Assistance to gesture with therapeutic applications

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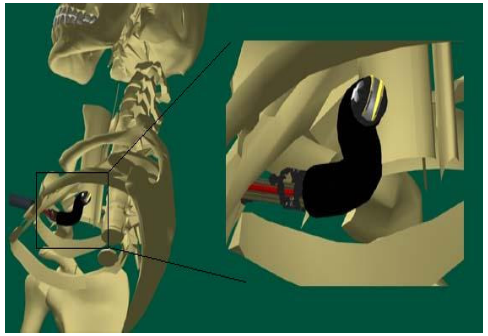
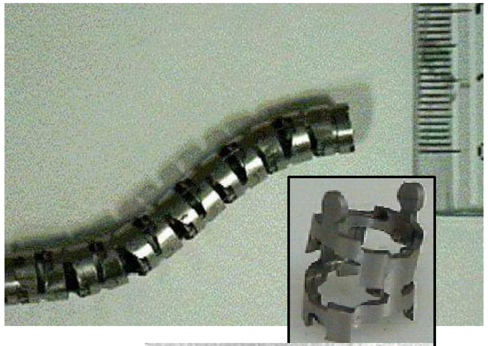
Institut des Systèmes Intelligents et de Robotique

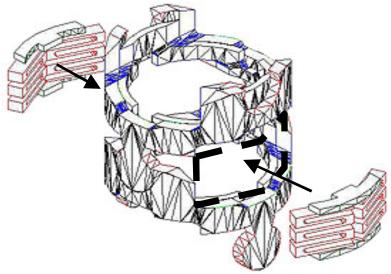
- Institutions: Univ. Pierre & Marie Curie (Paris 6), CNRS.
- Location: 3 sites in Paris and its close suburb, soon grouped in the heart of Paris.
- 30 faculty members (Mechanical Engineering, EE, Control Engineering, Computer Science) 40 PhD students, 10 postdocs.
- 3 research groups:
  - Mobile and integrated autonomous systems.
  - Human perception and movements
  - Interactive systems :
    - Assistance to micro-nano manipulation
    - Assistance to gestures for therapeutic applications
- **We are encouraging applications for:**
  - **Short stays (1-3 months) of PhD students from other labs;**
  - **PostDocs (2 positions available right now).**

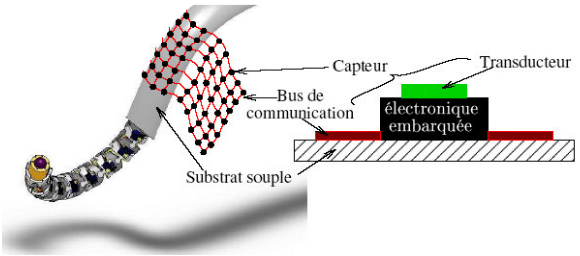
Main projects

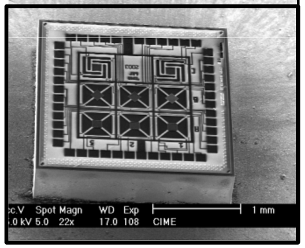
1. Dexterous Instruments for Minimally Invasive Surgery

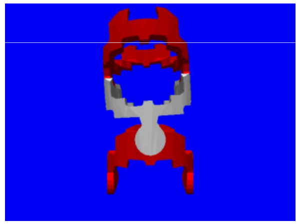


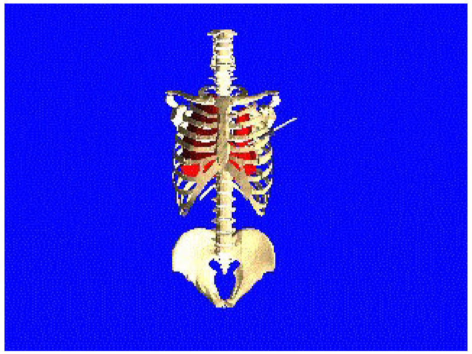


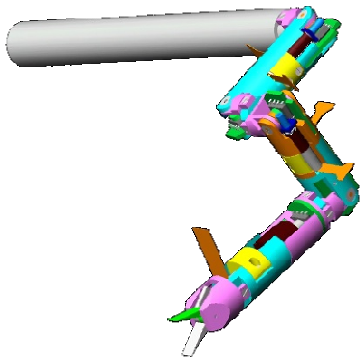






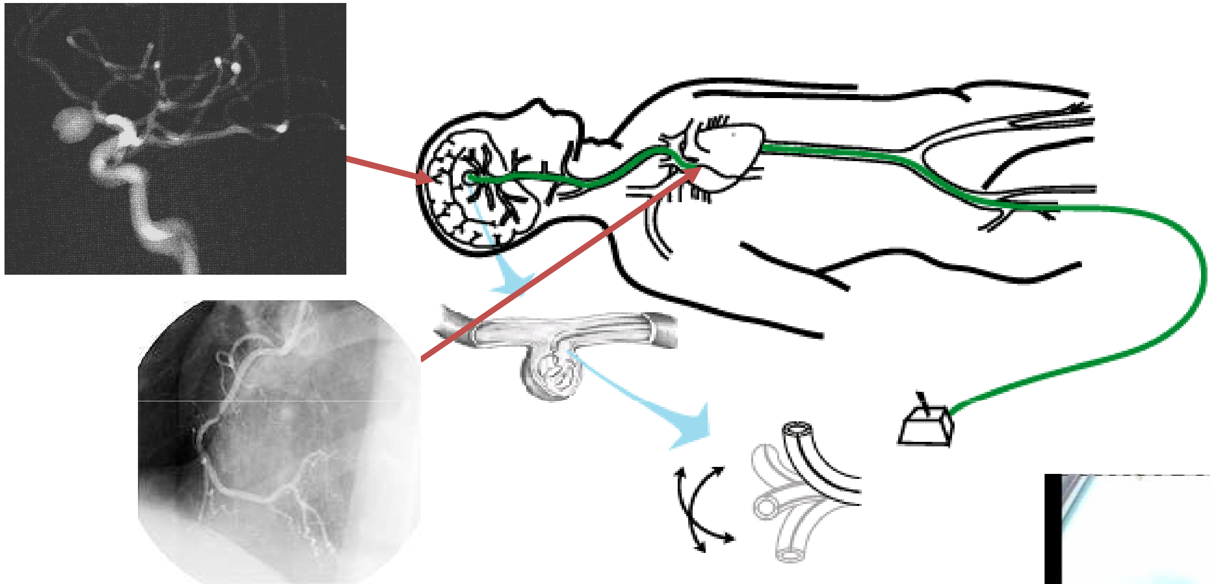




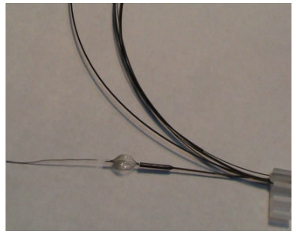


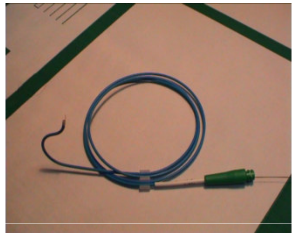
Main projects

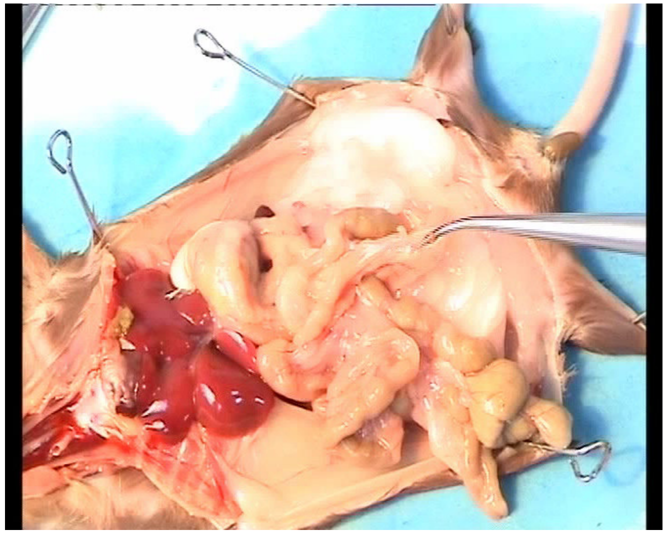
2. Active Catheterism



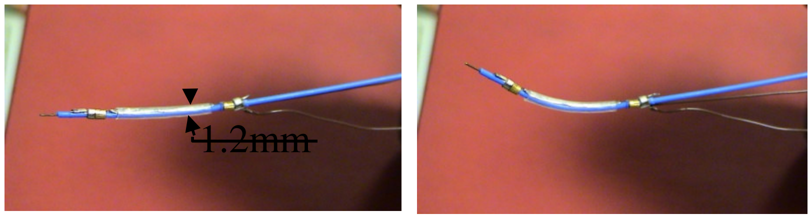
Sclérose





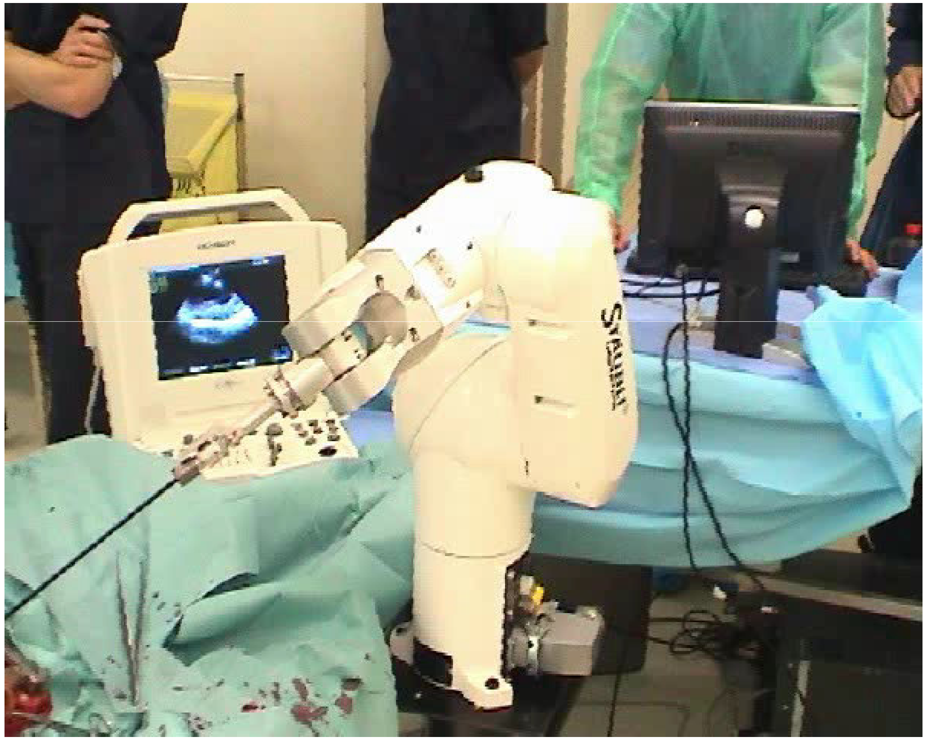


First attempt : active SMA based catheter



Main projects

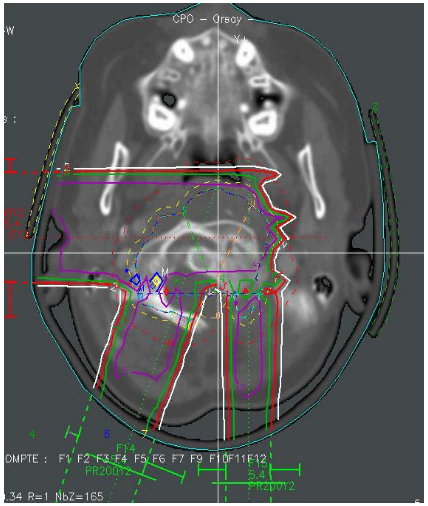
3. Automatic Instrument Guidance from Ultrasound Imaging

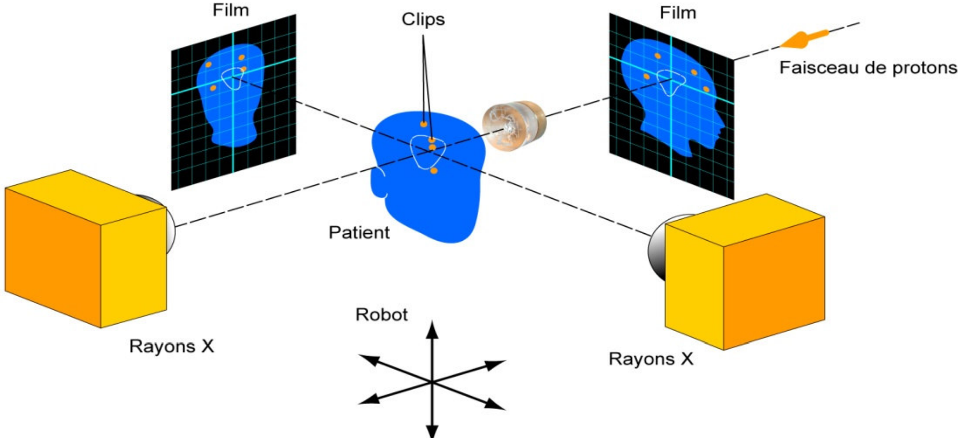


Experiences realized at the Surgical School of Paris - APHP (*in vivo*).

Main projects

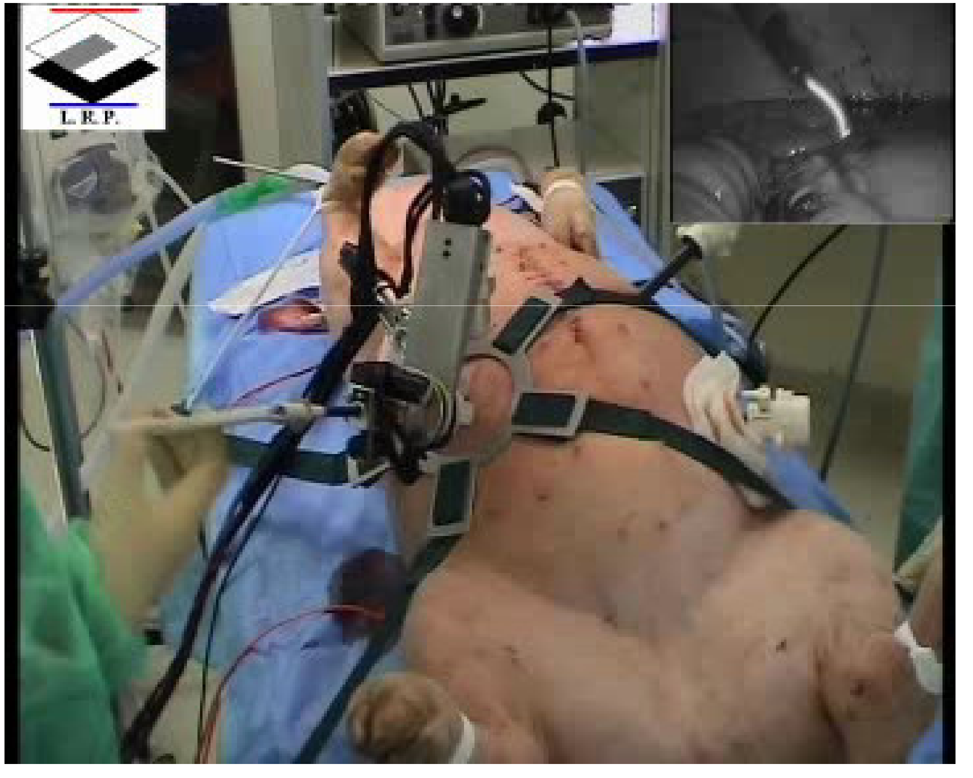
4. Automatic Patient Positionning for Protontherapy from Xray Images





Main projects

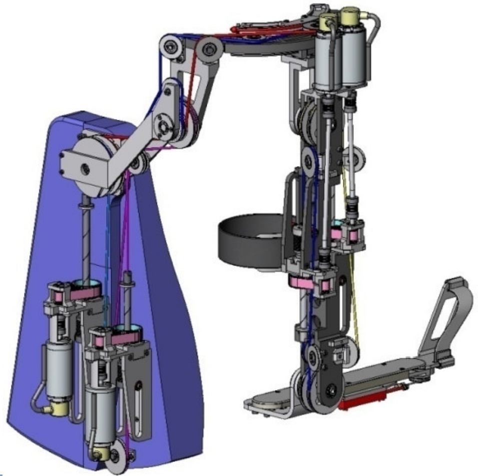
5. Force feedback assistance in Minimally Invasive Surgery



(to be detailed later in the talk)

Main projects

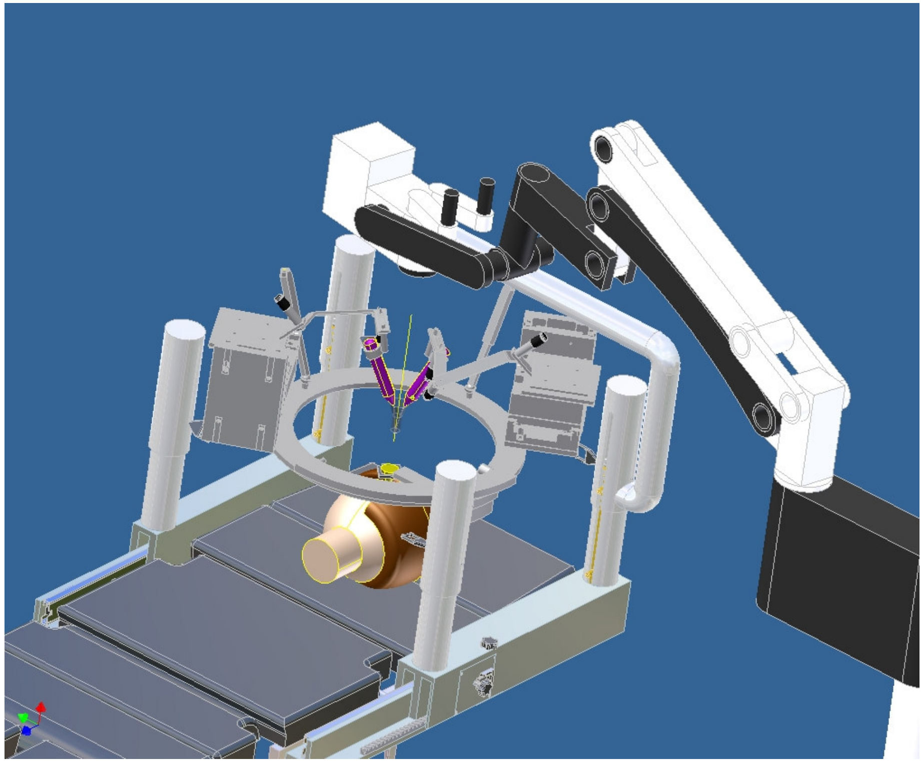
6. Upper arm rehabilitation

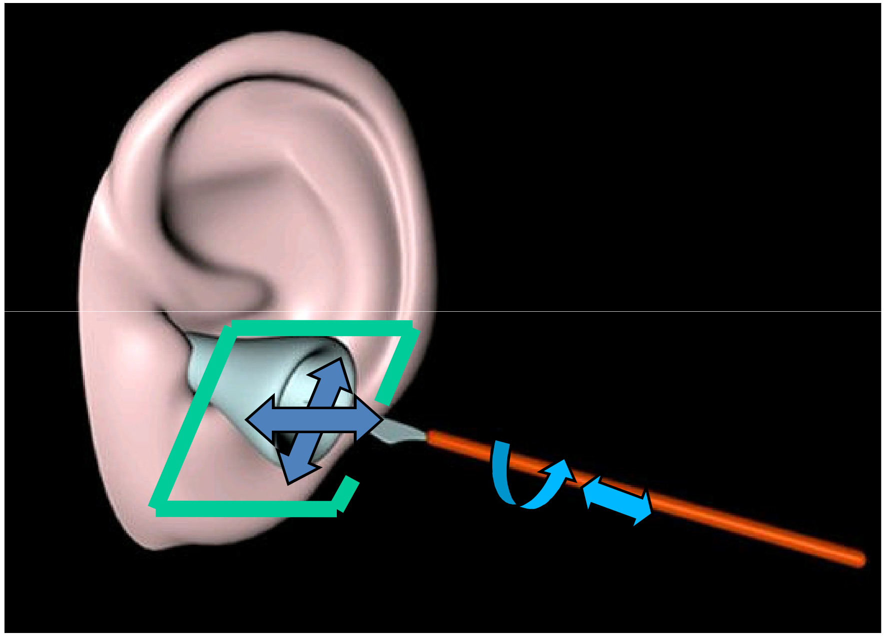


This orthosis was designed by CEA-LIST

Main projects

7. Otological robot





Ask Mathieu Miroir (one of the attendee with a red T shirt) for details

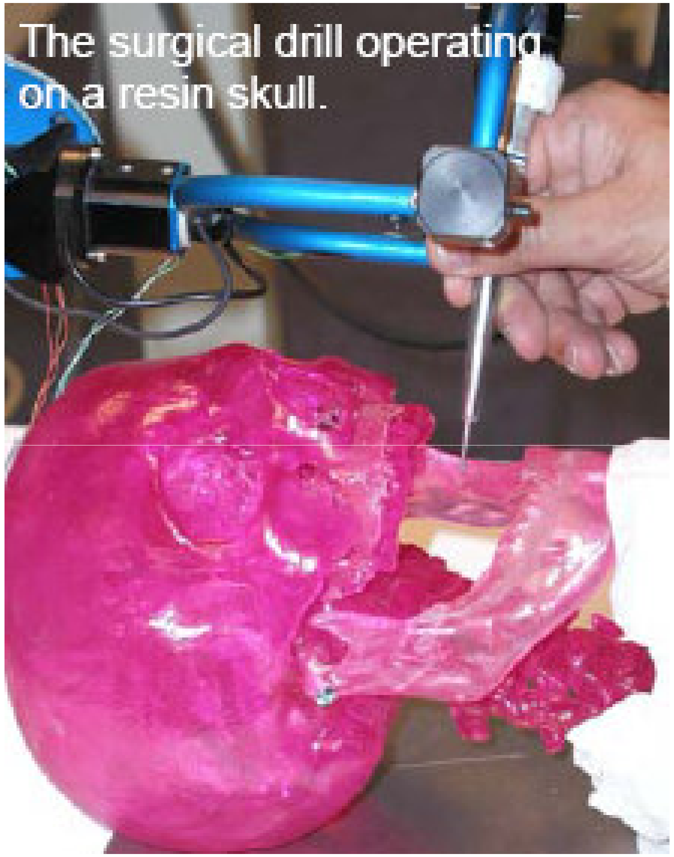
Topic of the talk

- ***Assistance to gesture***: robotic systems designed to help a human subject in performing a manipulation task: cobots, comanipulators, hands-on devices, interactive systems, …
- ***Therapeutic applications***:
  - **Surgery**: a robot that assists a surgeon in performing the operation.
    - Fine and dexterous motions.
    - Increase sensitivity, add information, provide guidance
  - **Rehabilitation**: a robot that assists a (e.g. post stroke) patient in performing exercises.
    - Basic simple motions (reaching and grasping tasks).
    - Increase strength, provide guidance, exert large corrective forces.

Example 1: Acrobot

Extracted from
http://www.acrobot.co.uk/ *:*
*Acrobot® is an acronym for **Active Constraint Robot**. A tool mounted on the device is confined, by hardware and software, to a certain volume in space. The device **does not move autonomously**; it reacts to the actions of the surgeon holding a handle attached to the device. It aids motion, if the surgeon is moving the tool inside an allowed spatial volume; it prevents motion outside this volume. The technology has been successfully proven in clinic. **A first series of clinical trials, involving 7 TKRs, took place in 2002**.*

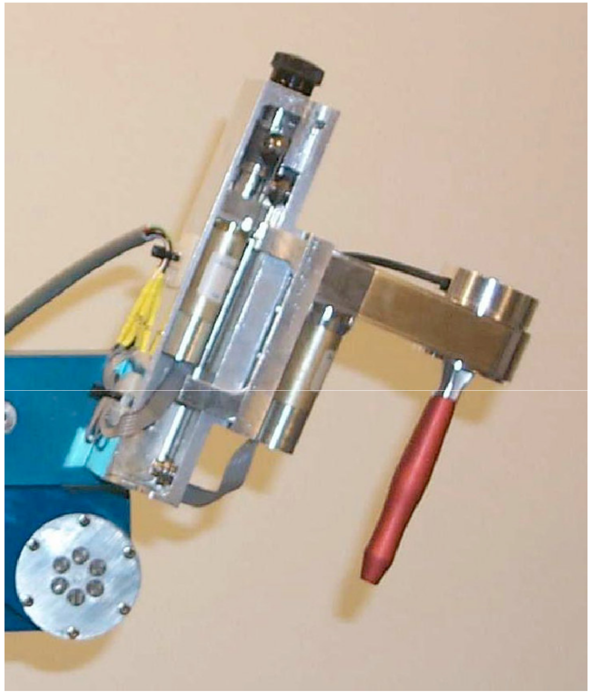
Example 2: Surgicobot

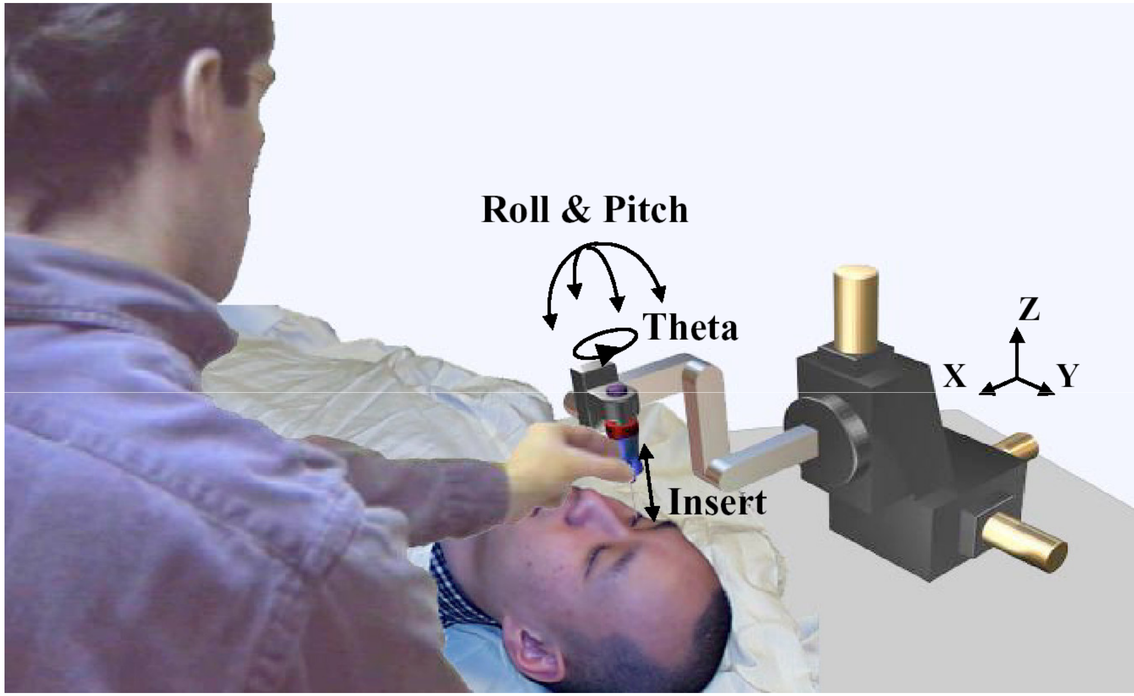


Credit: P. Gravez – CEA LIST

- Same functional principle as Acrobot
- Lighter robot, no force sensor.

Example 3: Hands-on system

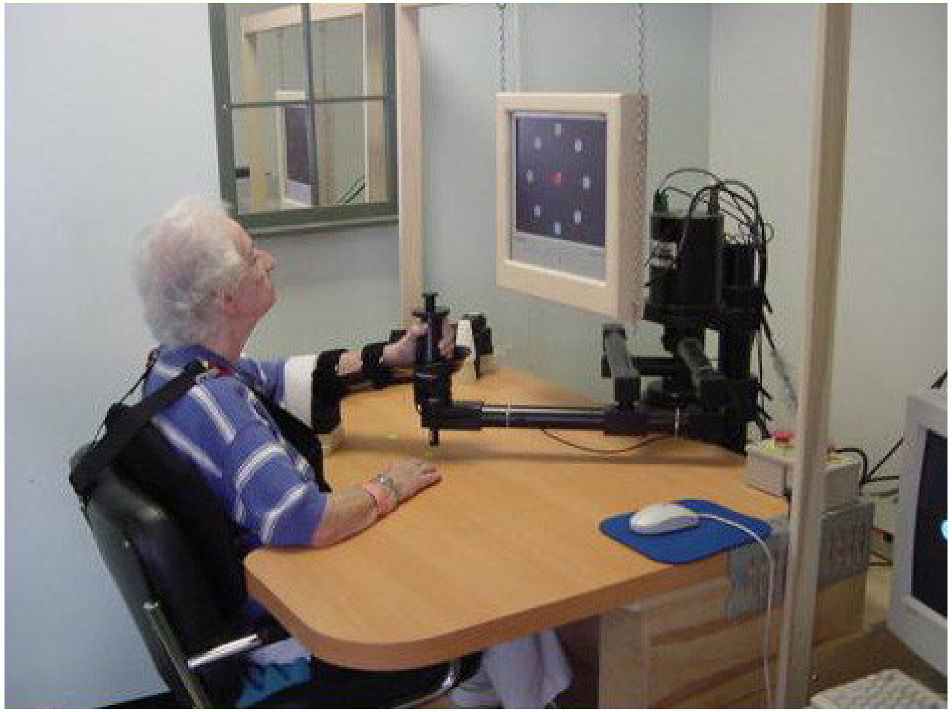


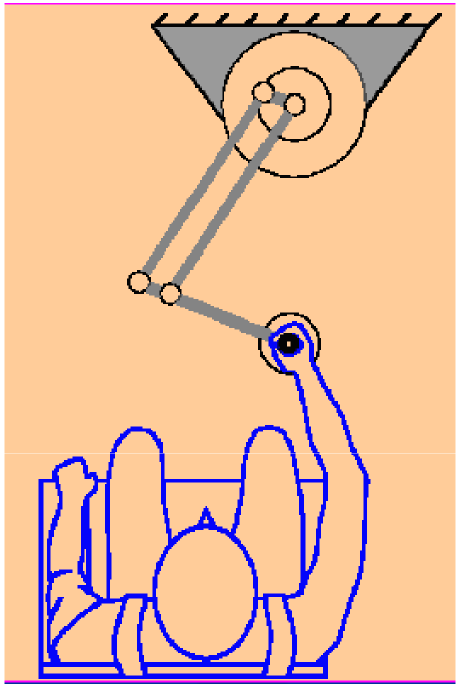


- Force amplification for microsurgery
- Tremor filtering

Credit: R. Taylor – JHU Univ.

Example 4: MIT Manus

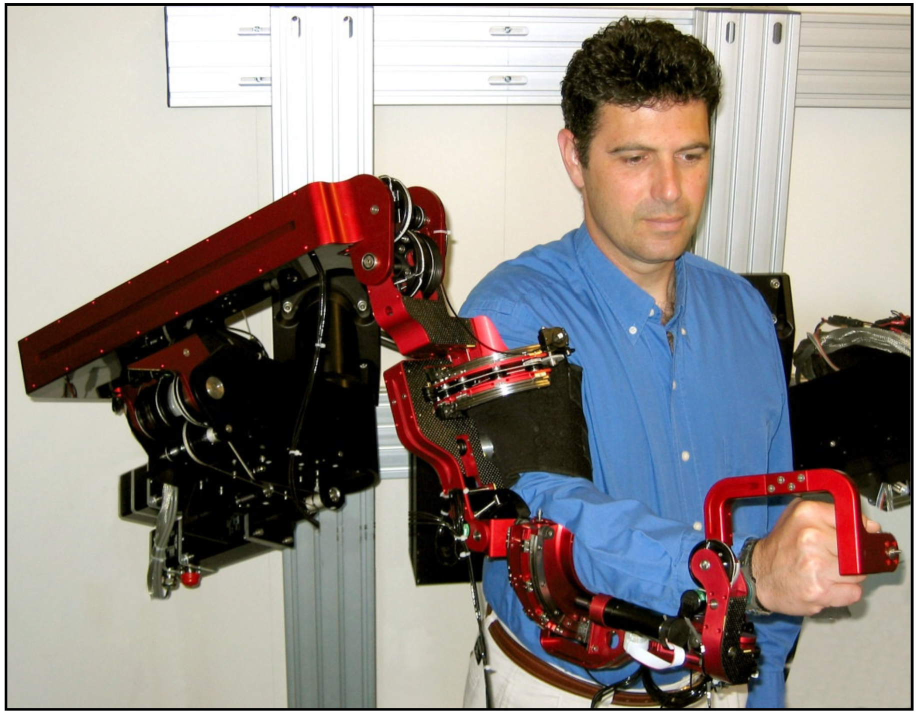


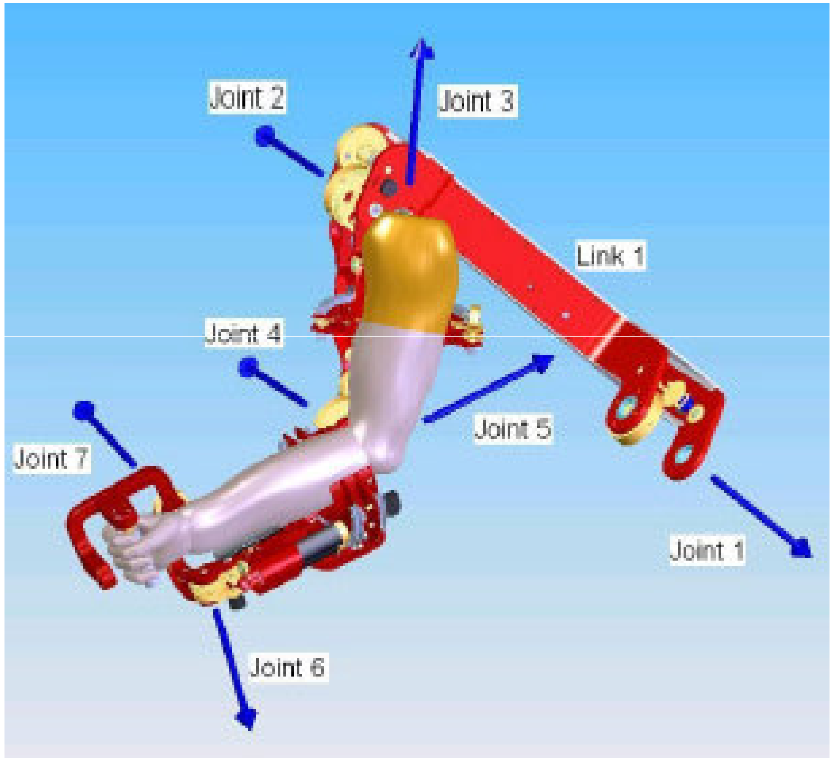


– Assistance to post-stroke rehabilitation
– Tunable assistance for simple planar movements

Credit: N. Hogan, MIT

Example 5: Univ. of Washington exosqueleton





Credit: J. Rosen, Univ. Of Washington

Overview of the talk

- **One question**: how to control the interaction with the human subject so as to provide an “intuitive” assistance that “eases” movements?
- **One viewpoint**: system-level design and interaction control:
  - sensors, actuators, devices, human-machine interfaces.
  - Interaction control, stability issues
  - close cooperation control by integrating knowledge about human motor control
- **One class of interaction: direct contact** between the subject and the machine (motion guidance, force magnification, …)
- A **prospective section** about other classes of interactions, such as BMI, EMG, Gaze, etc.
- Note: nothing about Functional Electrical Stimulation.

1. Mechanical design

- Lightweight (no inertia)
- Rigid (no deformation)
- **Transparent** (no resistive force – friction – inertia)
- Key issue : transmissions
  - Direct drive (mass to power ratio issues)
  - Cable transmissions (rigidity issues, design complexity)
- Particularly complex for whole arm motion assistance (wide geometrical range + large forces).

Existing active solutions from haptics

Haption Virtuoses

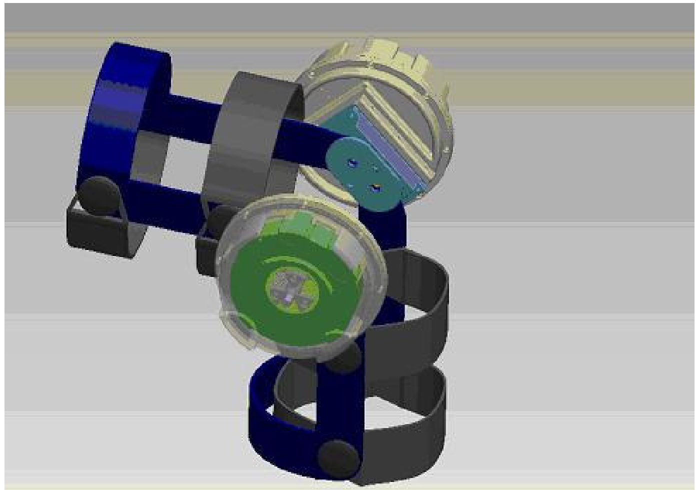
Existing active solutions from haptics

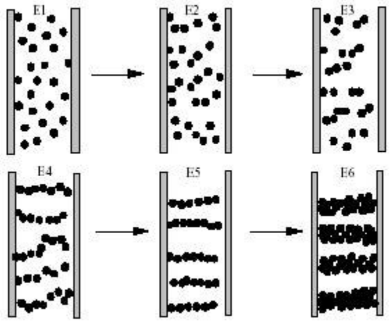
Force Dimension parallel devices

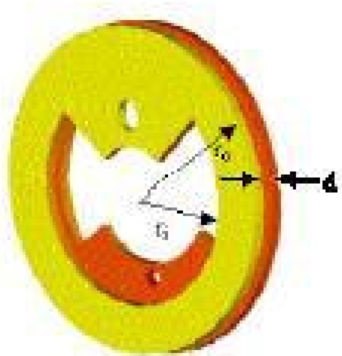
“Passive” devices

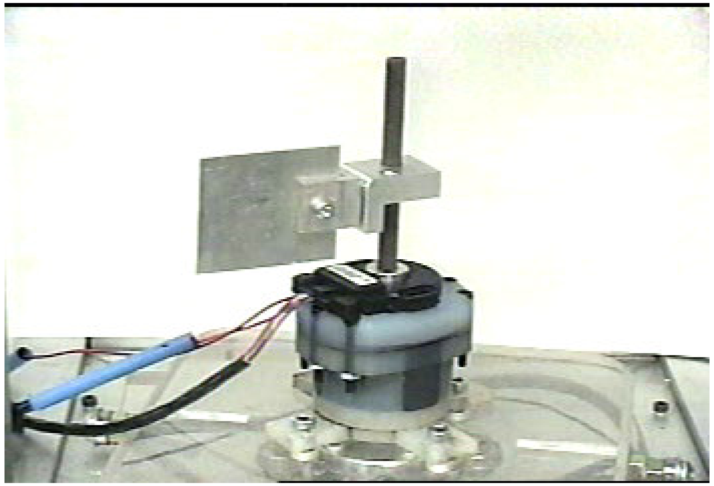
- Capable only of resisting to subject’s forces.
- Most of them use brakes.
- Combine high strength with low inertia.
- Difficulty to control in open-loop the terminal resistive force
  - Either closed loop force control
  - Or binary control : blocked / free

Example 1: electrorehologic fluids



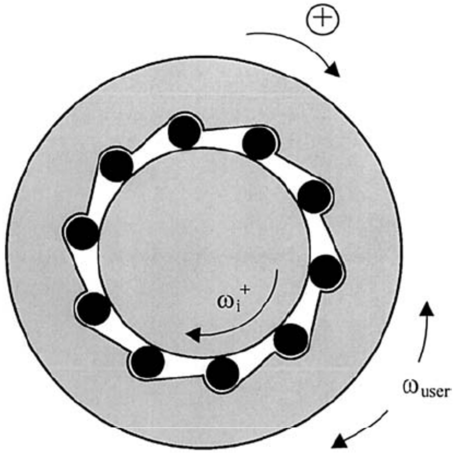






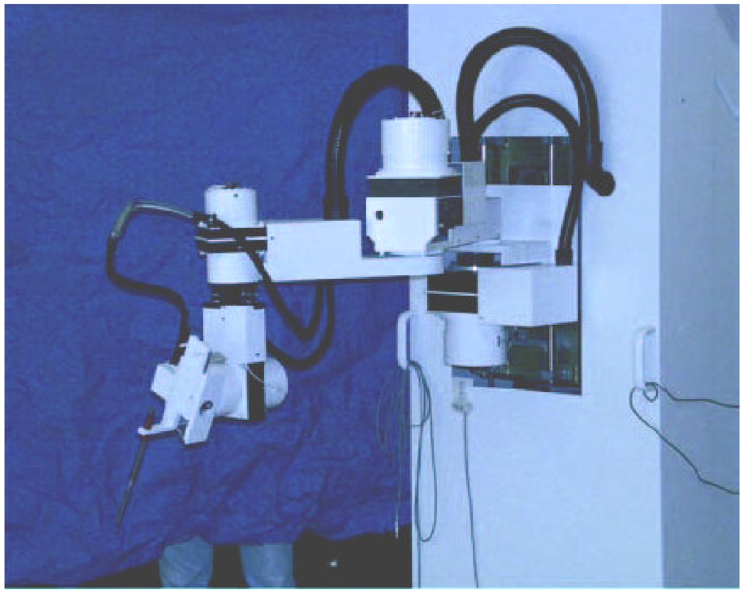
Credit: D. Mavoirdis – Northeastern Univ.

Example 2: PADDYC



Principle: two freewheels connected and mounted in opposite directions.
Two motors rotating at ω_i^+, ω_i^-.
The ”user velocity” is mechanically limited by:

$$\omega_i^+ > \omega_{user} > \omega_i^-$$

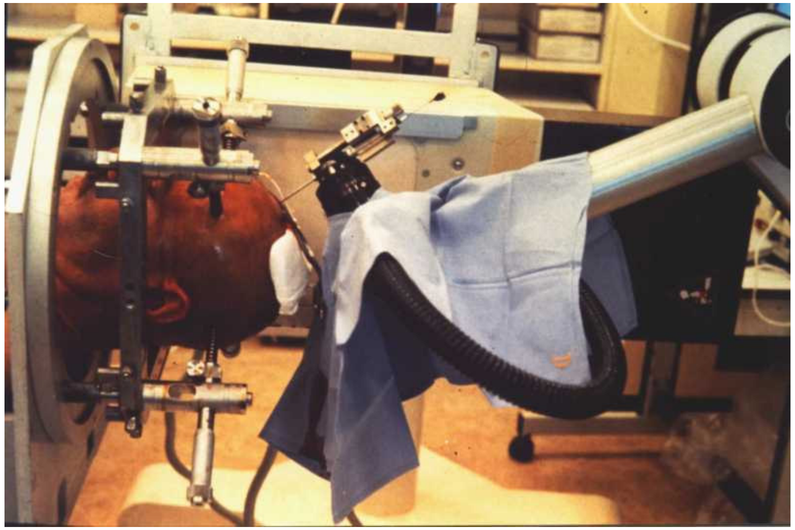


Main advantage : safety, dynamic constraints.

Credit: J. Troccaz.

2. Principle of geometrical guidance

- Objective: impose a geometrical constraint to the subject.
  - **One pioneer example: static constraint**



Lavallee, S., Troccaz, J., Gaborit, L., Cinquin, P., Be nabid, A., and Hoffmann, D. **Image guided operating robot : a clinical application in stereotactic neurosurgery.**In *Proc. of the IEEE International Conference on Robotics and Automation*, pages 618-624. Nice, France, **1992**.

Principle : DoF sharing.
1 dof only is left to the surgeon (needle insertion)

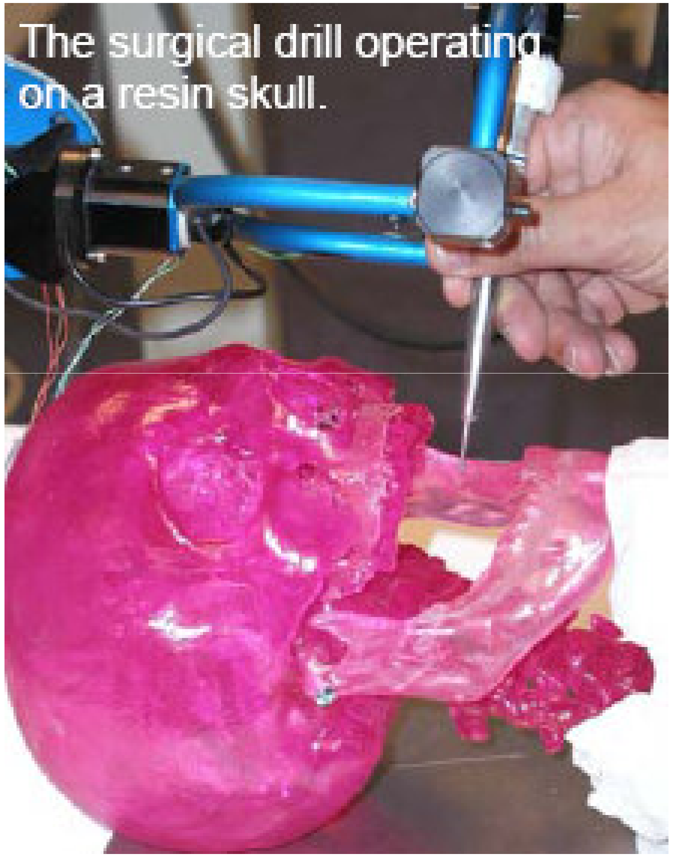
  - **For a dynamic assistance, two basic capabilities are required:**
    - **Transparency =** ability of not disturbing the motion when no guidance is required (free region, free directions)
    - **Rigidity /strength** = ability of strongly blocking movements (forbidden region, forbidden directions)

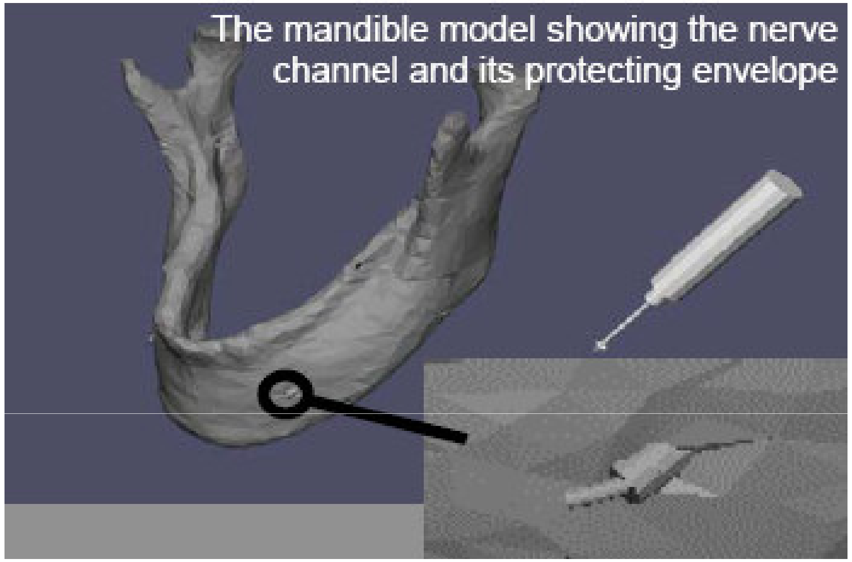
Coupling a navigation system and a robot.

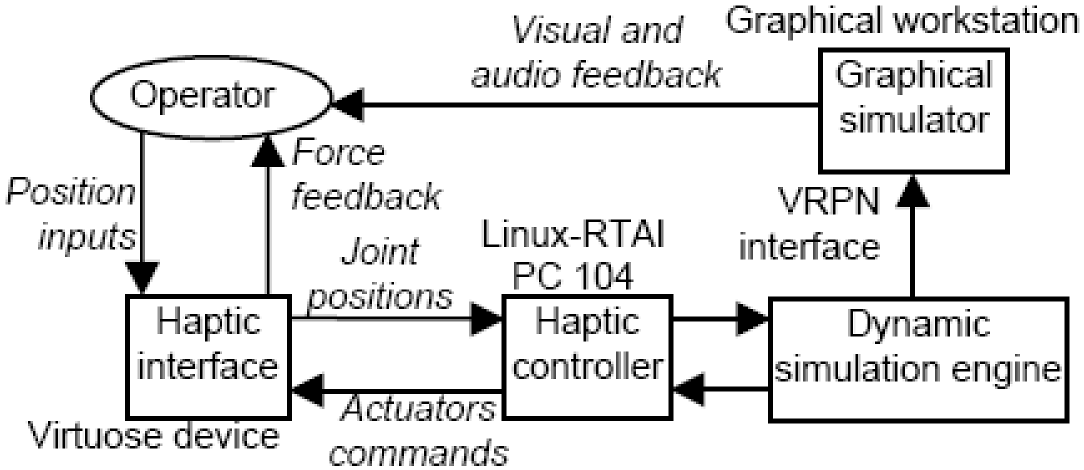
1. 3D imaging $\Rightarrow$ a patient model.
2. Preoperative planning $\Rightarrow$ 3D constraints w.r.t. the patient model.
3. Registration (see J. Troccaz talk) $\Rightarrow$ 3D constraints w.r.t. the robot frame.
4. Exert constraints depending on the end-effector position (variable impedance control).

Praxim's SURGETICS station

Control structure for a mechanically transparent device

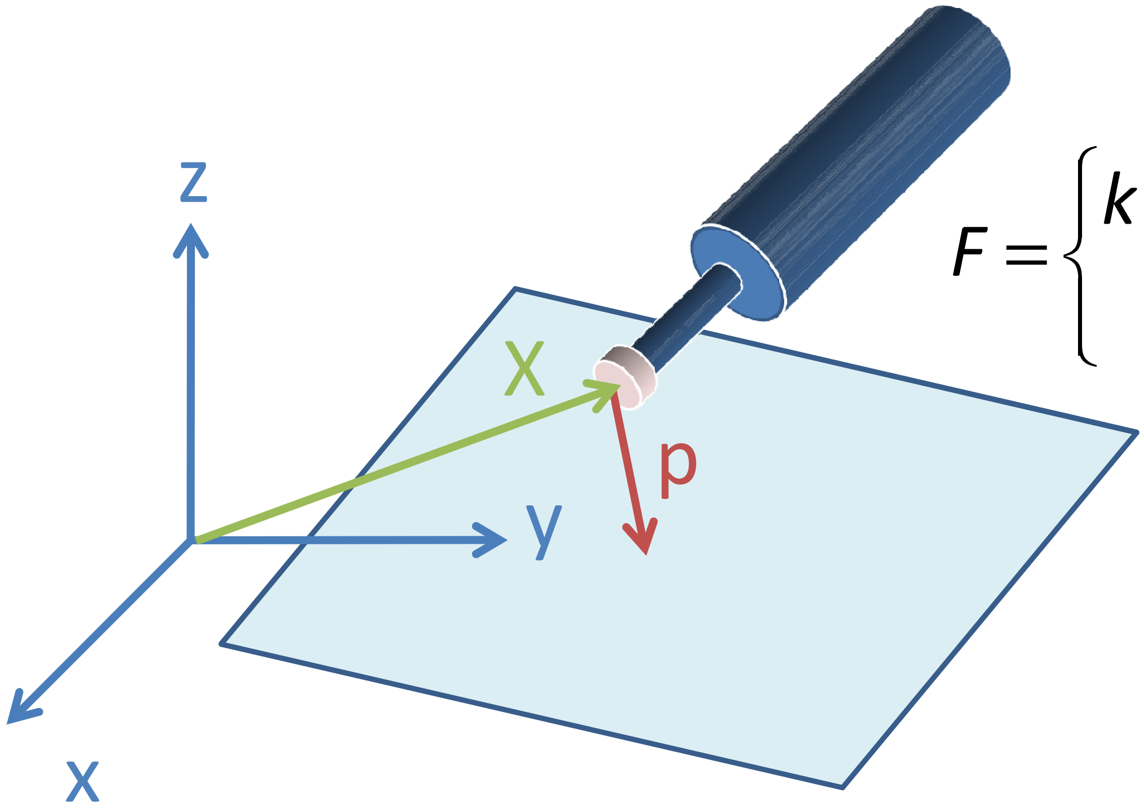




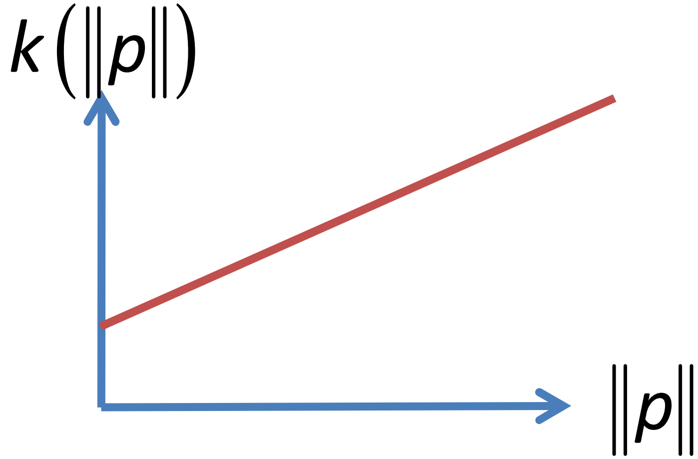


Credit: F. Gravez – CEA LIST

Actuator commands computation



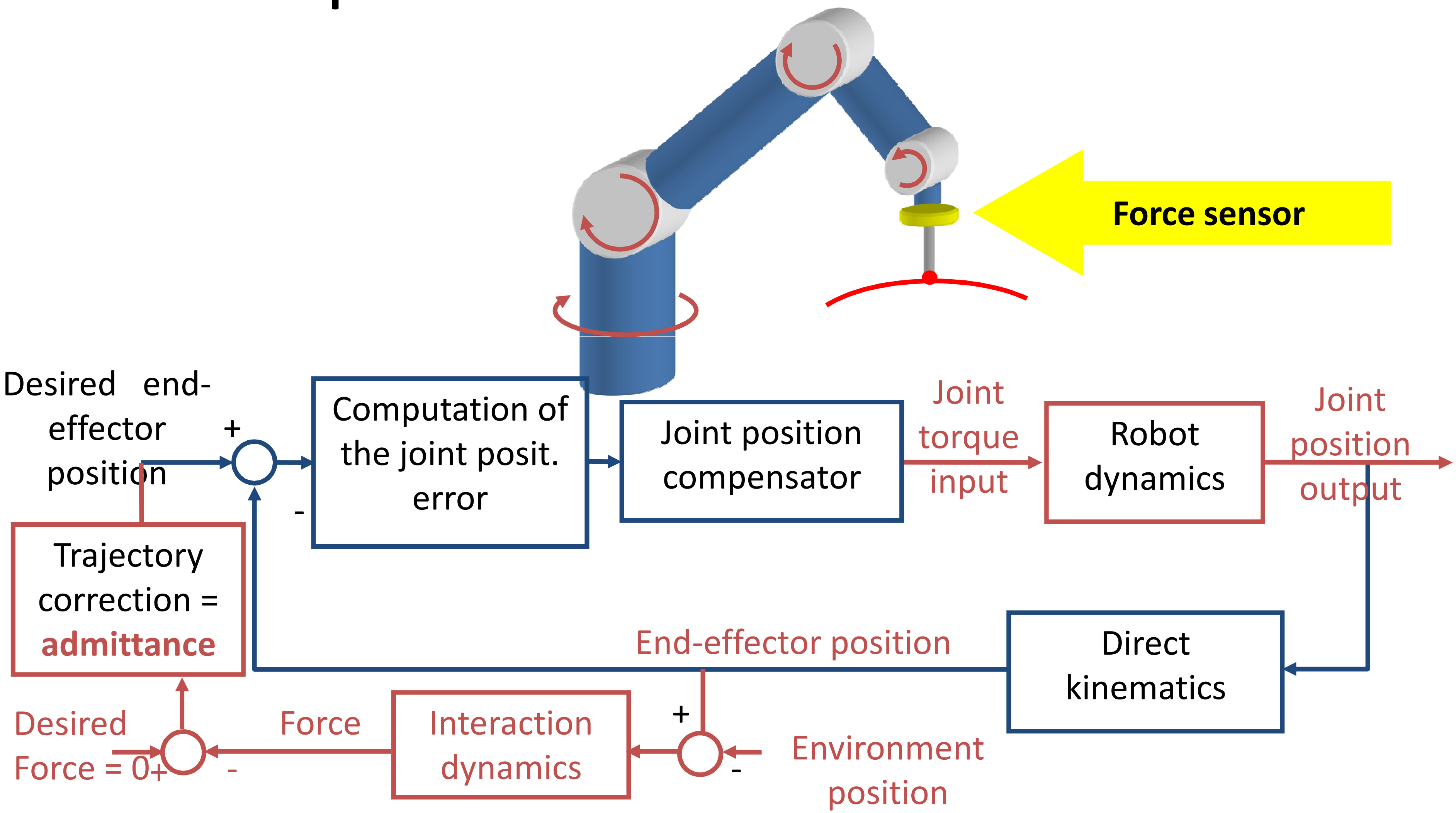
$$F = \begin{cases} k\left(\lVert p \rVert\right) p & \text{if } X \notin \text{ free space} \\ 0 & \text{otherwise} \end{cases}$$



$$\tau = J^T \begin{pmatrix} F \\ 0 \end{pmatrix}$$ $\Leftarrow$ Can be directly sent to the motors with good accuracy thanks to transparency

Video

3. Obtaining transparency through explicit indirect force control



Example 1: acrobot control

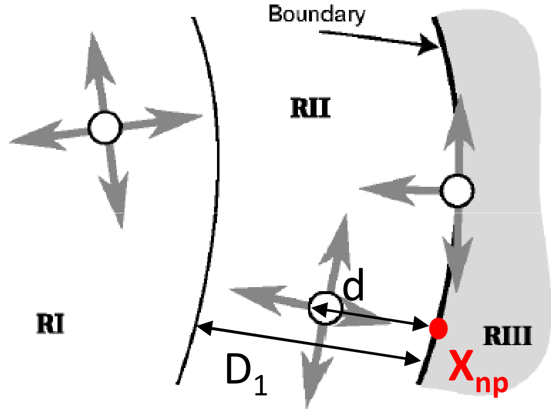
The basic idea behind active constraint control is to gradually increase the stiffness of the robot as it approaches the predefined boundary.

Low level control law:

$$\tau = K_P(\Theta_d - \Theta) + K_D(\dot{\Theta}_d - \dot{\Theta}) + \tau_C + f^*(\Theta,\dot{\Theta}) + g^*(\Theta).$$

The higher level « boundary controller » produces desired joint trajectory and an active torque by:

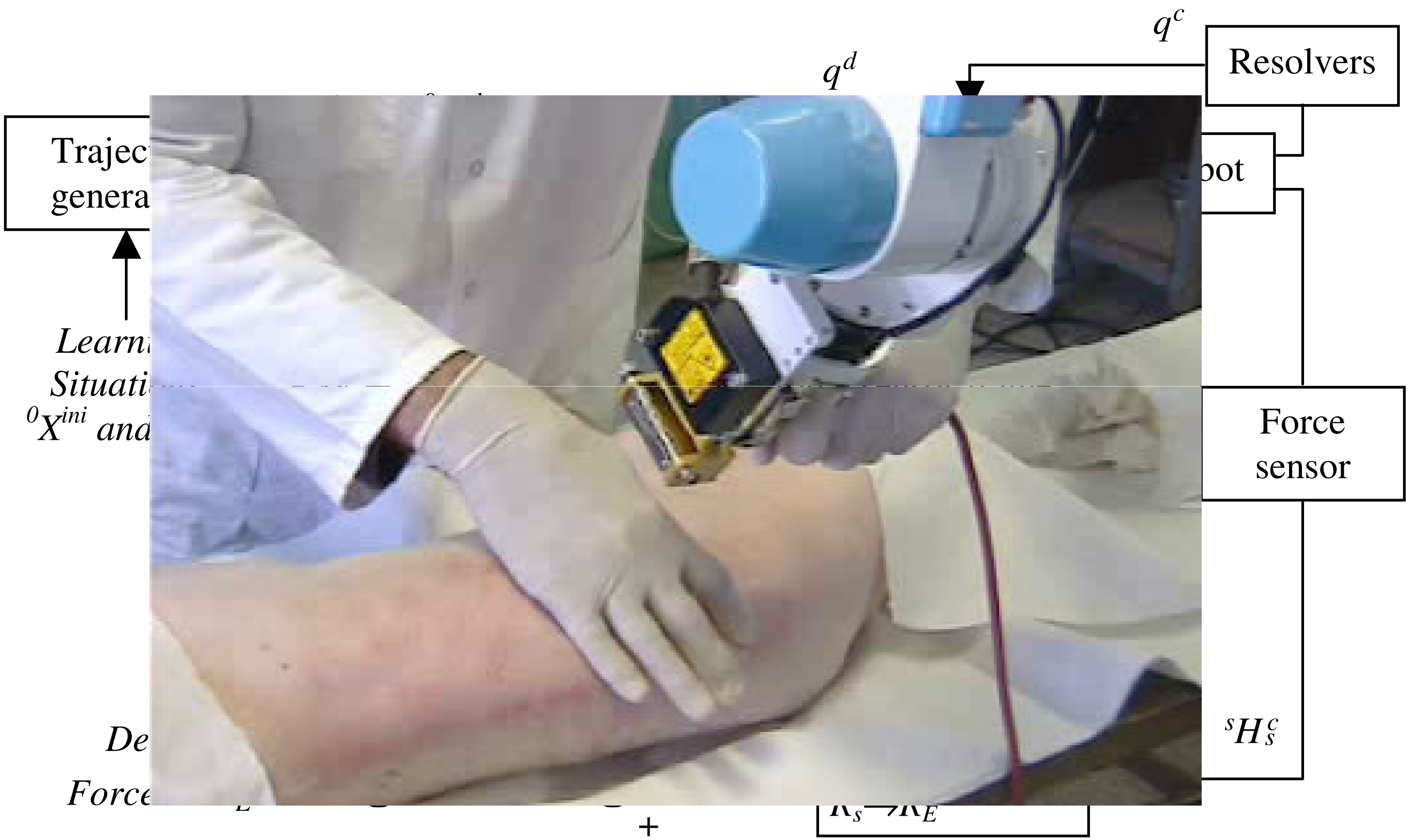
$$\Theta_d = K^{-1}(X_d)$$
$$\dot{\Theta}_d = J^{-1}\dot{X}_d$$
$$\tau_C = J^T F_C$$



Region RI	Region RII	Region RIII
$X_d = X$ $\dot{X}_d = AF_G$ $F_C = 0$	$\dot{X}_d = A_N F_{GN} + AF_{GT}$ $\quad A_N = \frac{d}{D_1}A.$ $F_C = -\frac{D_2 - d}{D_2}F_{GN}.$	$\dot{X}_d = AF_{GT}$ $F_C = -F_{GN}.$

Credit: B. Davies et al.

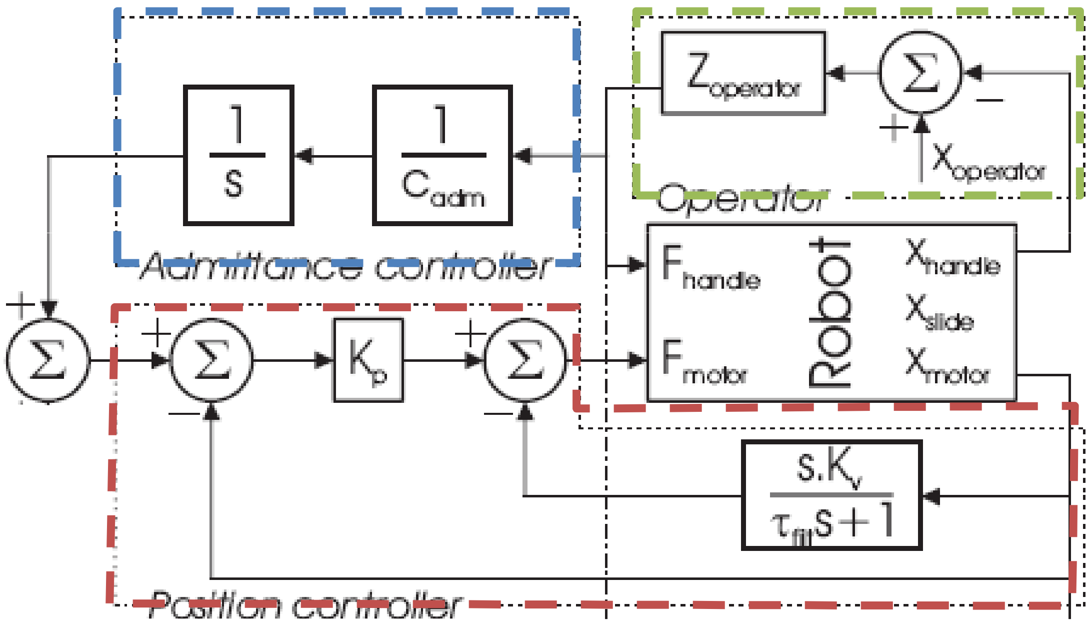
Example 2: Dermarob



Credit: E. Dombre – Montpellier.

Predicting human movement to increase transparency

Credit: J. de Schutter - Leuven



Predicting human movement to increase transparency

Research has shown that the transfer motions obey a specific rule [6], [9]. They all are executed approximately along a straight trajectory and with a bell-shaped speed profile. This speed profile is a characteristic of individual and cooperative human motion [1]. This means that the helper will go along with the transfer motion of the leader, once he knows approximately where to and how fast the motion should be. A widely accepted description of the speed profile in neurobiology is based on the 'minimal jerk criterion' [9]. This criterion minimizes the change in acceleration of the movement of the human hand. If the movement takes place along a straight axis Y and starts and stops with zero speed, the position along the trajectory is defined as:

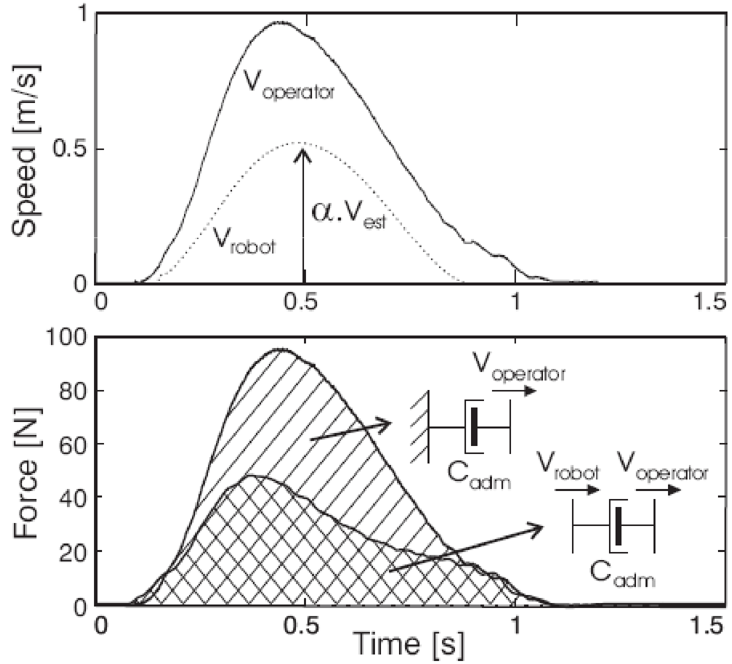
$$y(t) = \Delta y \ f\left(\frac{t-t_0}{\Delta t}\right) + y_0, \qquad (1)$$

$$f(\tau) = 6\tau^5 - 15\tau^4 + 10\tau^3, \qquad (2)$$

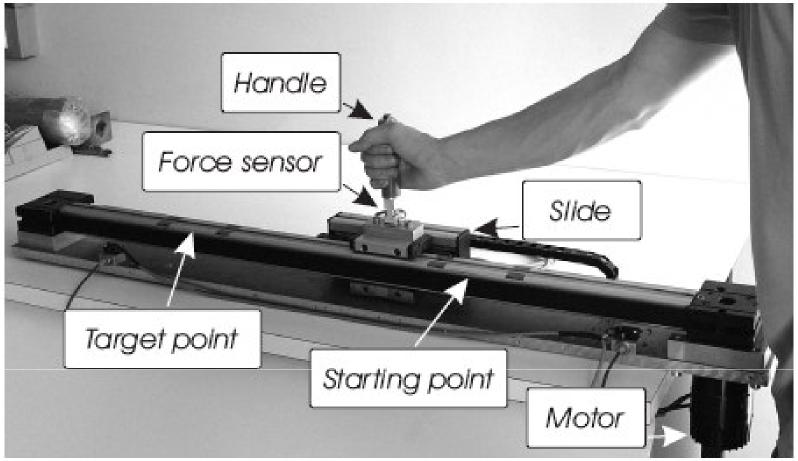
$$\Delta t = t_1 - t_0, \qquad (3)$$

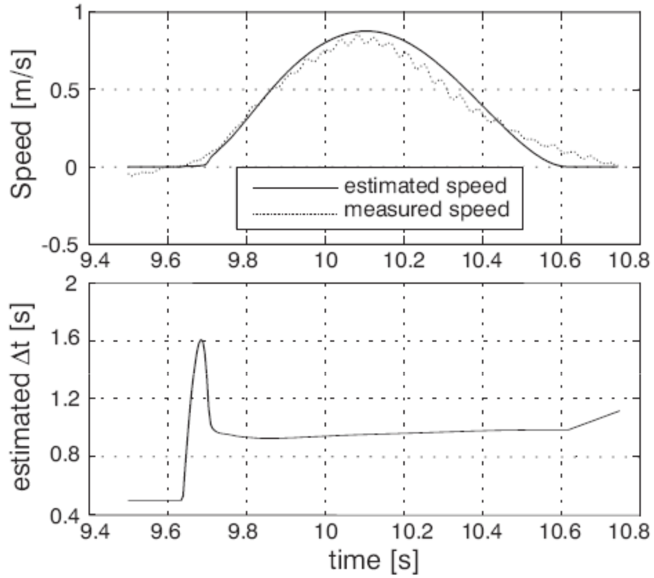
$$\Delta y = y_1 - y_0, \qquad (4)$$

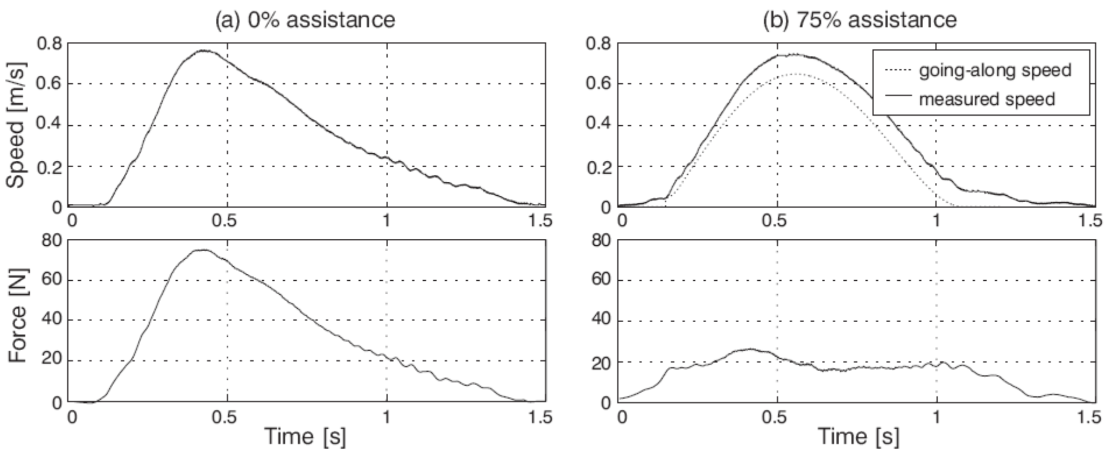
in which y_0, t_0 and y_1, t_1 are the position and time at the beginning and at the end of the motion.



Predicting human movement to increase transparency

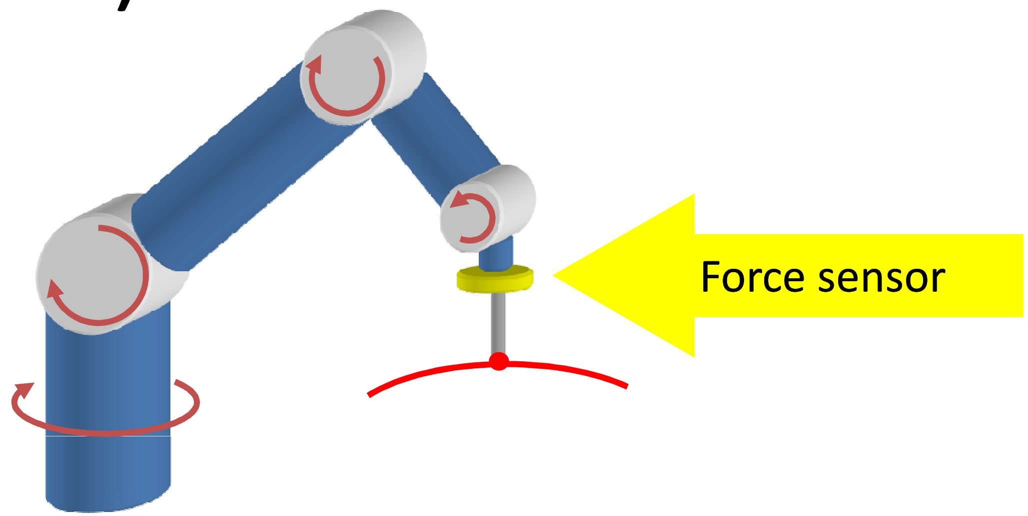


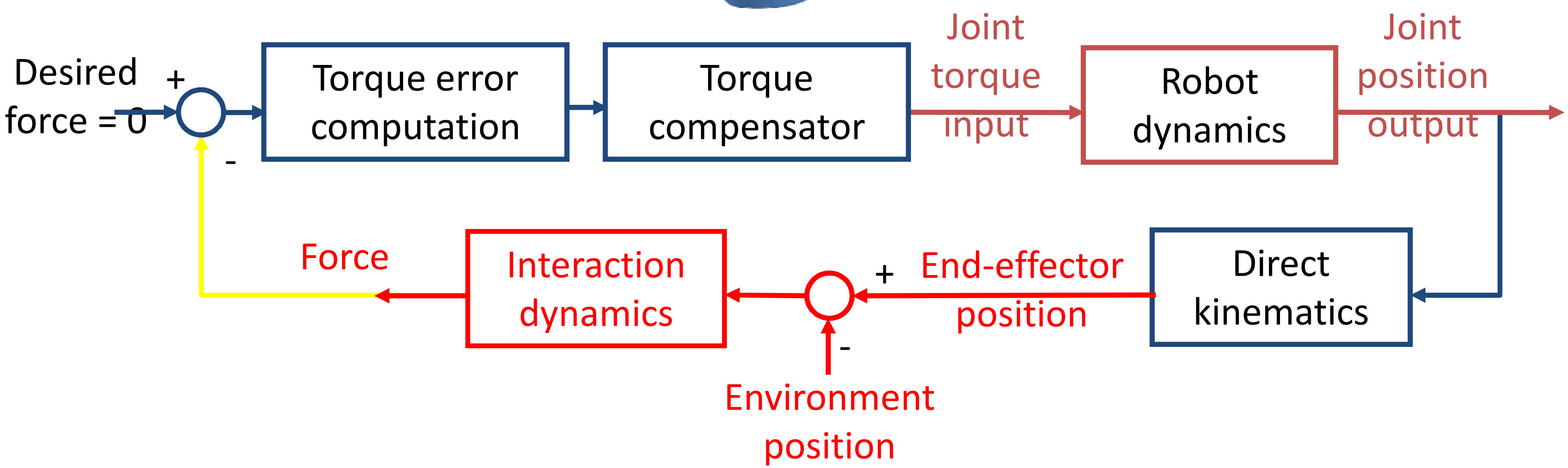




4. Obtaining transparency through explicit (direct) force control

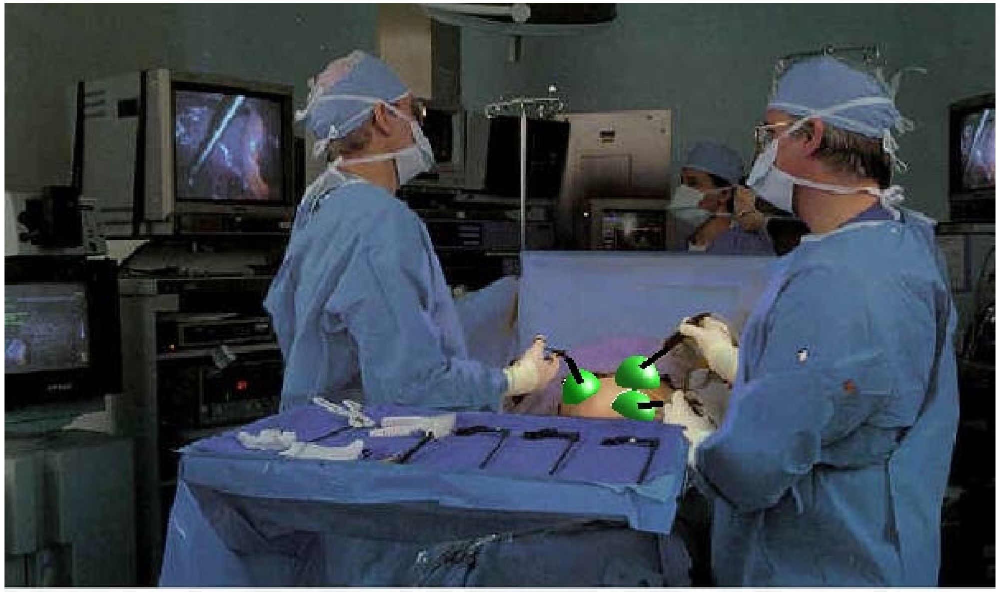
higher bandwidth than indirect force control
⇒ reduced force
= increased transparency

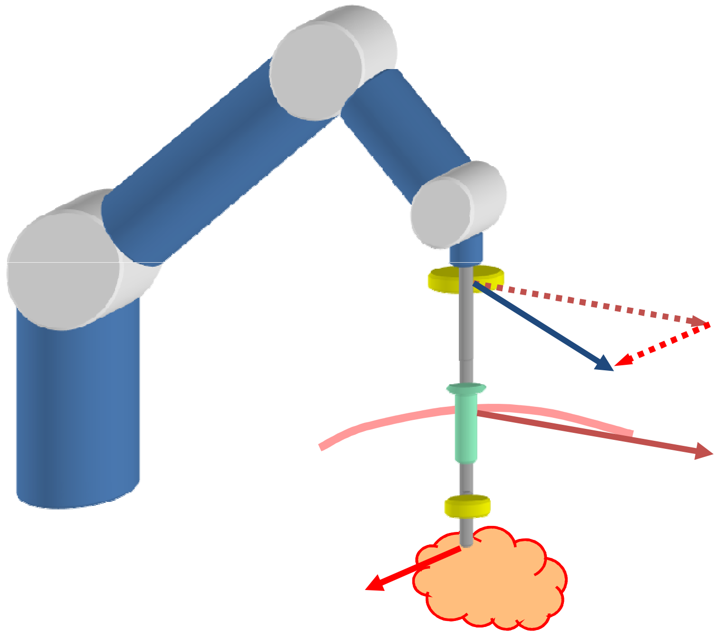


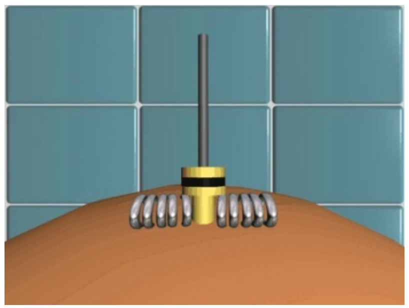


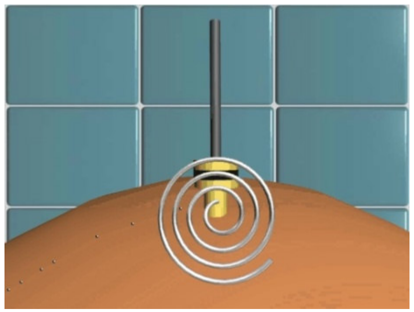
Example: transparent laparoscopic manipulation

1. Problem and objectives

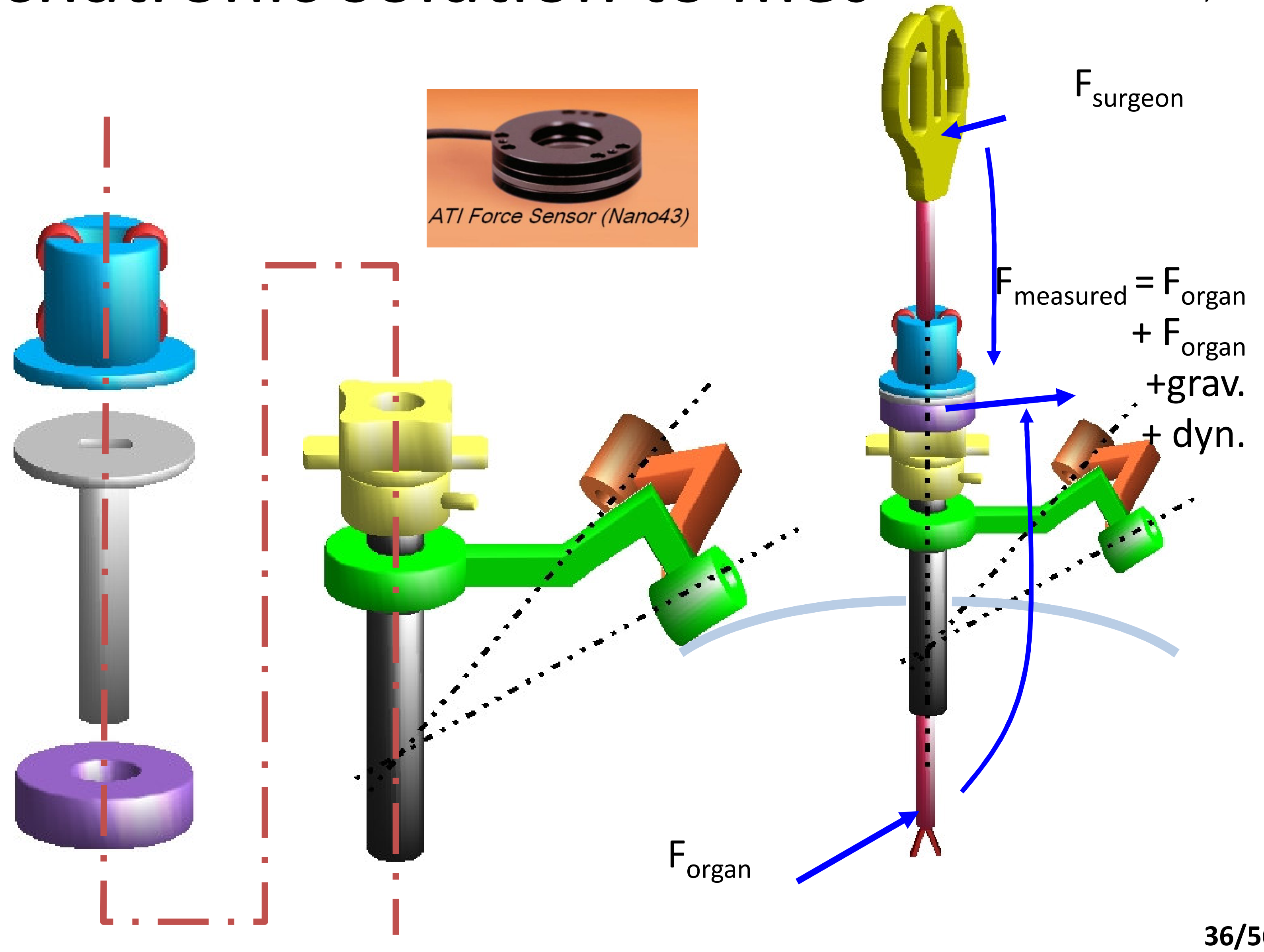








Mechatronic solution to measurement



A passive controller

TORQUE COMPENSATOR

$$\boldsymbol{\tau}_c = \boldsymbol{\tau}_d + \underbrace{\left(\mathbf{K}_p + \frac{\mathbf{K}_i}{s}\right)}_{:=\mathbf{C}_{\boldsymbol{\tau}}(s)} (\boldsymbol{\tau}_d - \boldsymbol{\tau}_e)$$

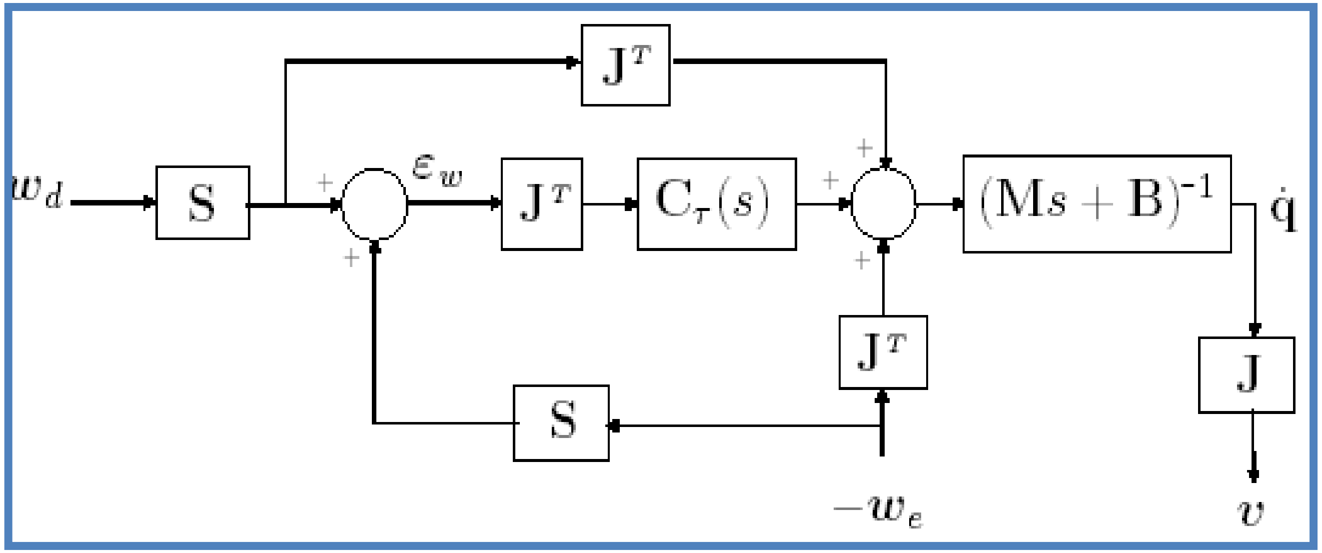
OUTPUT PORT ADMITTANCE

$$\mathbf{Y}_{\mathrm{w}}(s) = \frac{\mathbf{v}}{-\mathbf{w}_{\mathrm{e}}} = \mathbf{J}\mathbf{Y}_{\tau}(s)\,[\mathbf{J}^T + \mathbf{C}_{\boldsymbol{\tau}}(s)\mathbf{J}^T\mathbf{S}]$$

PASSIVITY CONDITIONS

$$\begin{cases} \text{a)} \quad \mathbf{B}^{-1}\mathbf{K}_i \text{ is PSD.} \\ \text{b)} \quad \mathbf{M} = \mathbf{K}_p\ \mathbf{M}\ \mathbf{K}_p^{-1}\ . \\ \text{c)} \quad (\mathbf{I}_n + \mathbf{K}_p)\mathbf{B} - \mathbf{K}_i\mathbf{M} \text{ is PSD.} \\ \text{d)} \quad \mathbf{B}\mathbf{K}_i = \mathbf{K}_i\mathbf{B}. \end{cases}$$

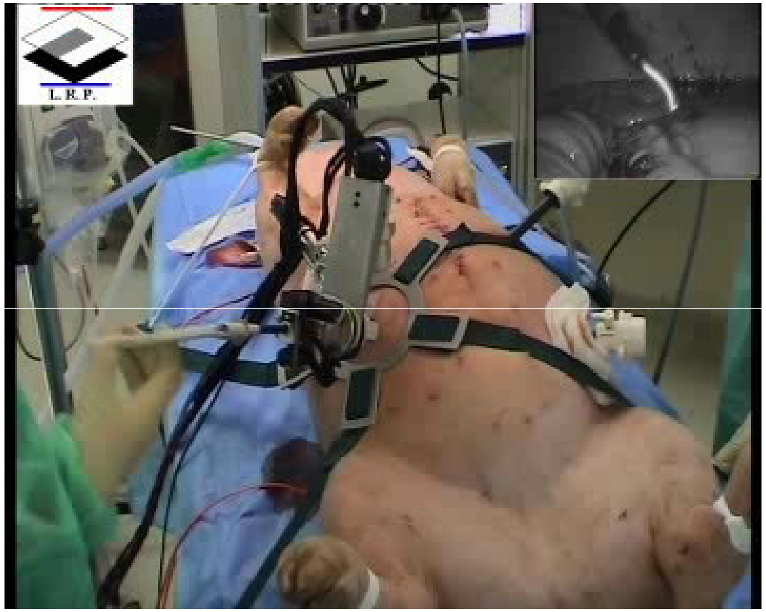
$$\mathbf{S}\mathbf{J} = \mathbf{J}$$

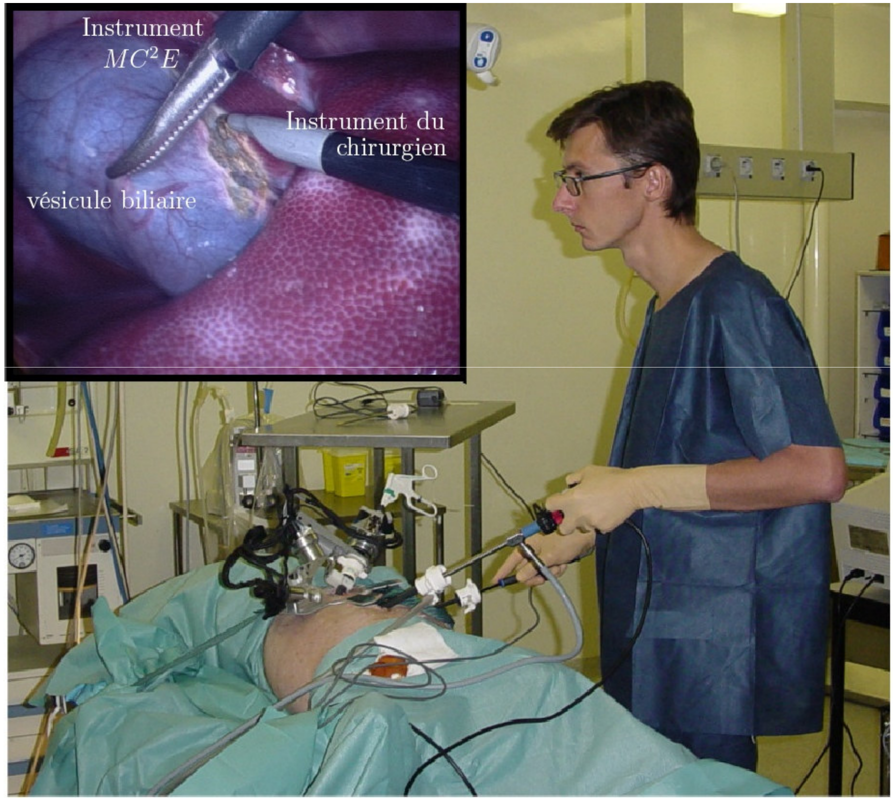


A video of MC²E.

Credit: N. Zemiti.

Application to intelligent assistance

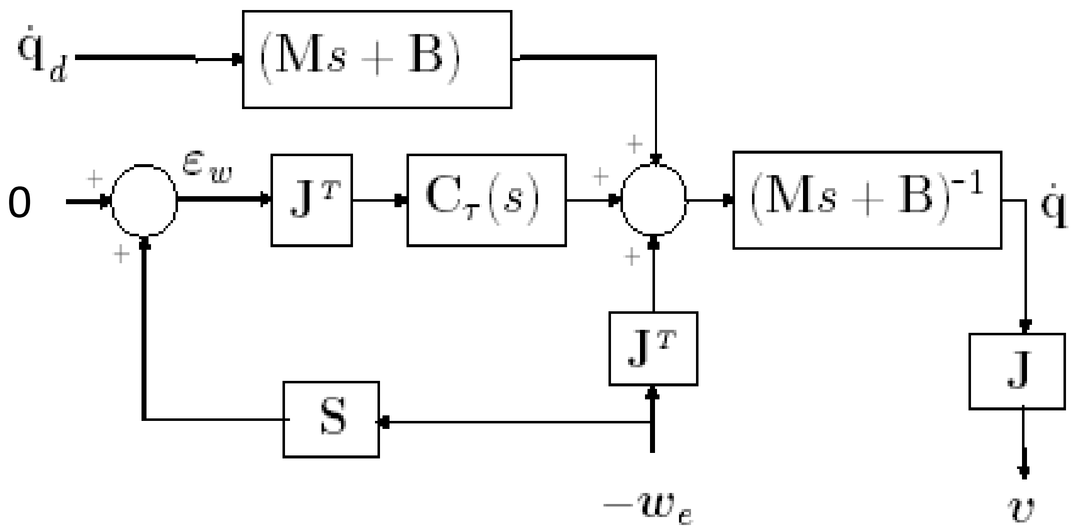




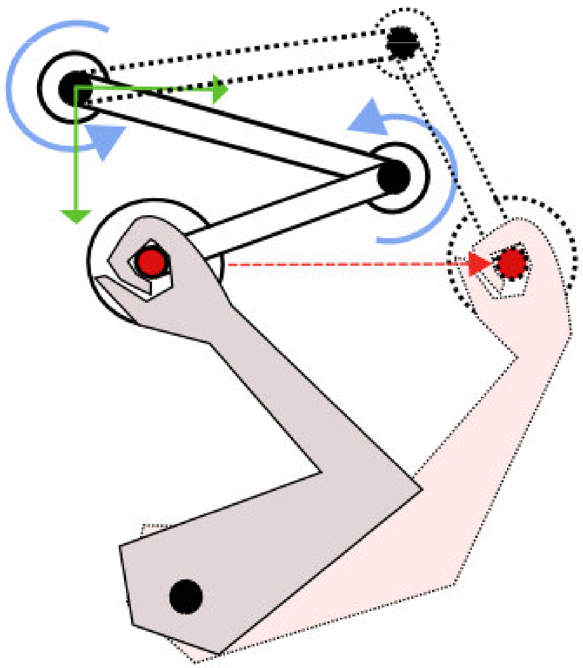
Two successful cholecystectomies realized with pigs by
Dr. N. Bonnet at the Surgery School of Paris (APHP).

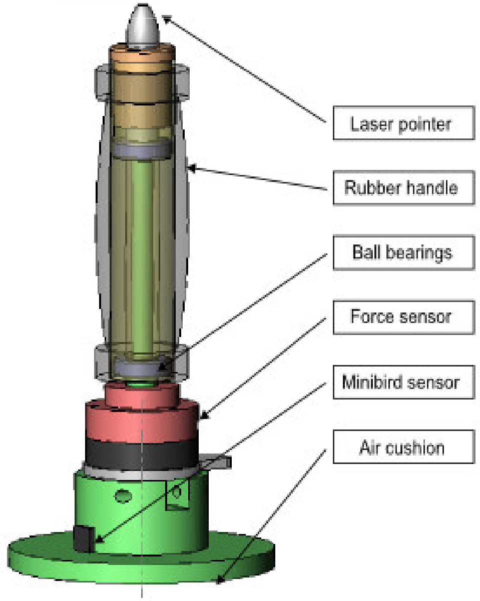
Accounting for human movement prediction with direct force control

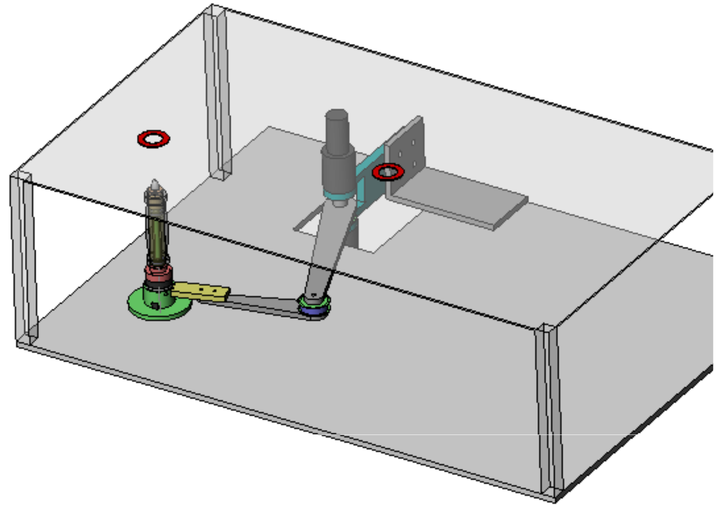
Assuming one has a prediction of the human movements, how to use it in a direct force control scheme ?



Accounting for human movement prediction with direct force control



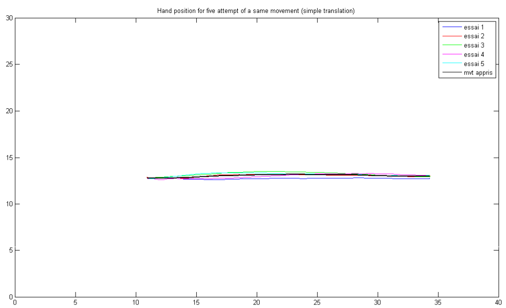


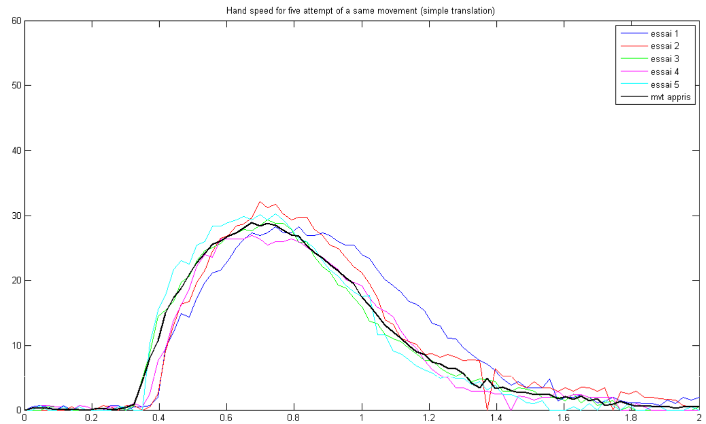


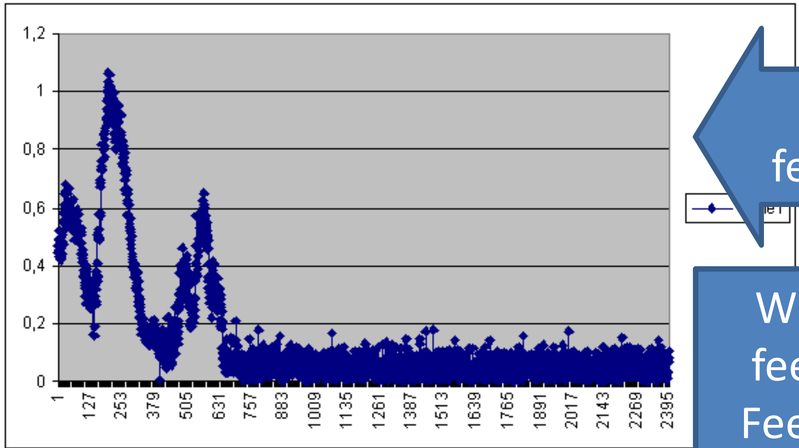
Credit: N. Jarrassé

Accounting for human movement prediction with direct force control

- First results

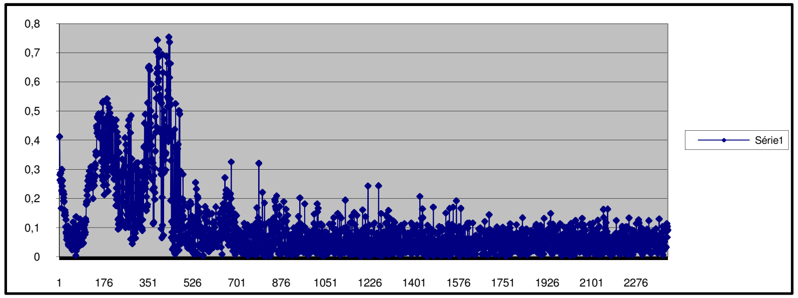






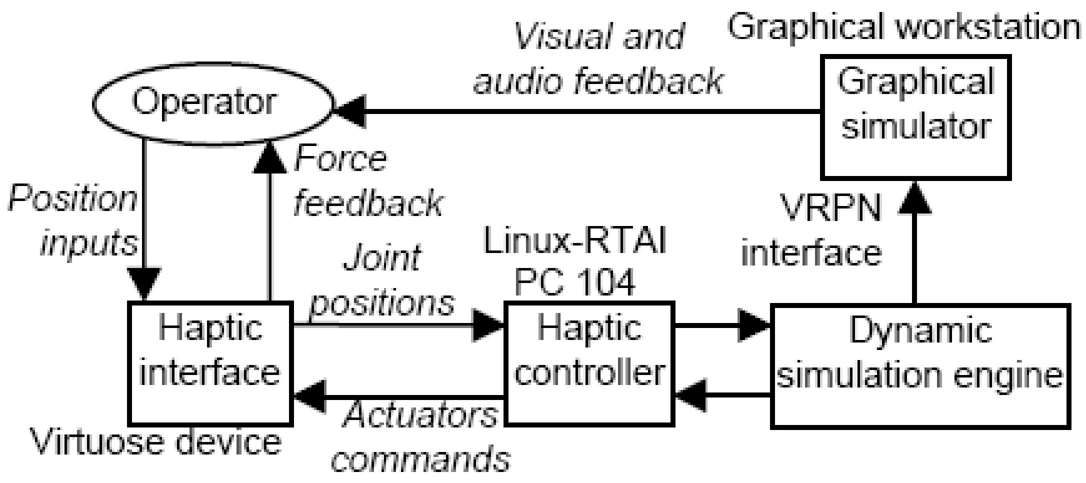
With force feedback only

With force feedback + Feedforxard



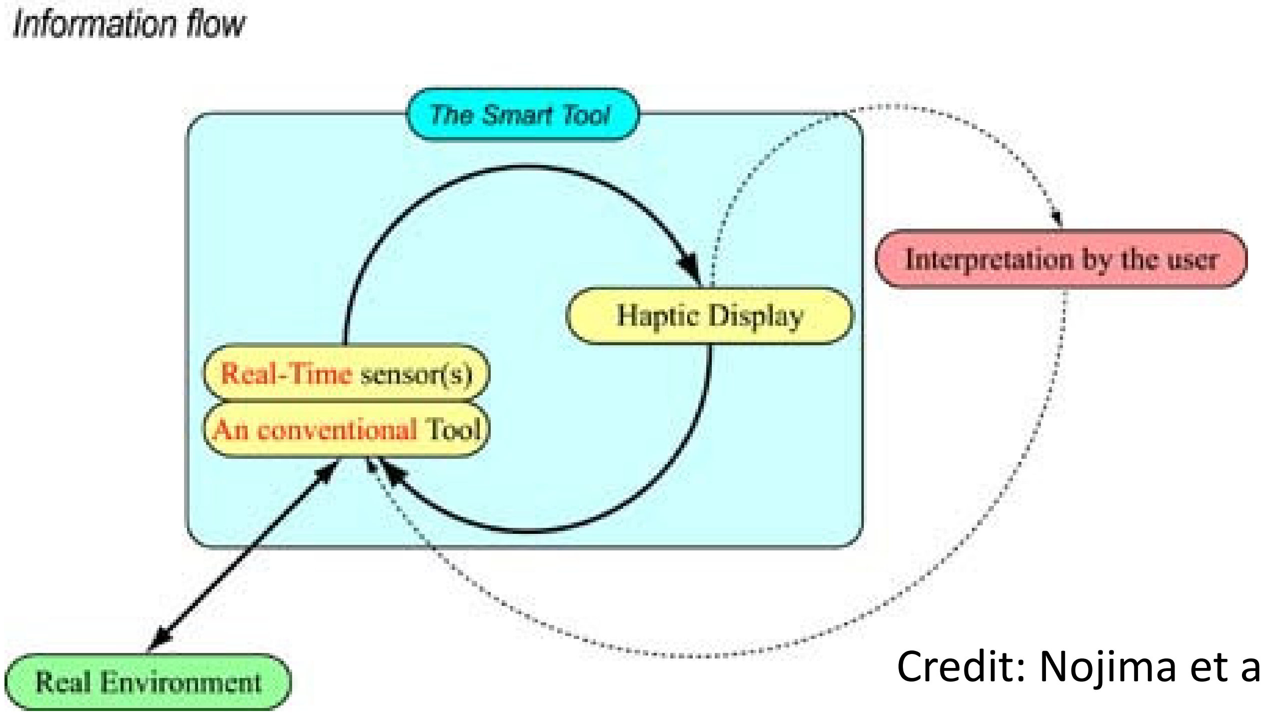
5. Geometrical guidance from a sensor-based reference

- Using a 3D model + a registration leads to a lack of precision.
- Indeed, total error = 3D imaging error + planning error + registration error + robot model error.



The smart tool concept

- Forces sent to the robotics device are not extracted from a virtual environment.
- Rather, they are provided from direct sensory data.



Credit: Nojima et al – Tokyo Univ.

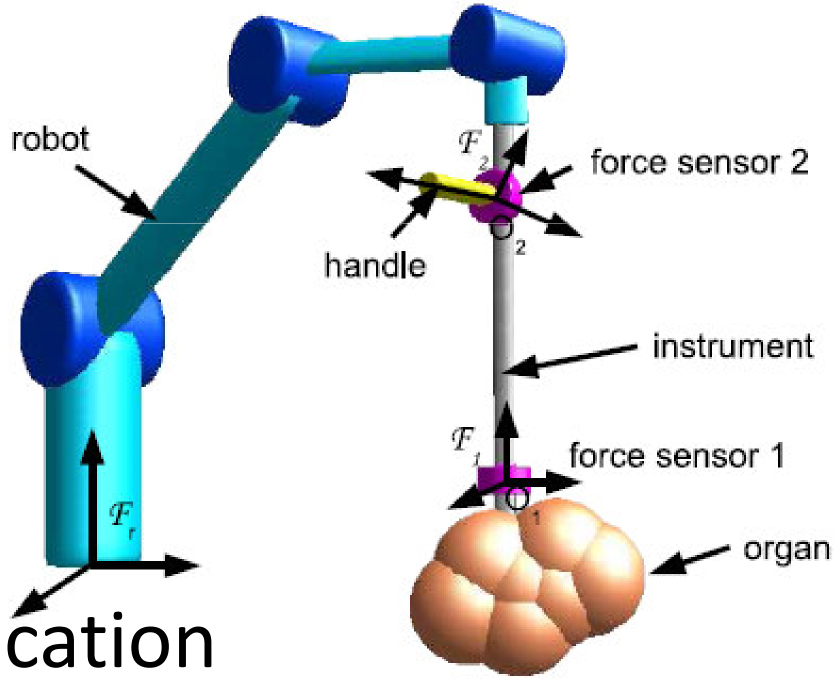
The smart tool concept

6. Other types of assistance

- By contact (parallel devices):
  - Guidance is not limited to applying a geometrical constraint.
  - Changing the dynamics is also of interest:
    - Gravity compensation.
    - Force amplification.
    - Tremor cancelling
    - Conformation to "correct movements".
    - Compensating for periodic physiological motion.
- Manipulation extension (serial devices):
  - Handheld active tools
  - Prosthetics

6.a Force amplification

- Two force sensors.
- One for the organ (W_e)
- One for the surgeon (W_s)

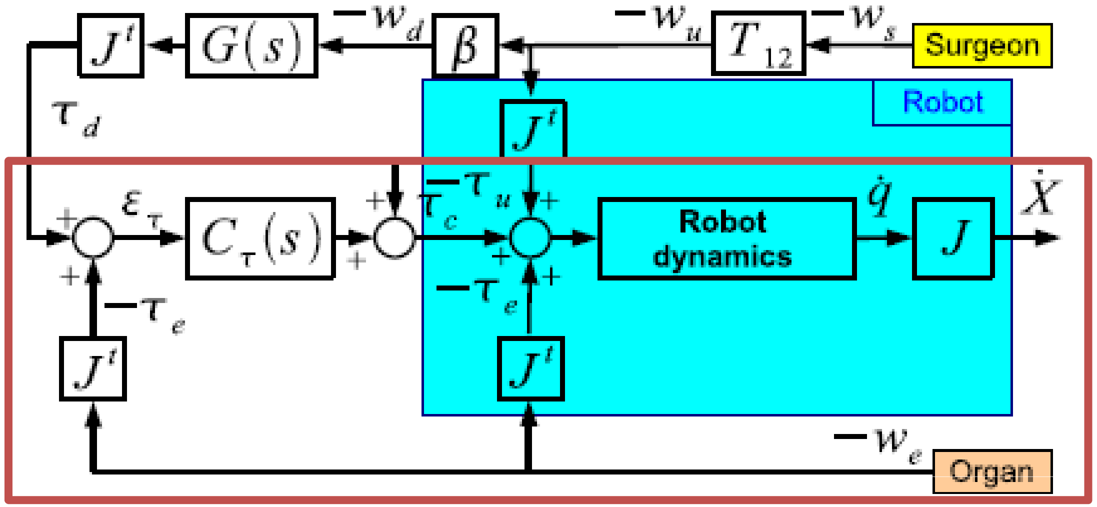


We want :

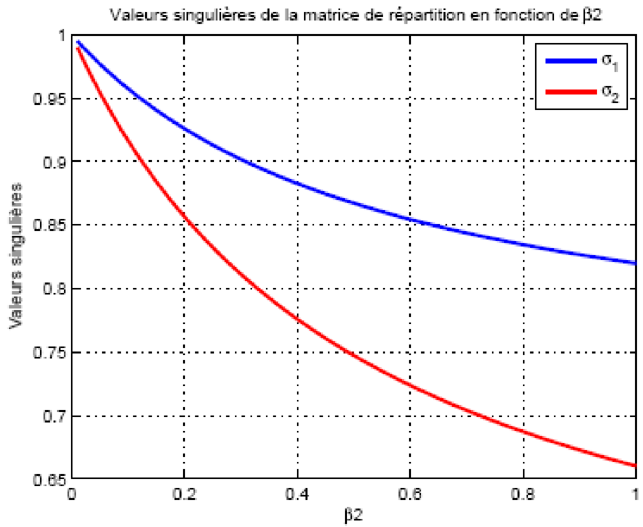
$$J^T(W_e + \beta W_s) = 0$$

- Low β = high force amplification

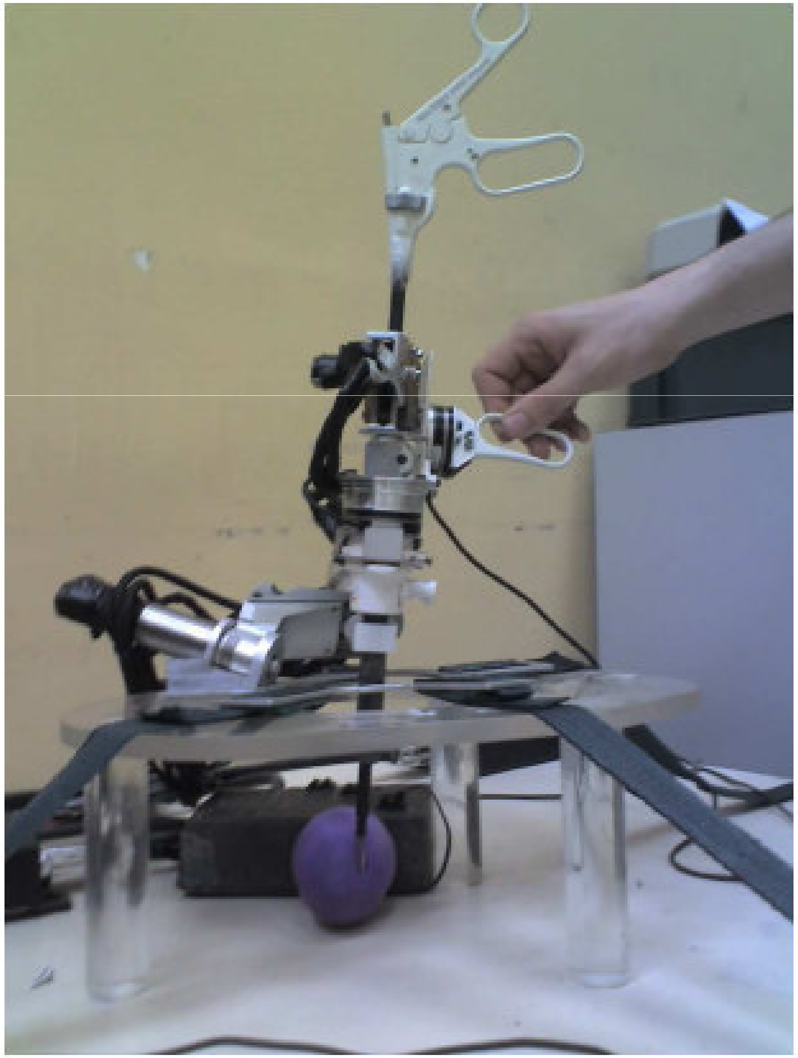
Control scheme

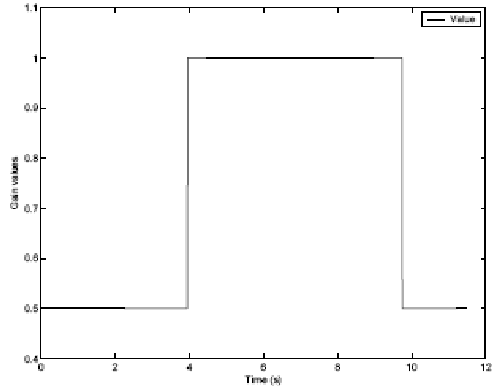


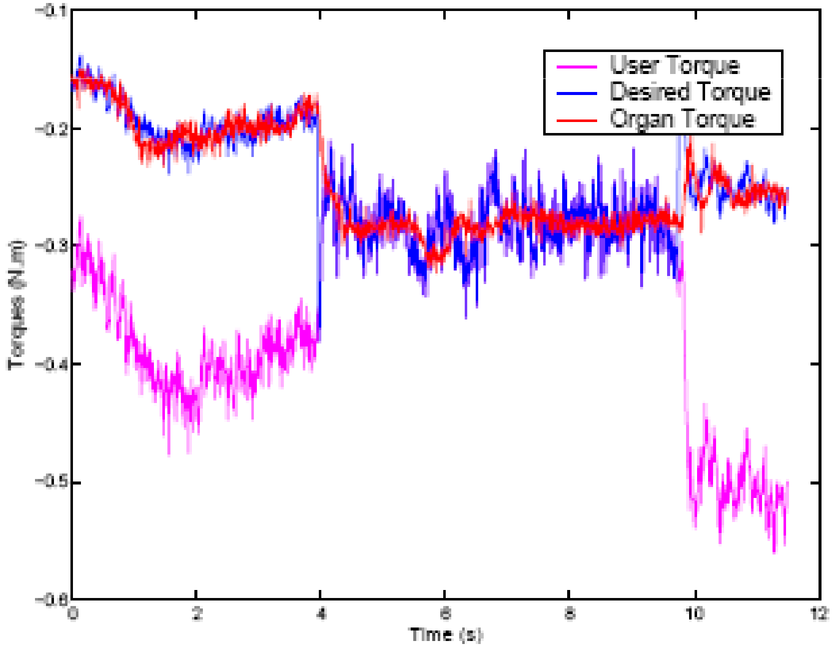
The passivity is kept even for β<<1



Results



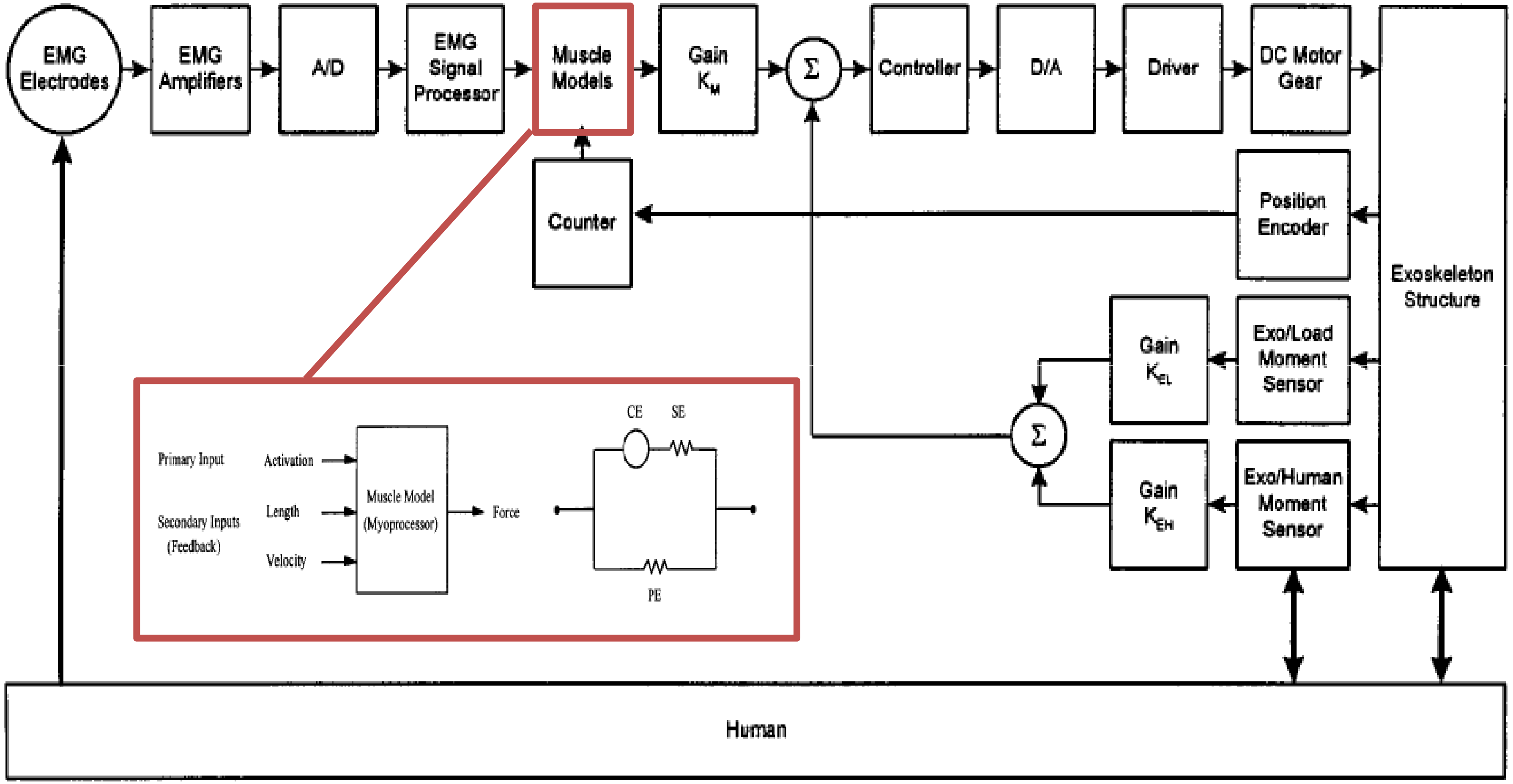

Value
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
2
4
6
8
10
12
Time (s)


User Torque
Desired Torque
Organ Torque
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
Torques (N.m)
0
2
4
6
8
10
12
Time (s)

6.b – Using EMG signals in cooperation with contacts

- Force amplification for assistance to manipulation with an exosqueleton

6.b – EMG-based control



Please ask Blake Hannaford for details

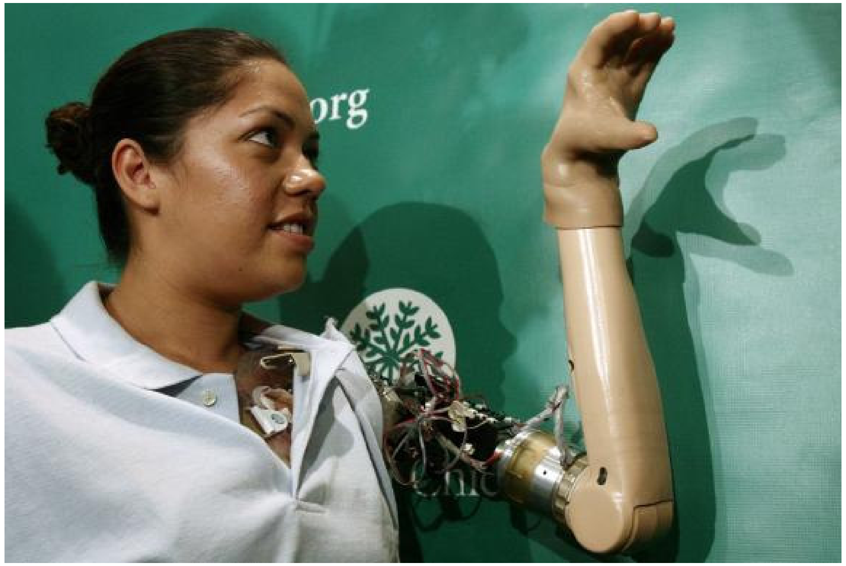
6.c Hand held tools

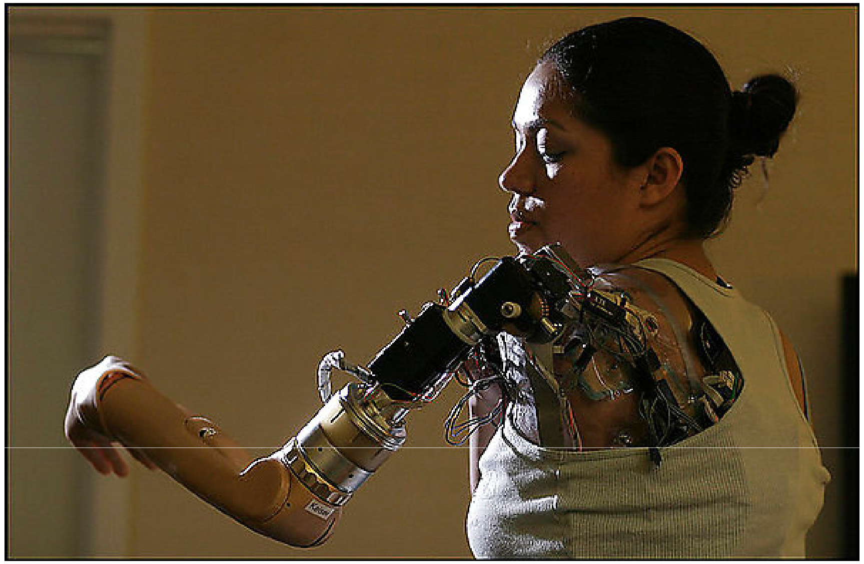
Please refer to Wei Tech Ang's talk!

6.c Hand held tools

Please ask Elena Troia for details

6.d Prosthetics



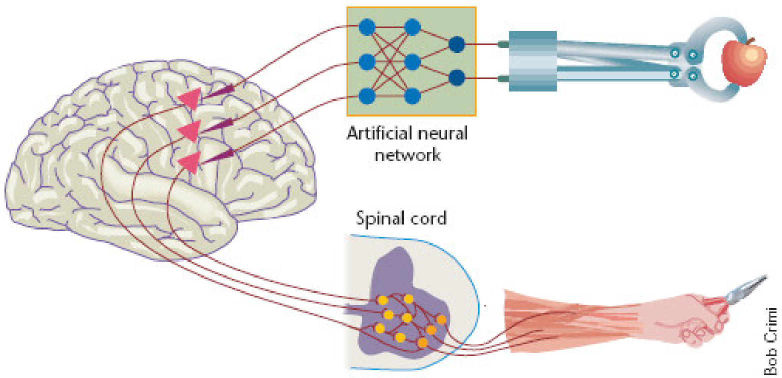


- Connect nerve termination of the missing arm in the pectoral muscles
- Use surface electrodes to interface with them
- Both motor and sensing capabilities are recovered
- Learning is very long.

Chicago Institute of Rehab.

And even more channels

- Eye-tracking : the eye motion is a precursor of hand motion in reaching tasks.
- Brain-Machine interfaces :
  - Monkeys and rats can provably control robotic arms from the signal measured in brain-installed electrodes.



- Functionnal electrical stimulation (feel free to ask questions to Prof. Ang and Prof. Poignet).

Conclusions

- Assistance to gesture differs from
  - Haptics.
  - Teleoperation.
- Numerous possible cooperation channels.
- The machine control loops are deeply interconnected with the operator control loops :
  - Sensorimotor control
  - Learning
- A wide range of new problems and therapeutic applications.