega) = Y \cdot f(\omega)$

Analogy – Electrical Impedance

frequency-dependant resistance

Resistor:  $$Z = \frac{V}{I} = R$$

Capacitor:  $$Z = \frac{V}{I} = \frac{1}{j\omega C}$$

$\omega \rightarrow 0$ (DC) → Z large (open circuit)

$\omega \rightarrow \infty$ → Z small (short circuit)

Inductance:  $$Z = \frac{V}{I} = j\omega L$$

$\omega \rightarrow 0$ (DC) → Z small (short circuit)

$\omega \rightarrow \infty$ → Z large (open circuit)

What is the Z-Width?

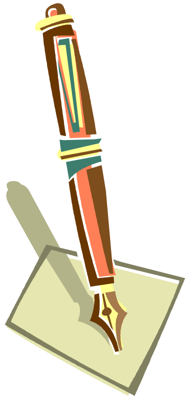
The range of admissible Z-values

Low mass rigid body
(almost no resistance to motion)

Z → 0; **Y** →∞

$$v(\omega) = Z^{-1} \cdot f(\omega) = Y \cdot f(\omega)$$

→ small force f results in a large motion

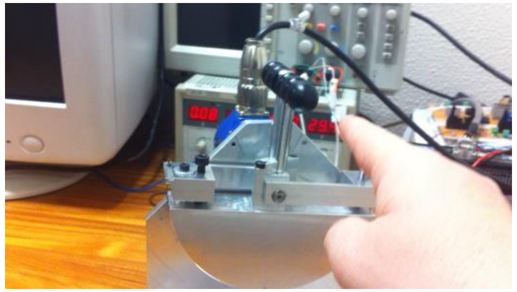


"Stiff viscoelastic body"
(almost complete resistance to motion in direction normal to paper)

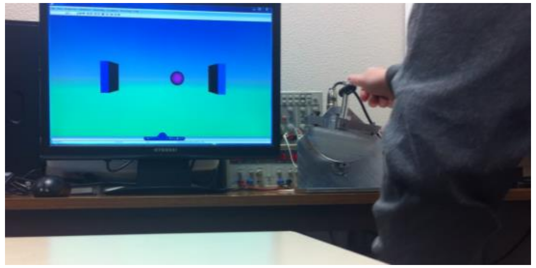
Z → ∞; **Y** →0

$$v(\omega) = Z^{-1} \cdot f(\omega) = Y \cdot f(\omega)$$

→ large force f results in a small motion



Z-Width:
Dynamic range of achievable impedances



The "Ultimate" Multi Purpose of a Haptic Device

How to build a haptic interface with **a broad Z-Width** and a robust stability property?

 Low end: limited by inertia and friction

 High end: - limited by system stability

[Increase high-end →More Force needed → larger actuators,
Drive mechanisms, linkages → More inertia, more friction → reduce low-end]
(Clover et al., 1997, Book and Ruis 1981)

Haptic Device Accuracy vs. Fidelity

Impedance **„accuracy“:**
how close matches the apparent impedance (felt impedance) that of the virtual environment

Impedance **„fidelity“:**
resolution – level of impedance discrimination that can be rendered at the haptic interface
(→ Fidelity is limited by the natural dynamics of the device)

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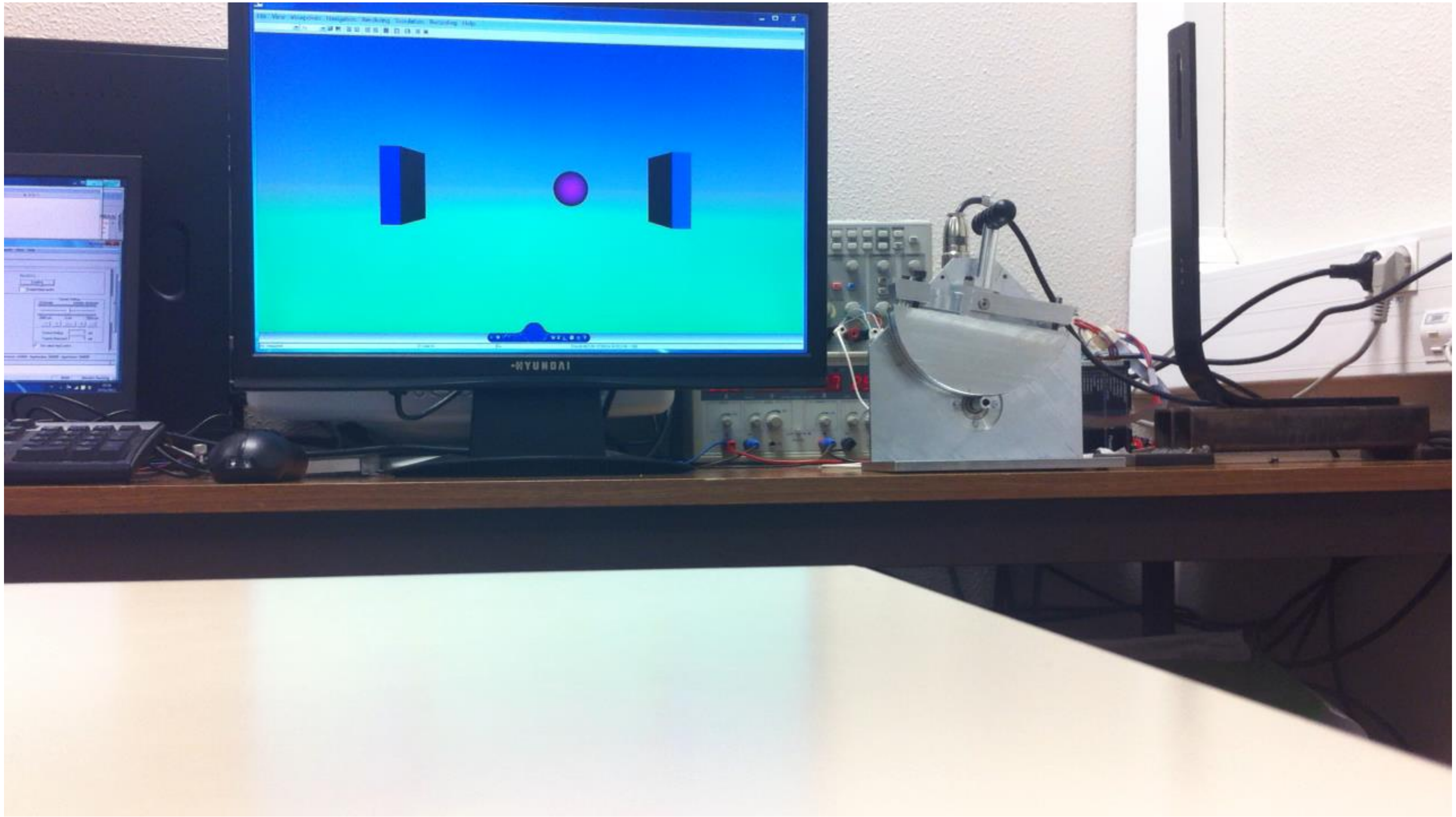
How to achieve a good-performance Haptic Device?

Take care about:

- The current loop Bandwidth. **Why?**
- Current resolution. **Why?**
- Position resolution. **Why?**
- Velocity resolution. **Why?**
- Sampling rates of both VR loop and force loop. **Why?**
- Reduce the dry friction in the mechanical transmissions. **Why?**

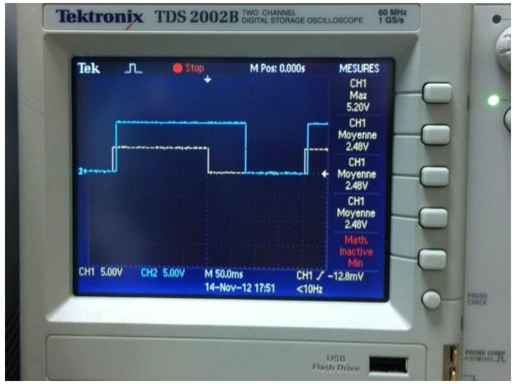
Performances – Effects of the Feedback Delay

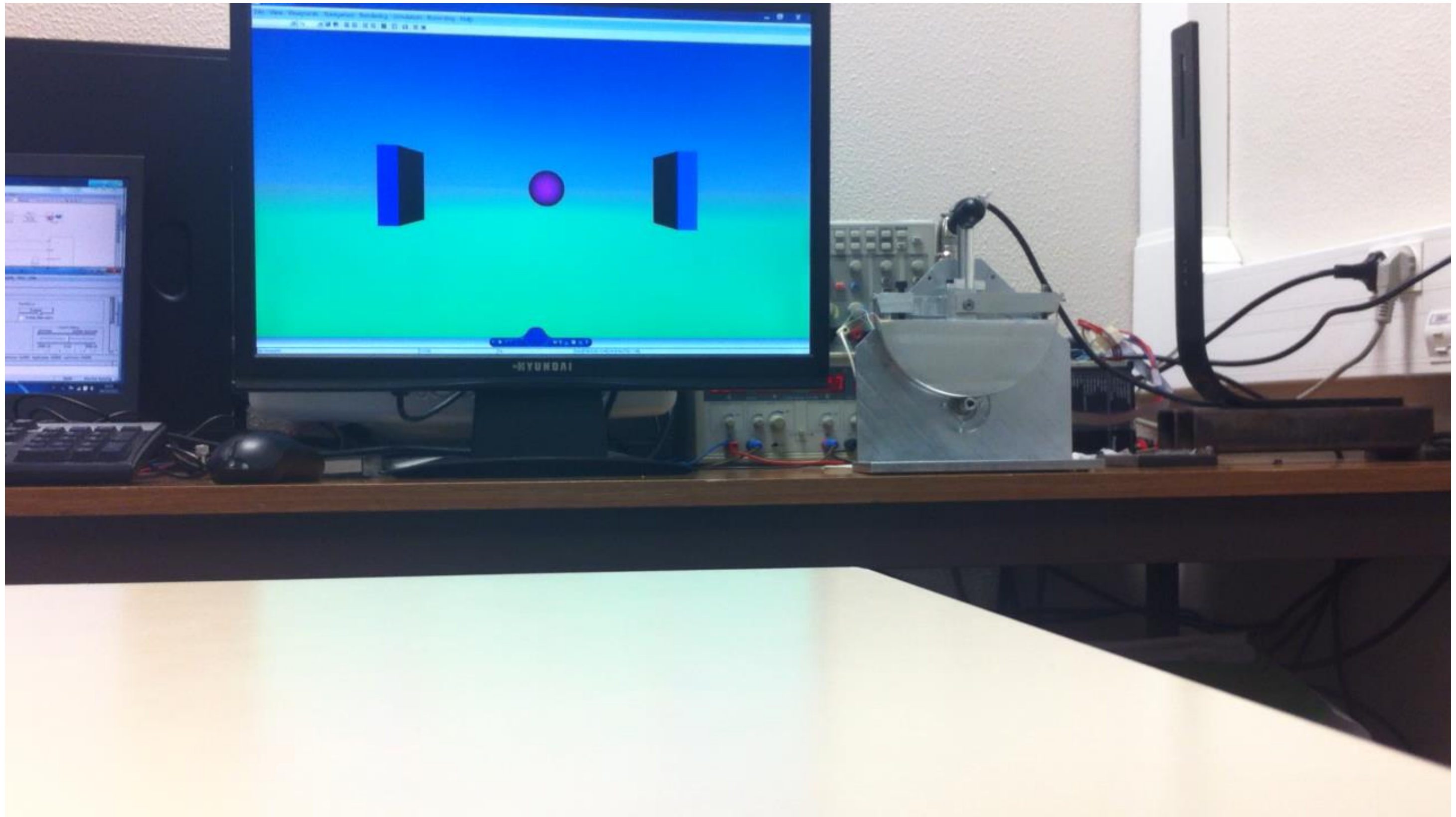
Wall effect stability – **No delay**



Performances – Effects of the Feedback Delay

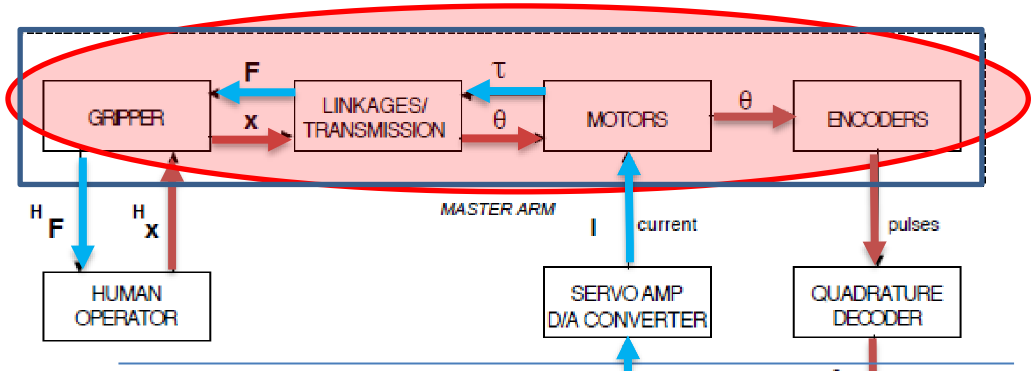
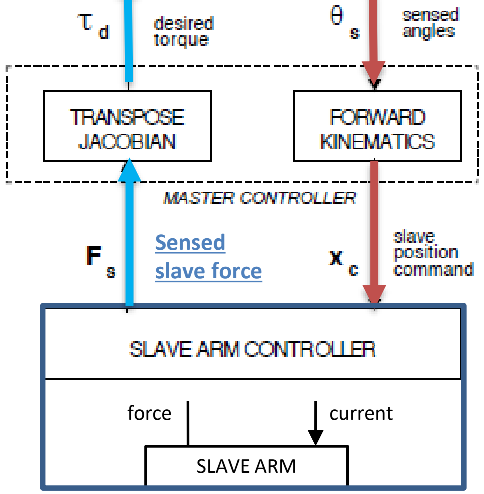
Under Delay





Typical Master Arm Control Scheme

Goertz, R. C., 1952, Fundamentals of general purpose remote manipulators, Nucleonics, Vol. 10 No. 11, pp. 36-42.

Da Vinci Surgical System, http://www.intuitivesurgical.com

www.forcedimension.ch

What human operator feels =

Reaction force +

Friction, gravity, inertia

Closed-loop force control for haptic simulation of virtual environments, Carignan and Cleary, 2000

Mirosurge from DLR