Assistance to gesture with applications to therapy (AGATHE)

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Institut des Systèmes Intelligents et de Robotique

- Institutions: Univ. Pierre & Marie Curie (Paris 6), CNRS.
- Location: Dowtown Paris
- 38 faculty members (Mechanical Engineering, EE, Control Engineering, Computer Science, Medicine) 45 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 (1 position available right now in mechatronics for minimally invasive surgery, starting beginning of 2010).**

Topic of the talk

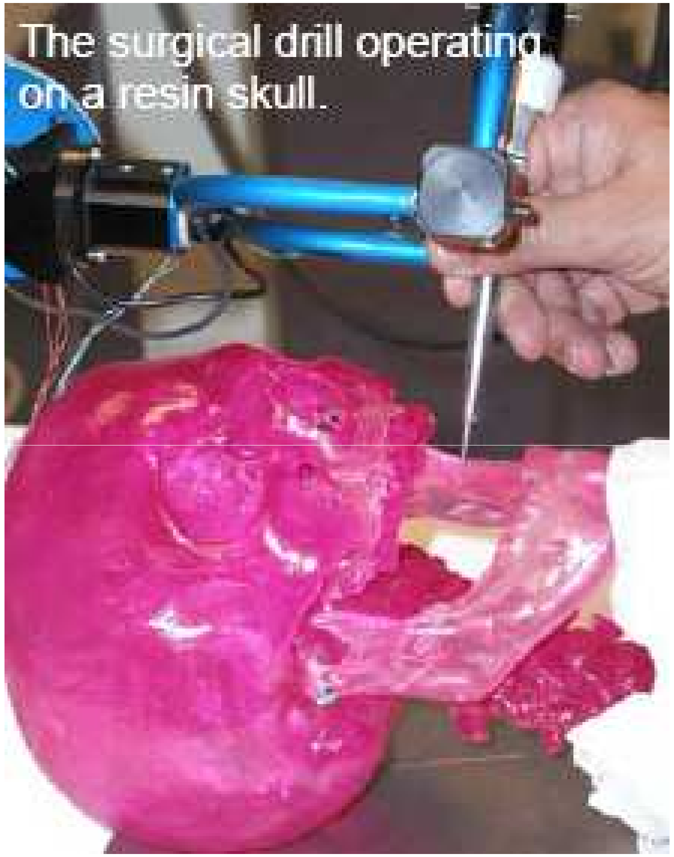
- ***Assistance to gesture***: robotic systems designed to help a human subject in performing a manipulation task: cobots, comanipulators, hands-on devices, interactive systems, …
- ***Therapeutic applications***:
  - **Surgery**: a robot that assists a surgeon in performing the operation.
    - Fine 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

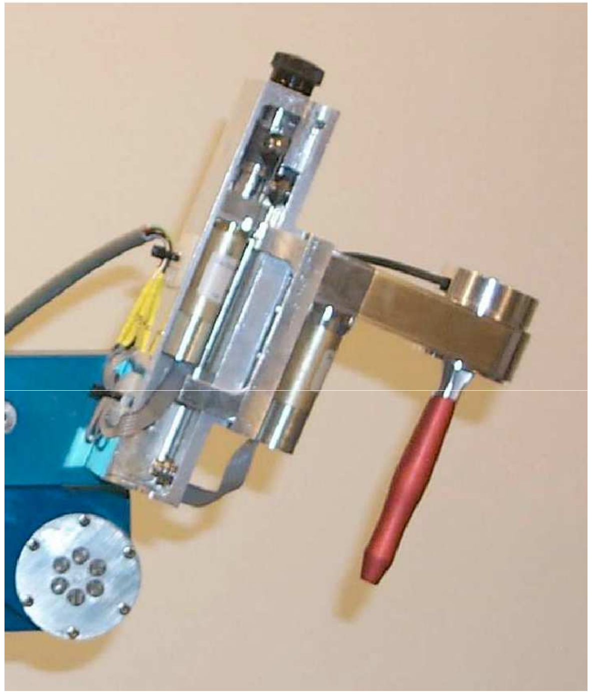


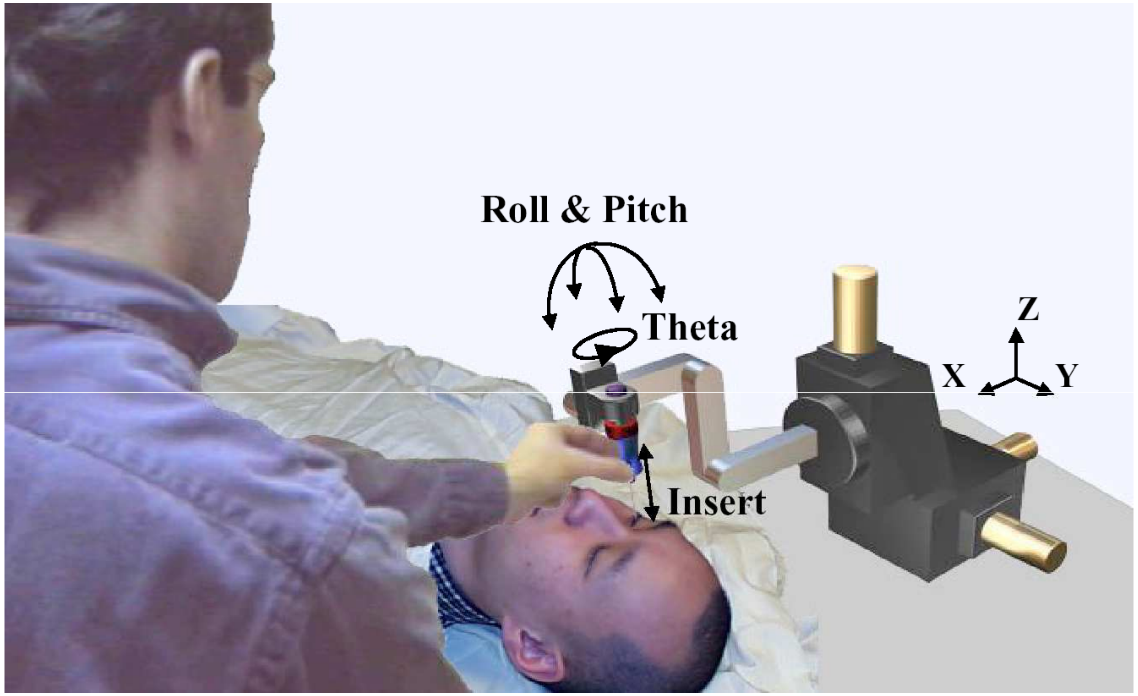
The surgical drill operating on a resin skull.

Credit: P. Gravez – CEA LIST

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

Example 3: Hands-on system

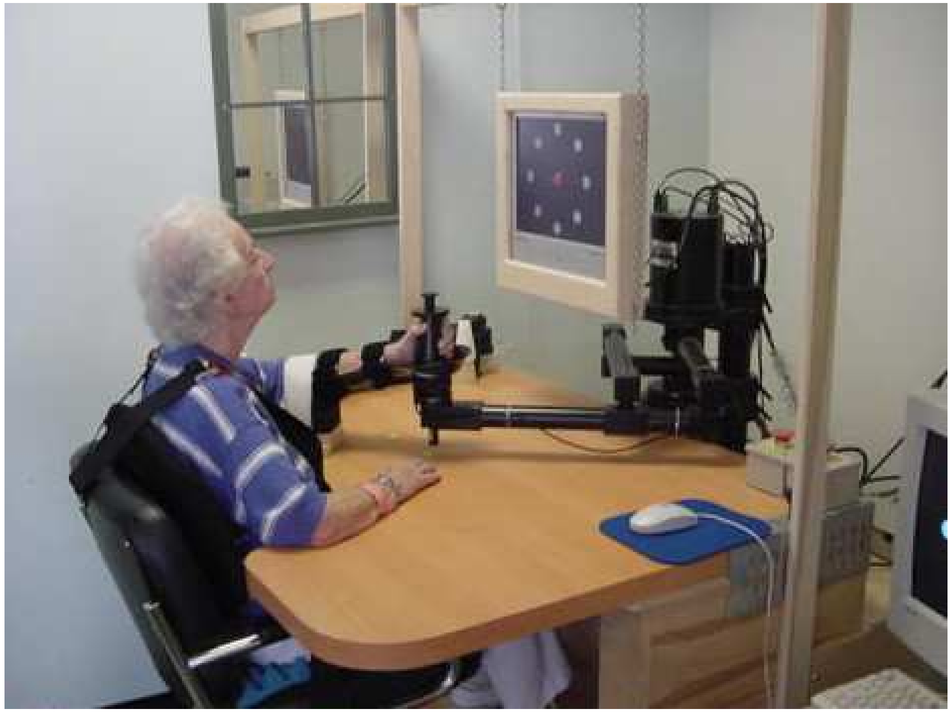


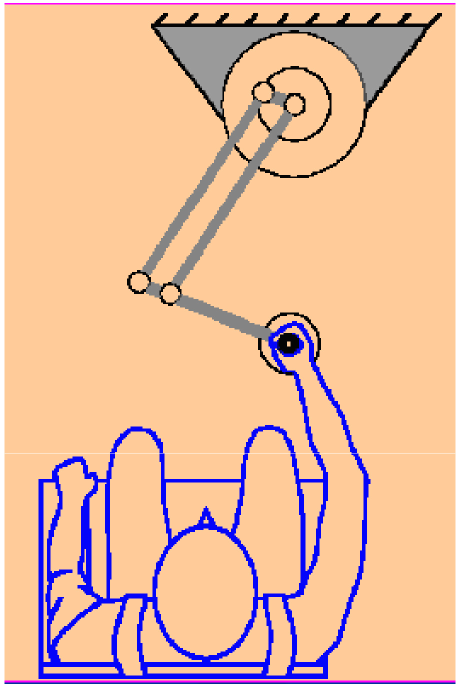


- Force amplification for microsurgery
- Tremor filtering
- Virtual Fixtures

Credit: R. Taylor – JHU Univ.

Example 4: MIT Manus

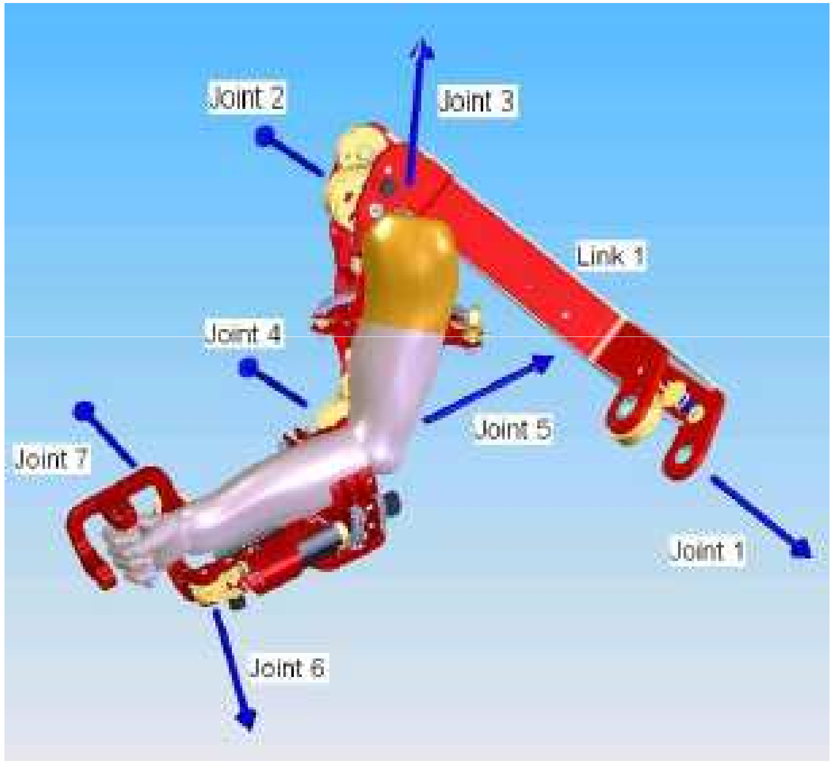




- Assistance to post-stroke rehabilitation
- Tunable assistance for simple planar movements

Credit: N. Hogan, MIT

Example 5: Univ. of Washington exosqueleton



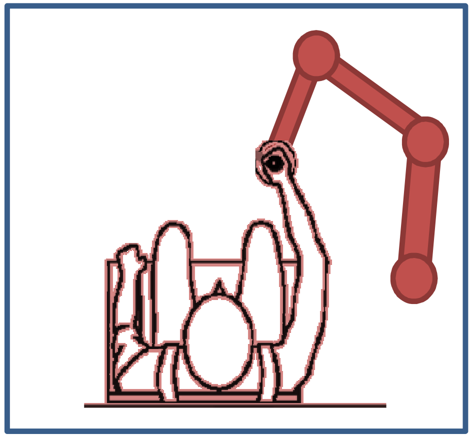
Credit: J. Rosen, Univ. Of Washington

Example 6: Hand held robot for microsurgery

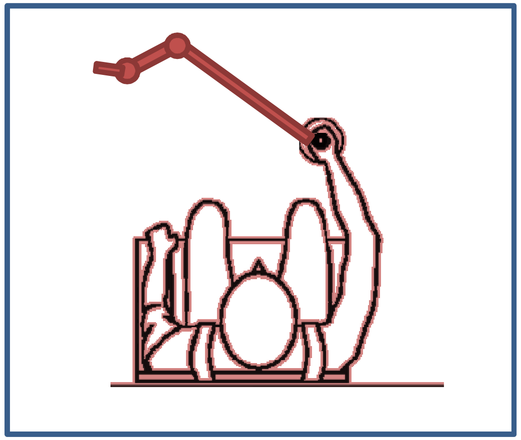
Credit: W.T. Ang, CMU -> Singapore Nanyang Univ.

Typology

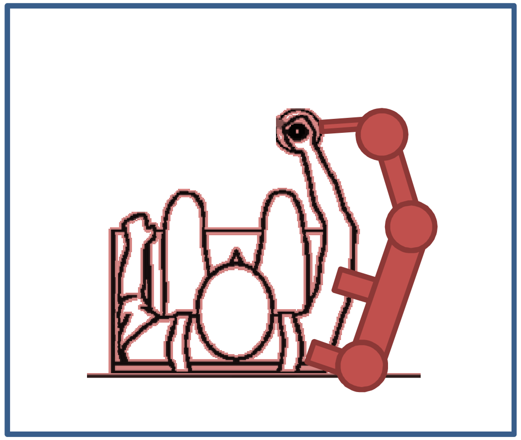
Parallel Comanipulation: summing operational forces



Serial Comanipulation: summing operationnal velocities



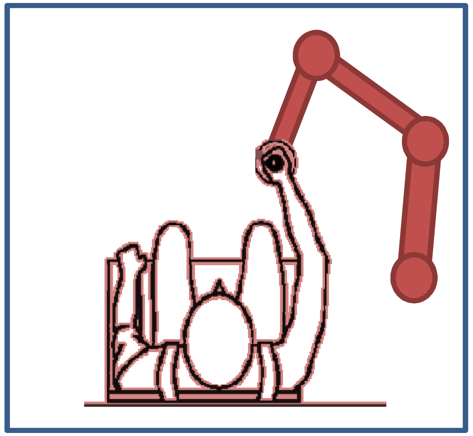
Orthotic Comanipulation : summing joint torques



Credo: comanipulation is not only interaction control. There’s a human involved, here

PART I: PARALLEL COMANIPULATION

Parallel Comanipulation: summing operational forces



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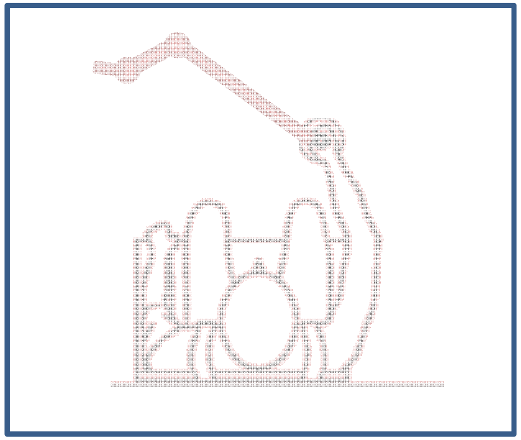
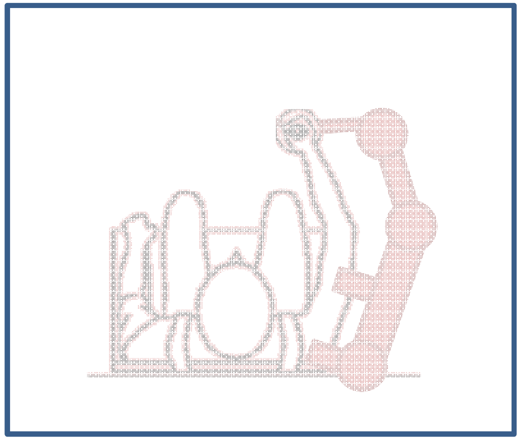


Orthotic Comanipulation : summing joint torques



I.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

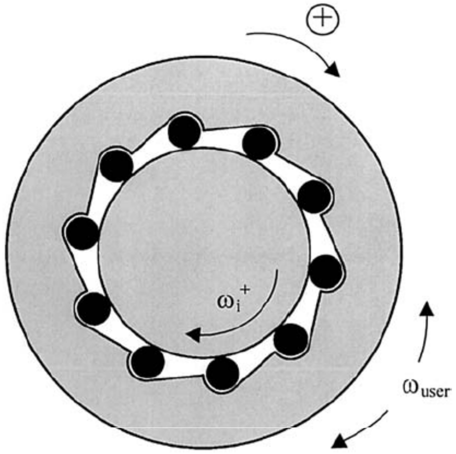
Existing active solutions from haptics

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 2: PADDYC

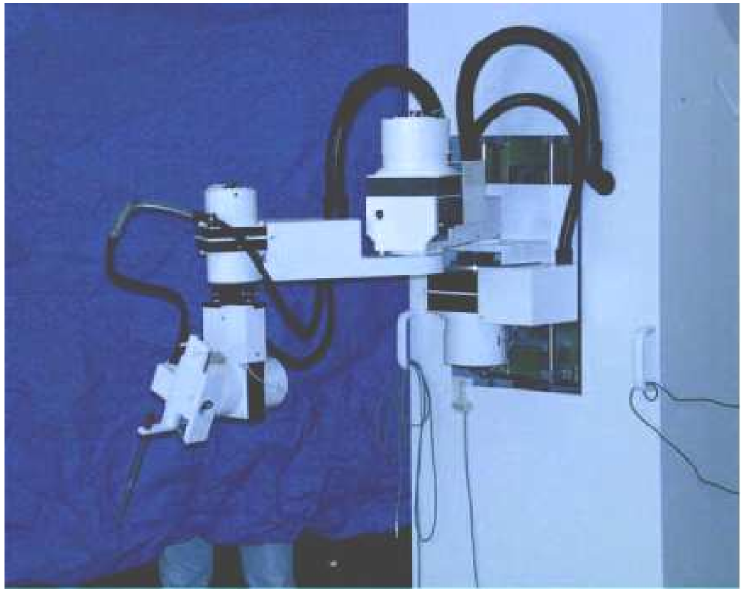


Principle: two freewheels connected and mounted in opposite directions.
Two motors rotating at ω_i^+, ω_i^-.
The ”user velocity” is mechanically limited by:

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

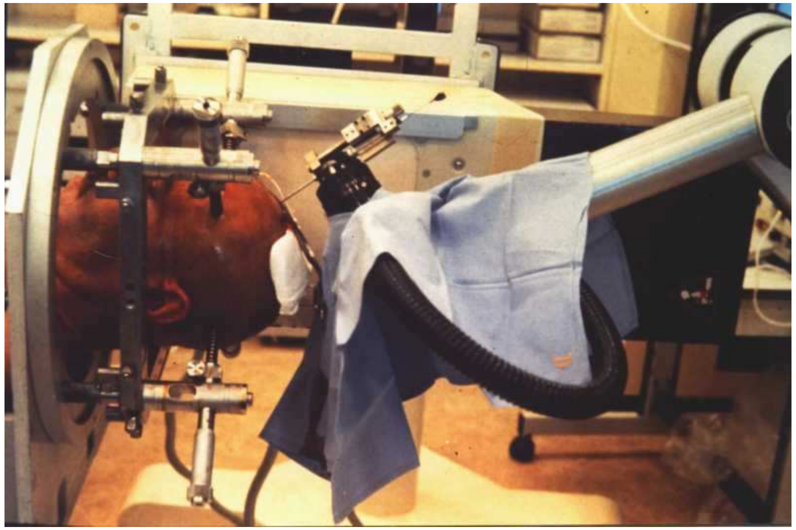
Main advantage : safety, dynamic constraints.

Credit: J. Troccaz.



I.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., Benabid, 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)

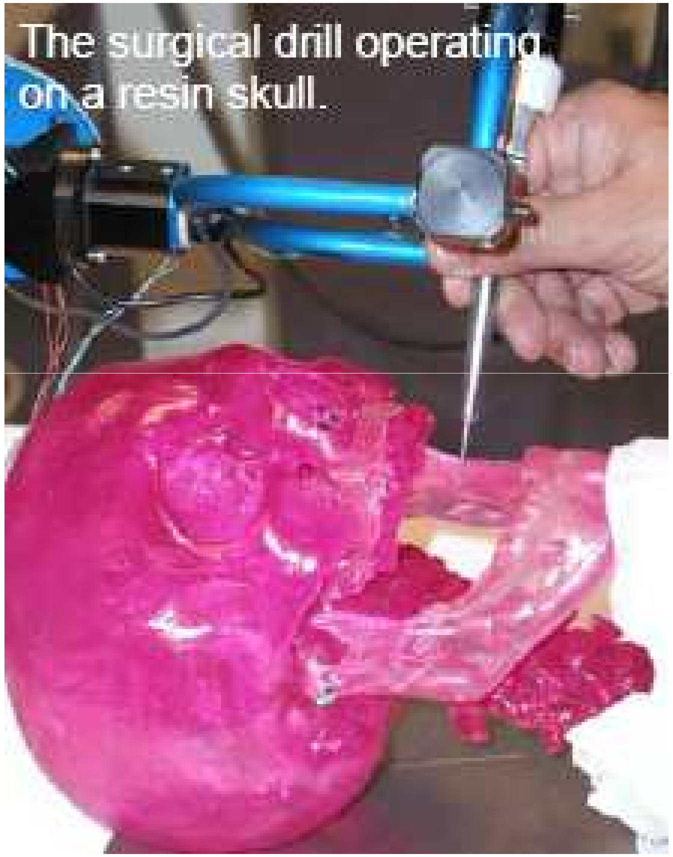
  - **For a dynamic assistance, two basic capabilities are required:**
    - **Transparency =** ability of not disturbing the motion when no guidance is required (free region, free directions)
    - **Rigidity /strength** = ability of strongly blocking movements (forbidden region, forbidden directions)

Coupling a navigation system and a robot.

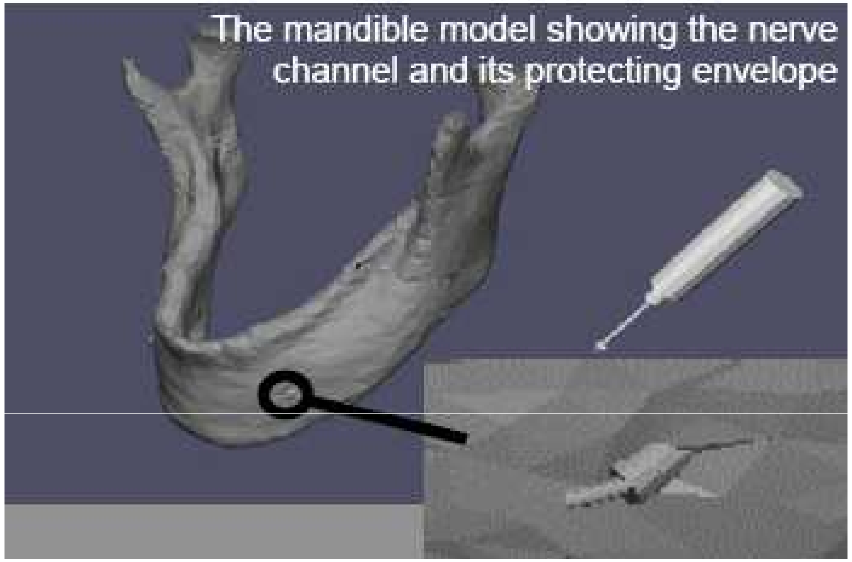
1. 3D imaging $\Rightarrow$ a patient model.
2. Preoperative planning $\Rightarrow$ 3D constraints w.r.t. the patient model.
3. Registration (see J. Troccaz talk) $\Rightarrow$ 3D constraints w.r.t. the robot frame.
4. Exert constraints depending on the end-effector position (variable impedance control).

Praxim's SURGETICS station

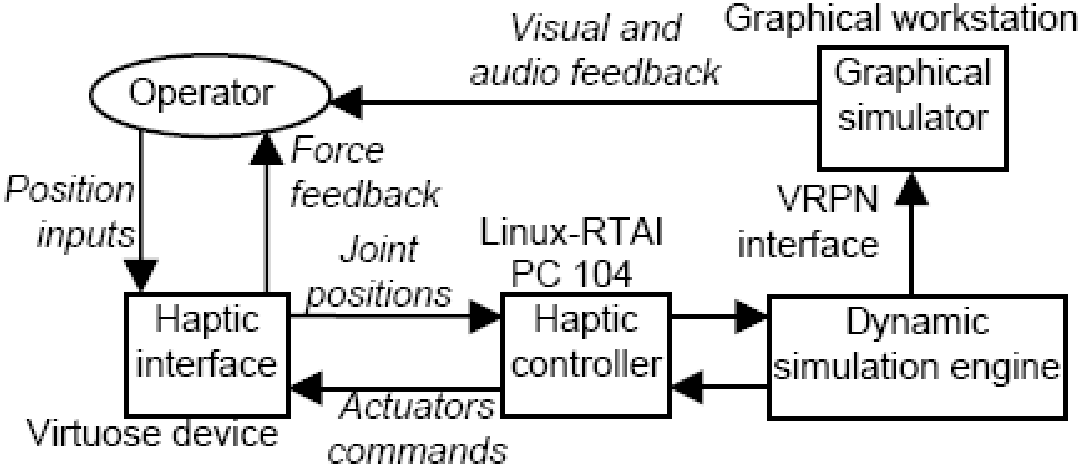
Control structure for a mechanically transparent device



The surgical drill operating on a resin skull.

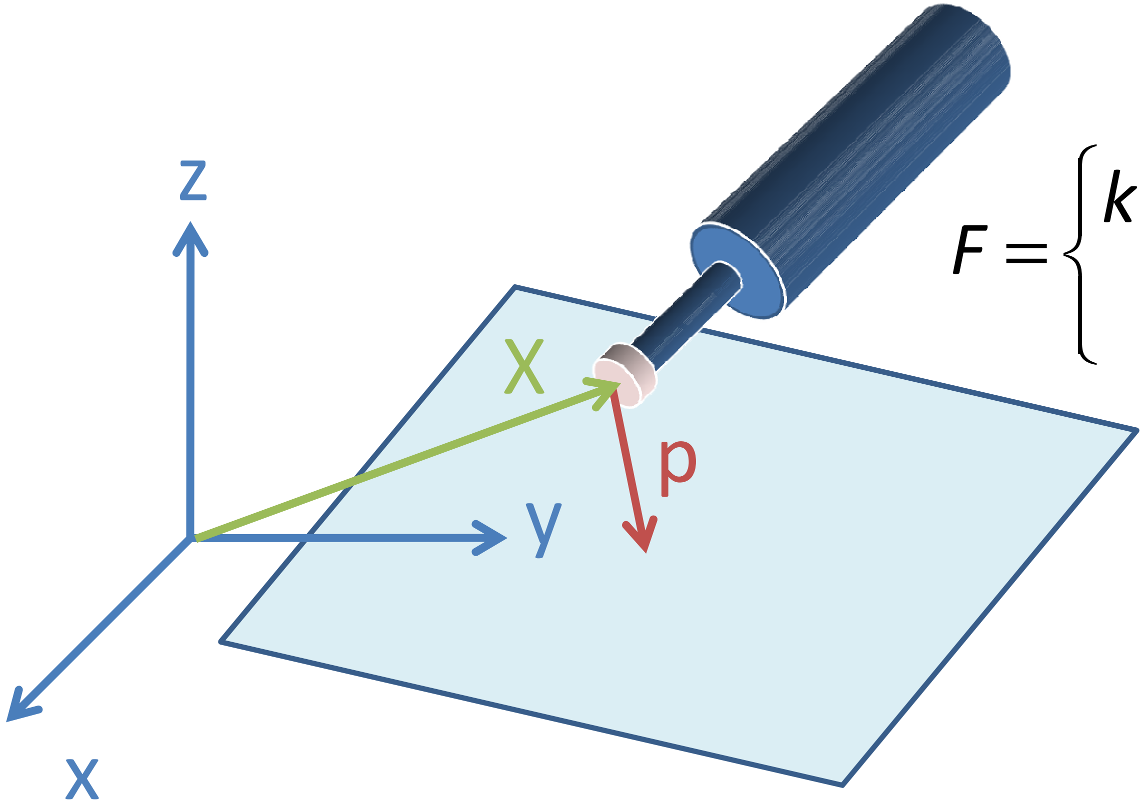


The mandible model showing the nerve channel and its protecting envelope

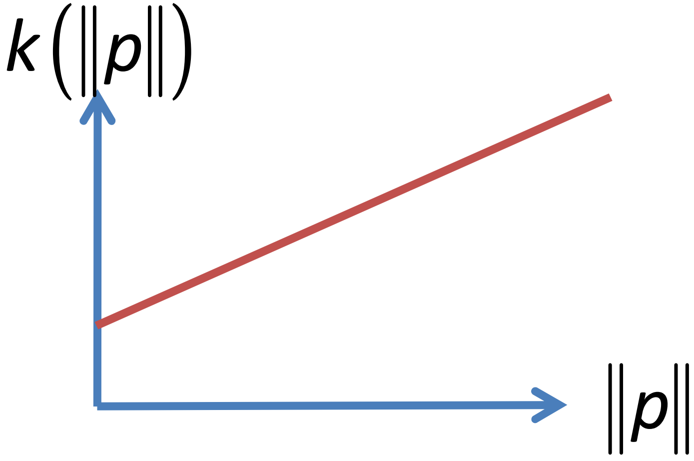


Credit: F. Gravez – CEA LIST

Actuator commands computation



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

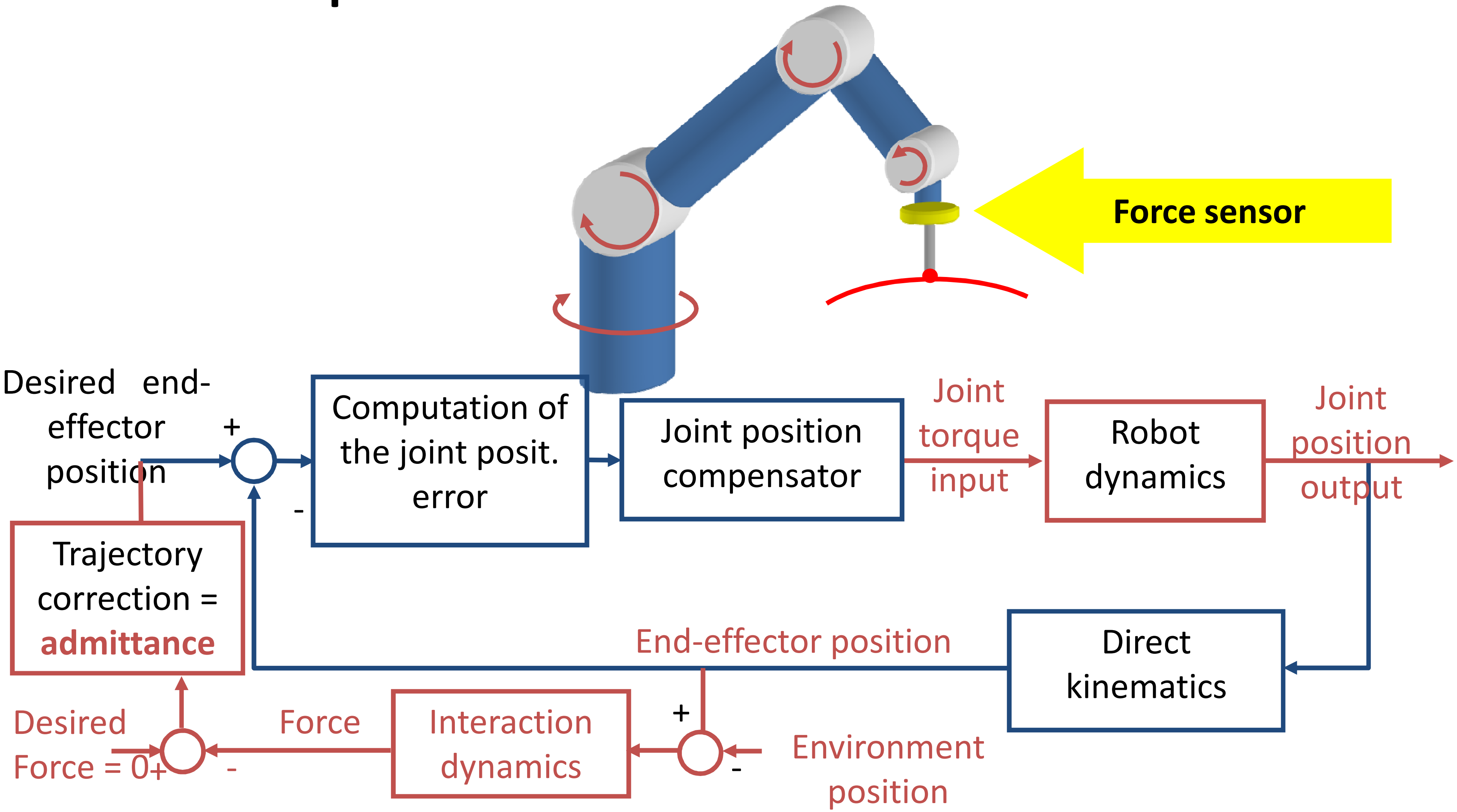


$$\tau = J^T \begin{pmatrix} F \\ 0 \end{pmatrix}$$

$\Leftarrow$ Can be directly sent to the motors with good accuracy thanks to transparency

Video

I.3. Obtaining transparency through explicit indirect force control



Force sensor

Desired end-effector position

+

-

Computation of the joint posit. error

Joint position compensator

Joint torque input

Robot dynamics

Joint position output

Direct kinematics

End-effector position

Trajectory correction = **admittance**

Desired Force = 0

+

-

Force

Interaction dynamics

+

-

Environment position

Example 1: acrobot control

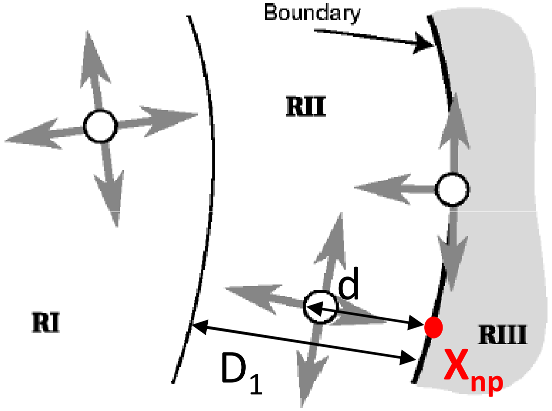
The basic idea behind active constraint control is to gradually increase the stiffness of the robot as it approaches the predefined boundary.

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

$$X_d = X$$
$$\dot{X}_d = AF_G$$
$$F_C = 0$$

Region RII

$$\dot{X}_d = A_N F_{GN} + AF_{GT} \qquad A_N = \frac{d}{D_1}A.$$
$$F_C = -\frac{D_2 - d}{D_2}F_{GN}.$$

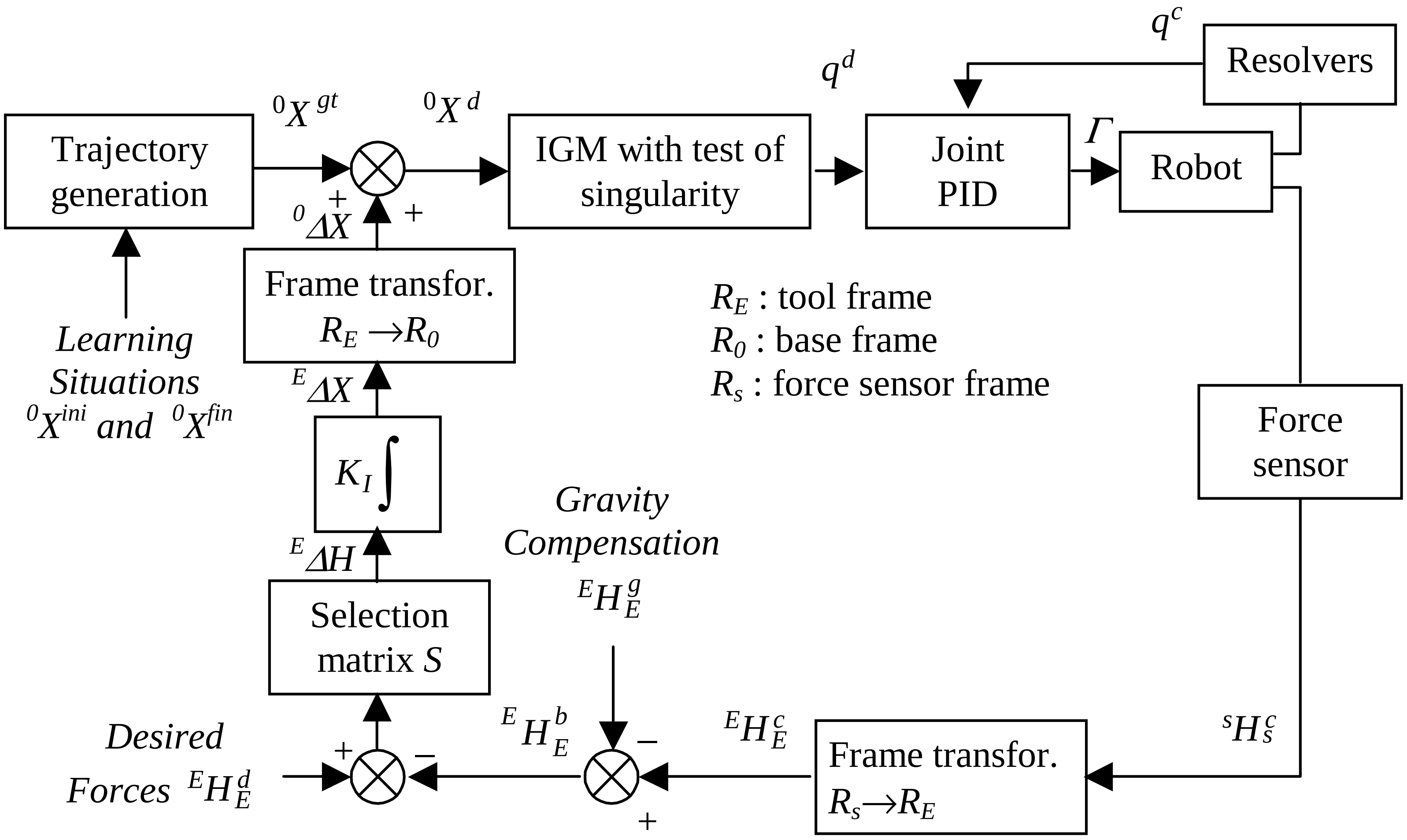
Region RIII

$$\dot{X}_d = AF_{GT}$$
$$F_C = -F_{GN}.$$

Credit: B. Davies et al.

Acrobot Scupltor

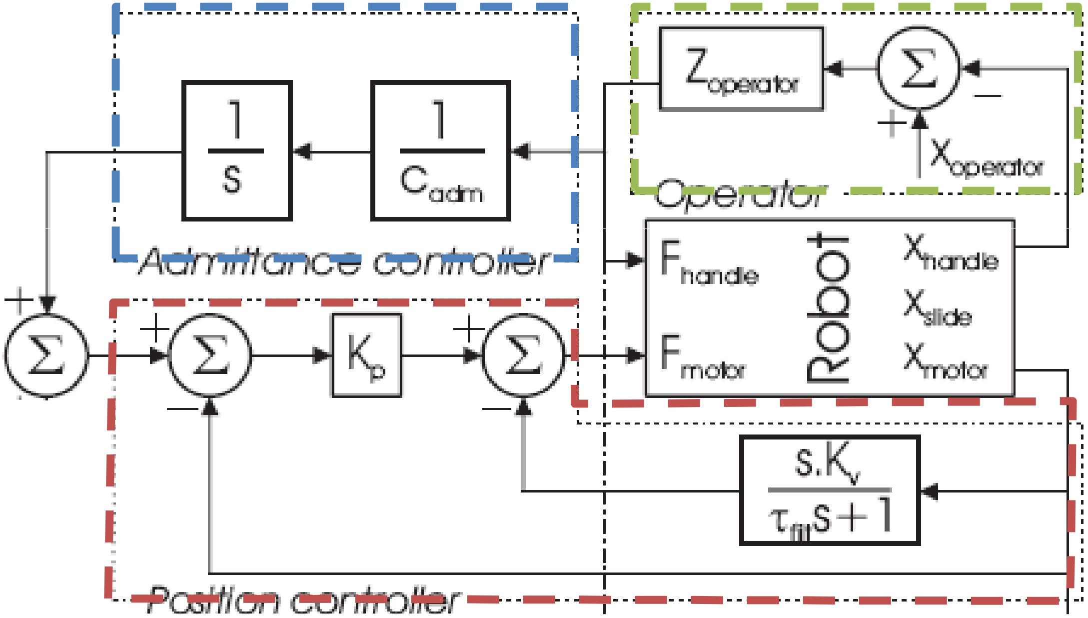
Example 2: Dermarob



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:

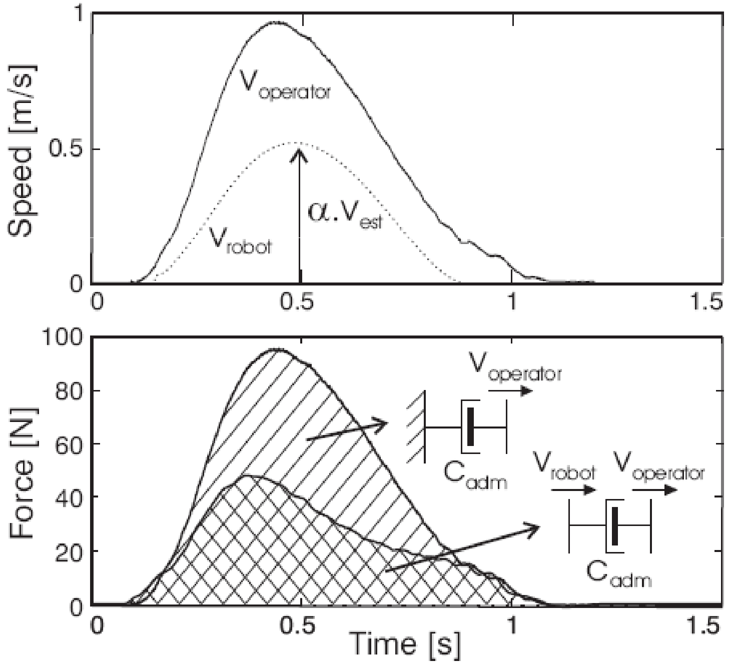
$$y(t) = \Delta y \ f\left(\frac{t-t_0}{\Delta t}\right) + y_0, \tag{1}$$

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

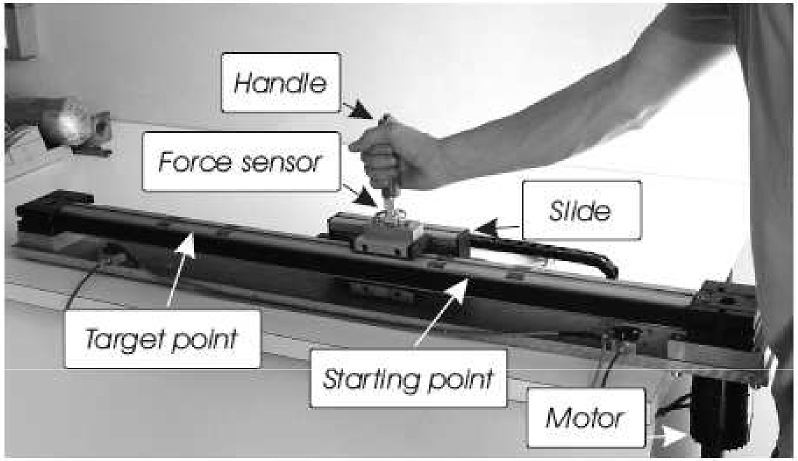
$$\Delta t = t_1 - t_0, \tag{3}$$

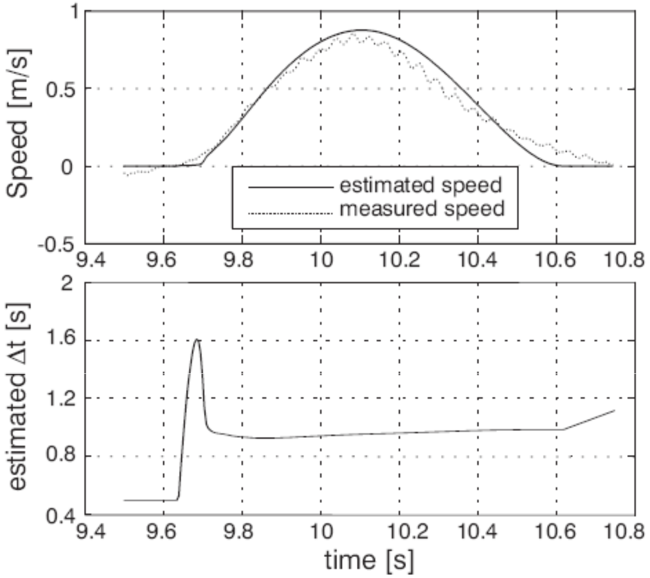
$$\Delta y = y_1 - y_0, \tag{4}$$

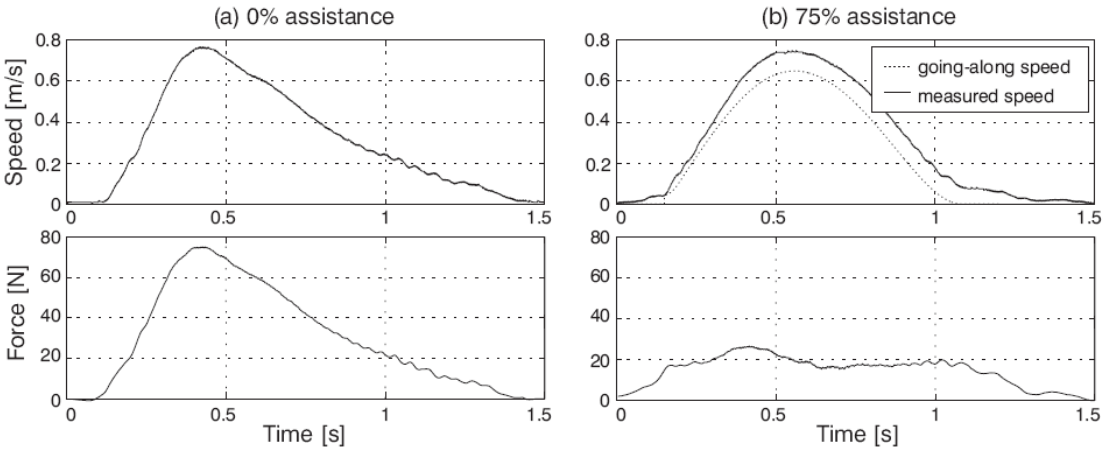
in which y_0, t_0 and y_1, t_1 are the position and time at the beginning and at the end of the motion.



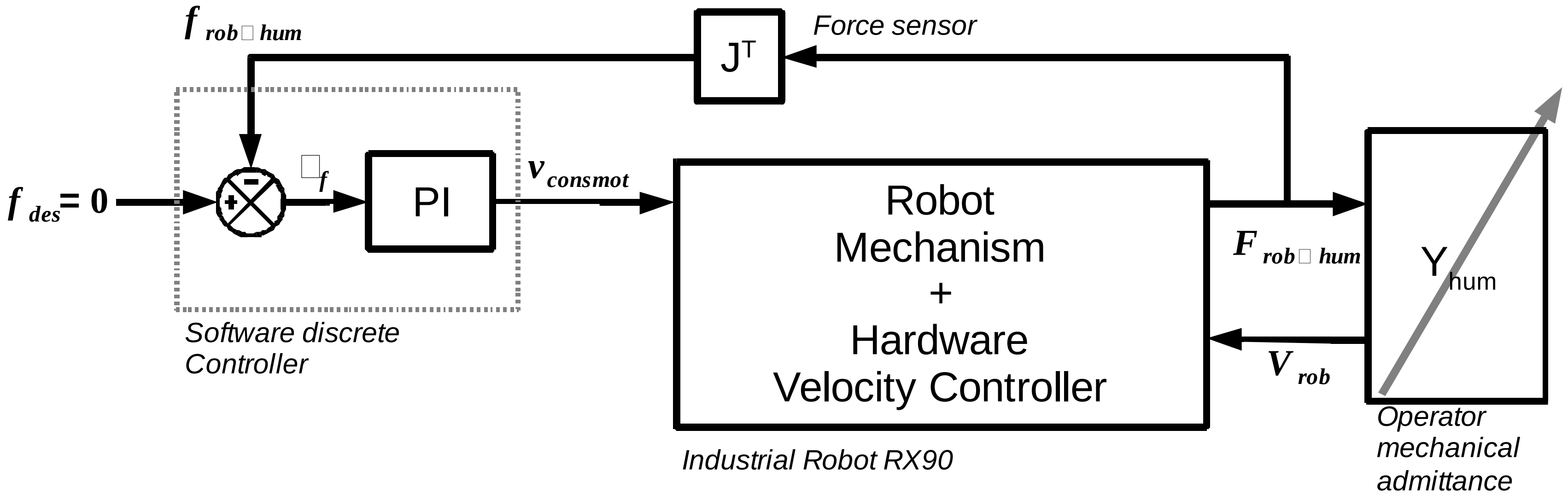
Predicting human movement to increase transparency







Adapting to human impedance variations



$f_{rob \square hum}$

J^T

Force sensor

$f_{des} = 0$

$\square_f$

PI

$v_{consmot}$

Robot
Mechanism
+
Hardware
Velocity Controller

$F_{rob \square hum}$

Y_{hum}

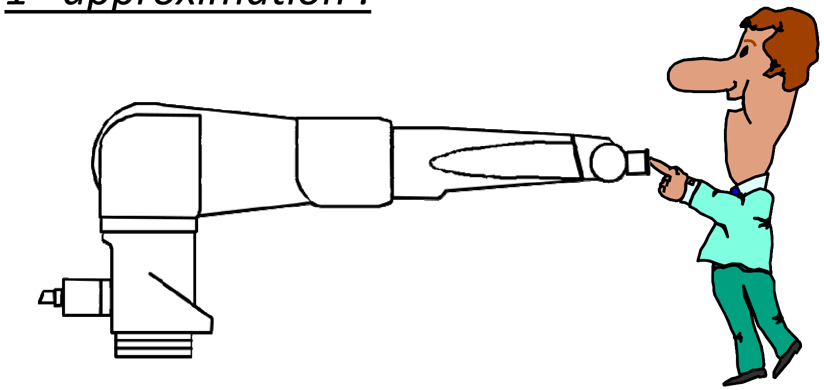
V_{rob}

Software discrete Controller

Industrial Robot RX90

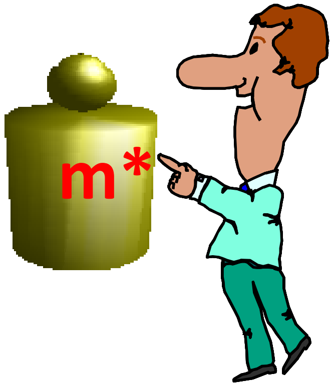
Operator mechanical admittance

1st approximation :

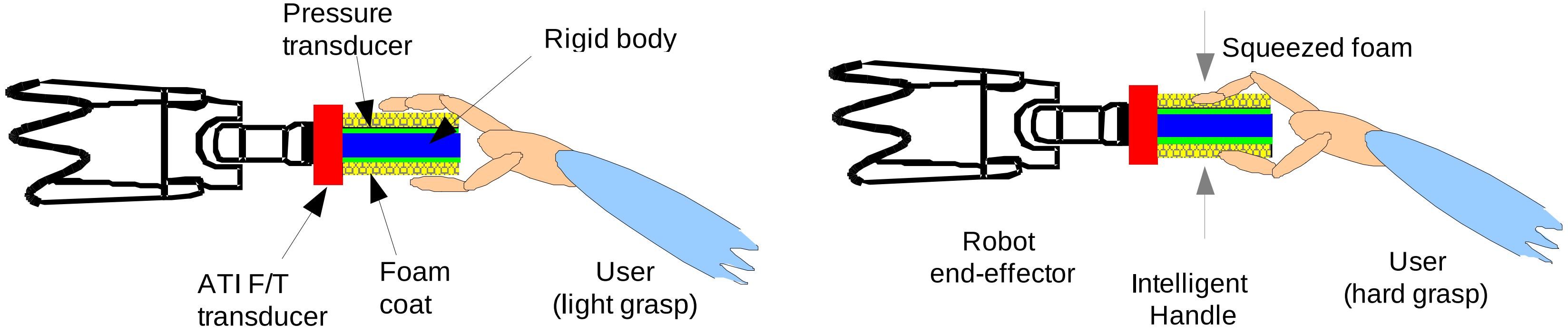


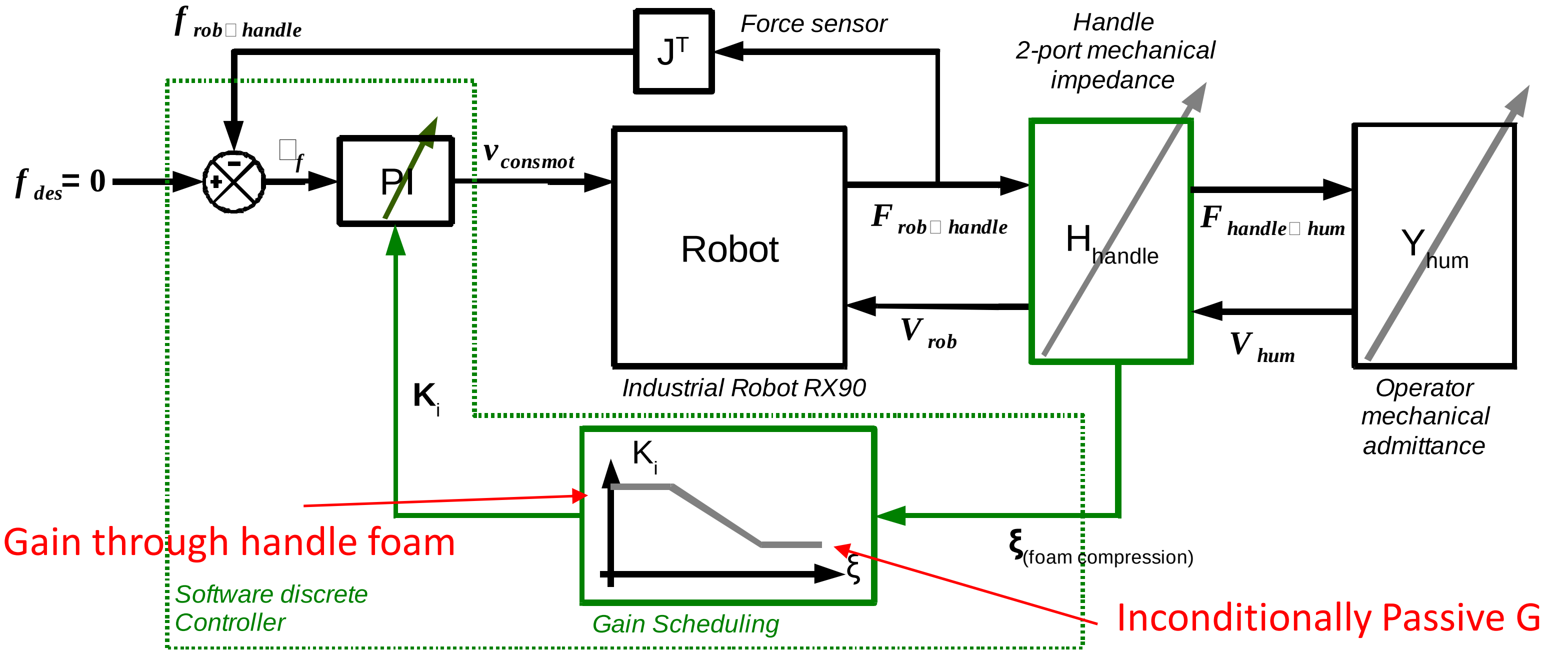
[Dohring 03]
minimum passive inertia achievable

$$m^* \geq \frac{1}{2} m_{robot}$$



Adapting to human impedance variations



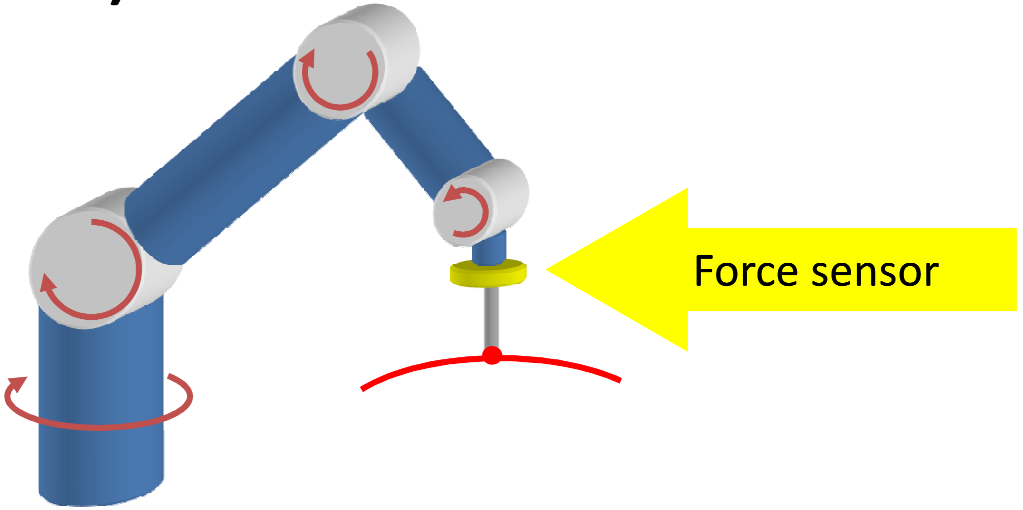


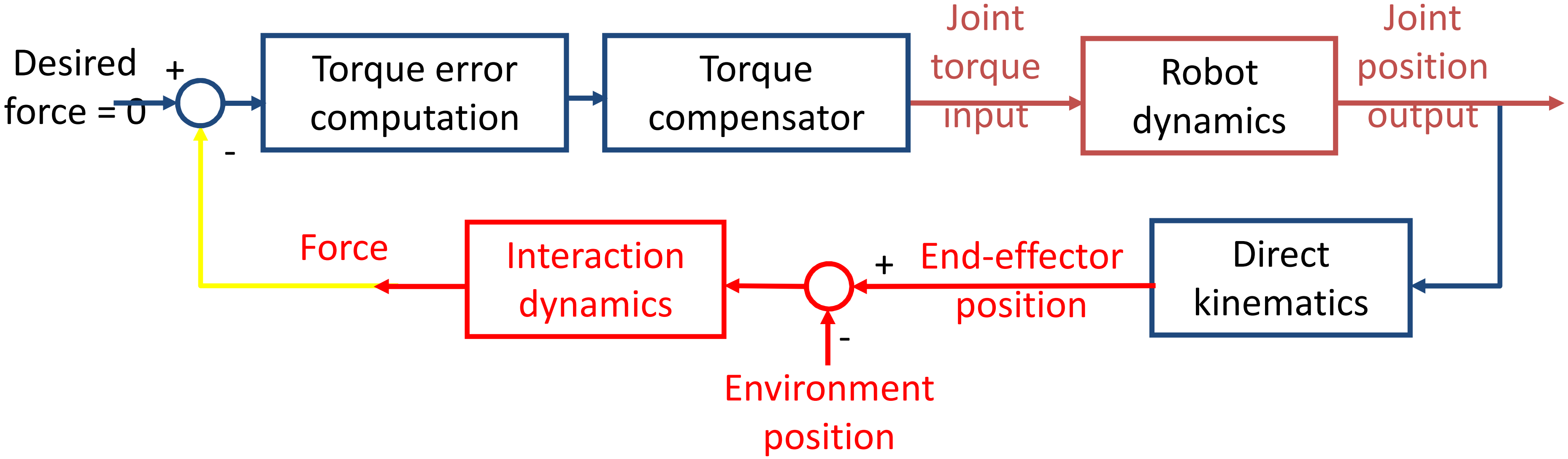
Passive Gain through handle foam

Inconditionally Passive Gain

I.4. Obtaining transparency through explicit (direct) force control

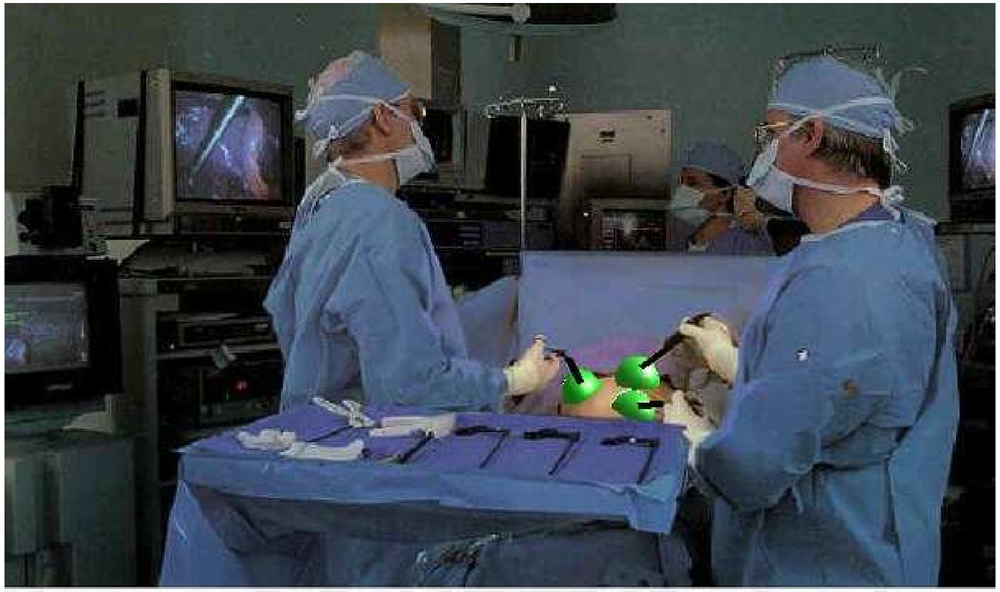
higher bandwidth than
indirect force control
⇒ reduced force
= increased transparency

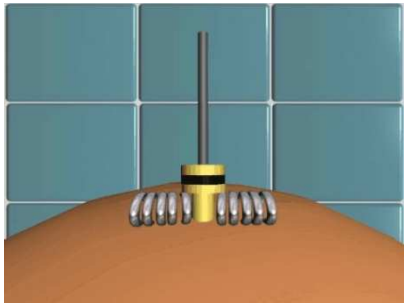


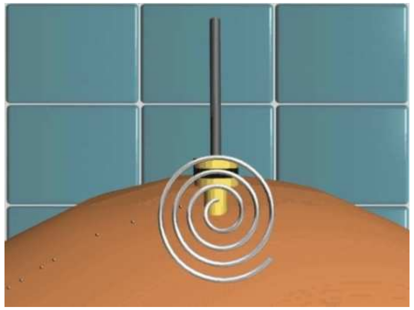

Desired force = 0
+
-
Torque error computation
Torque compensator
Joint torque input
Robot dynamics
Joint position output
Direct kinematics
End-effector position
+
-
Environment position
Interaction dynamics
Force

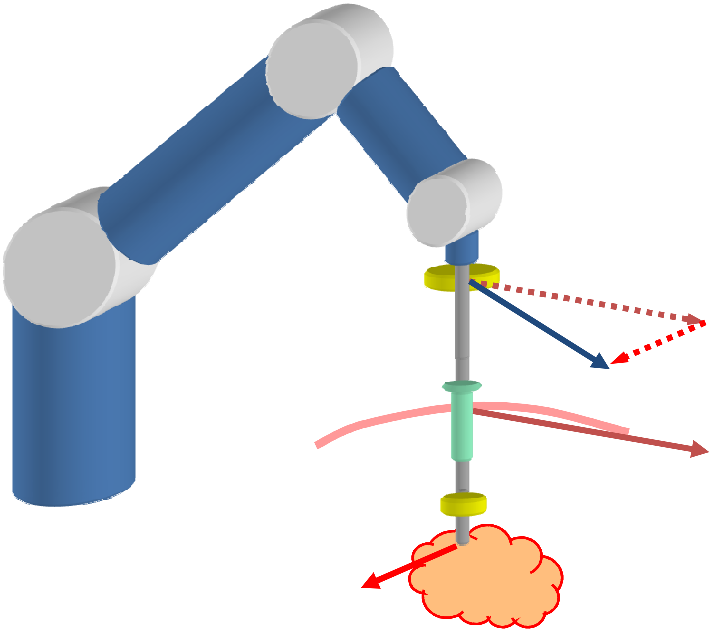
Example: transparent laparoscopic manipulation

1. Problem and objectives

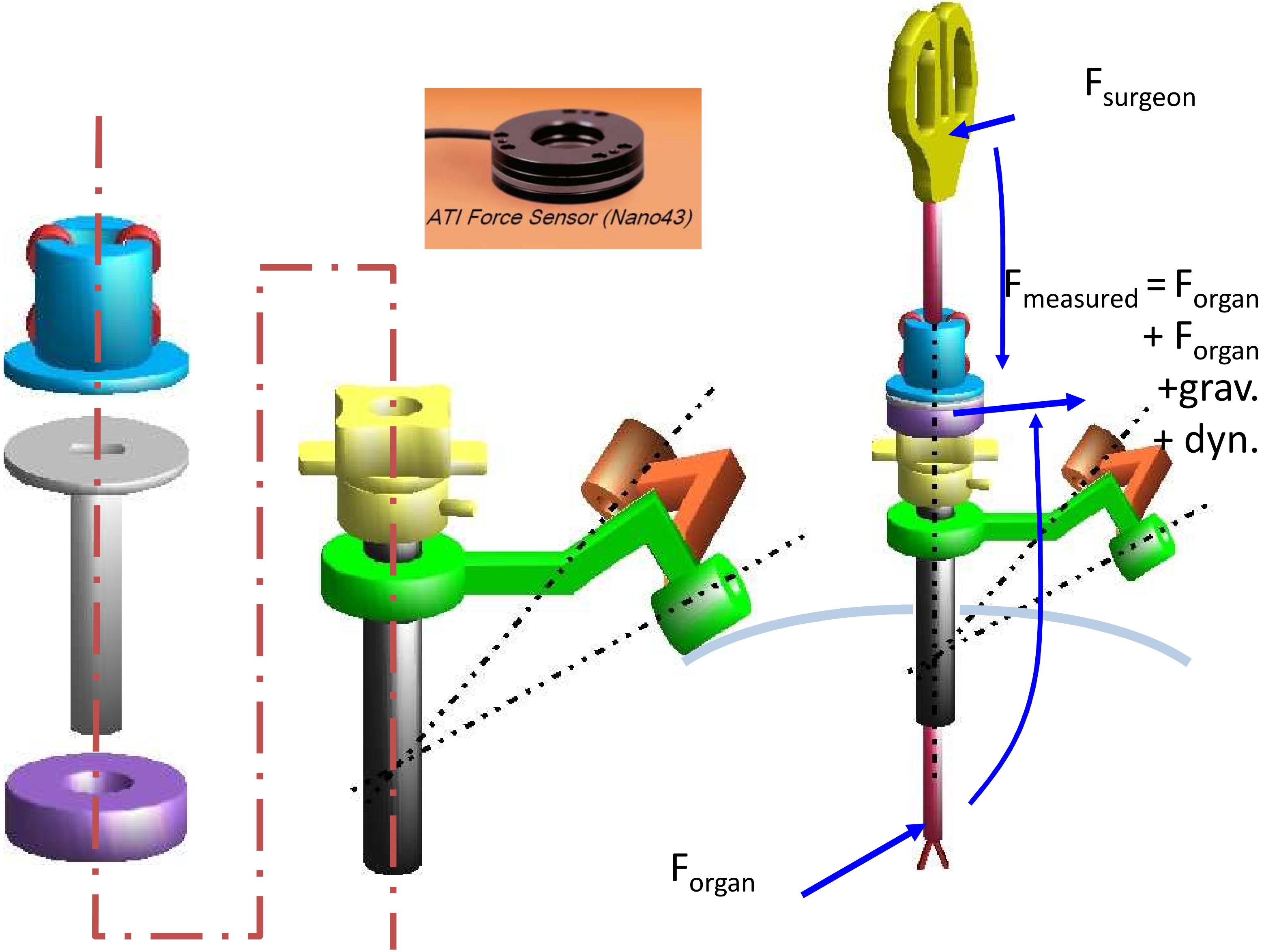








Mechatronic solution to measurement



ATI Force Sensor (Nano43)

A passive controller

TORQUE COMPENSATOR

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

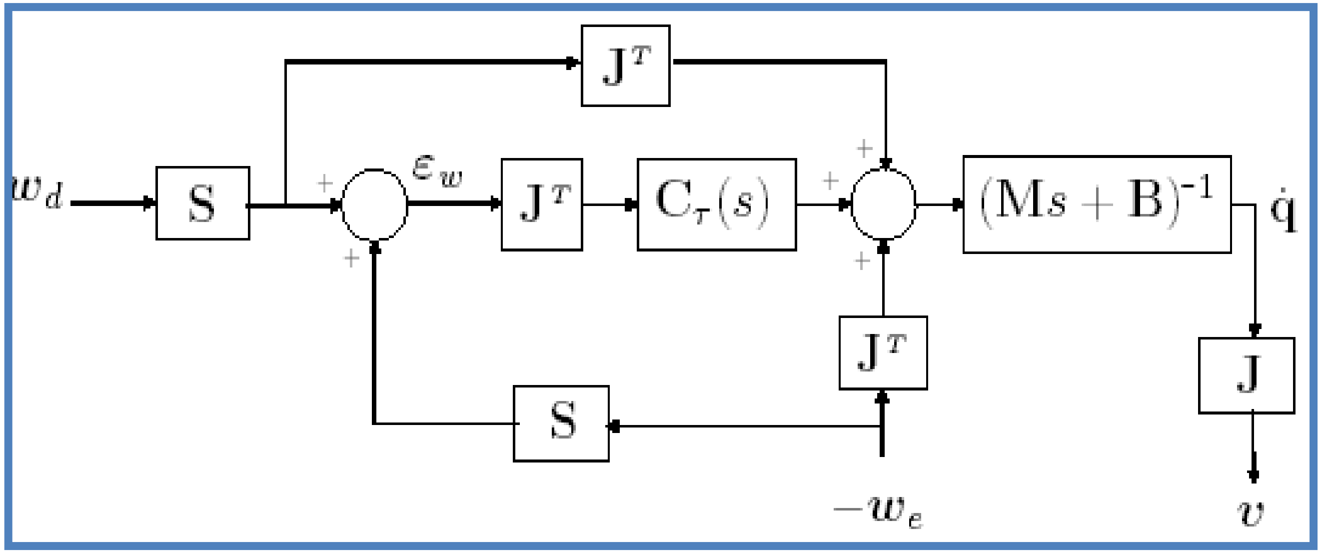
OUTPUT PORT ADMITTANCE

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

PASSIVITY CONDITIONS

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

$$\mathbf{SJ} = \mathbf{J}$$

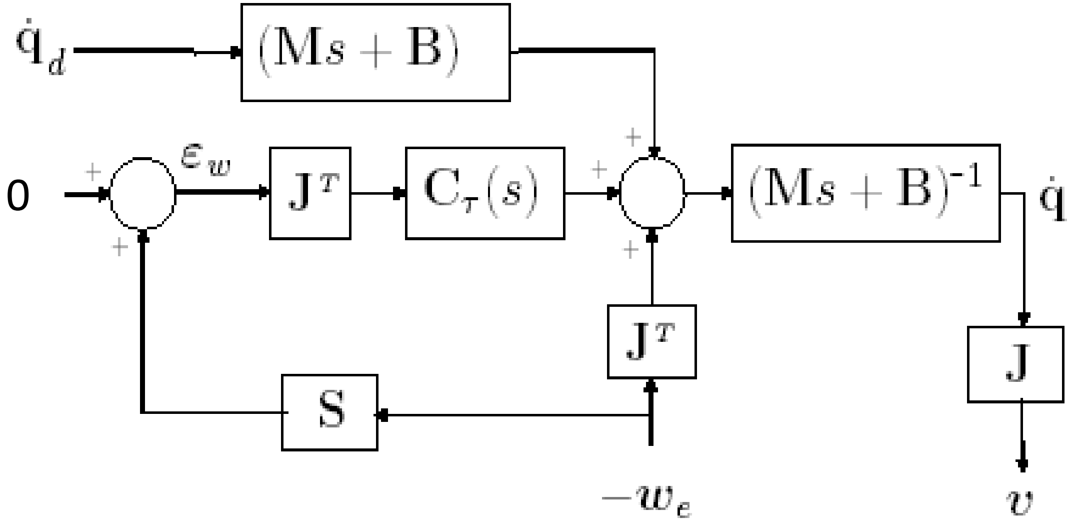


A video of MC²E.

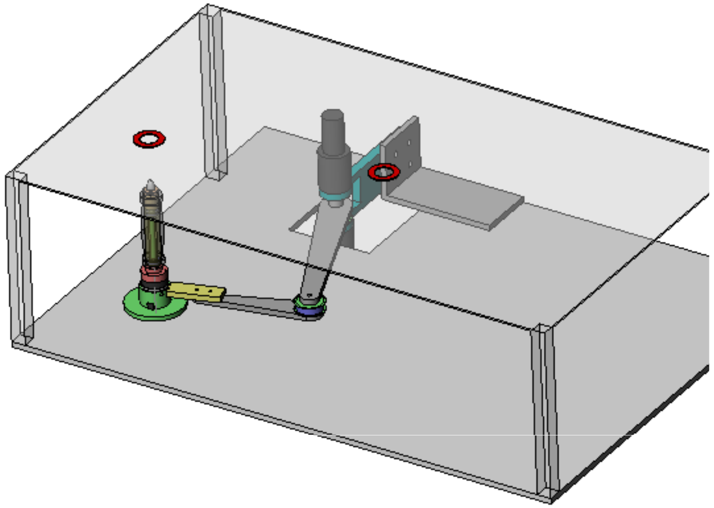
Credit: N. Zemiti.

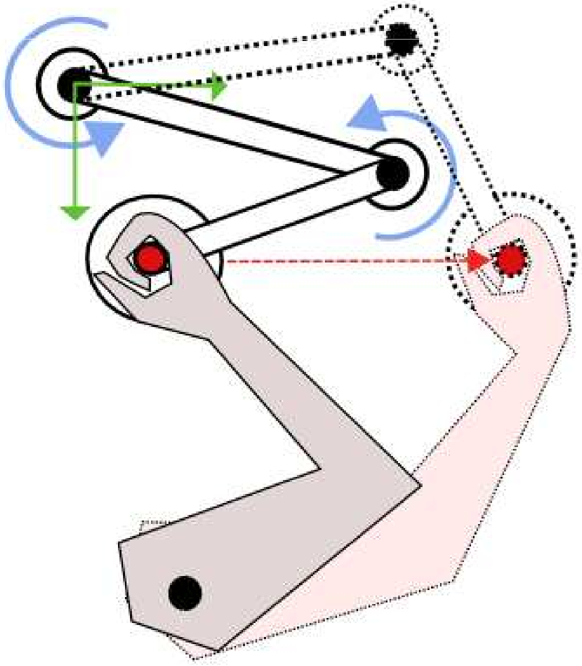
Accounting for human movement prediction with direct force control

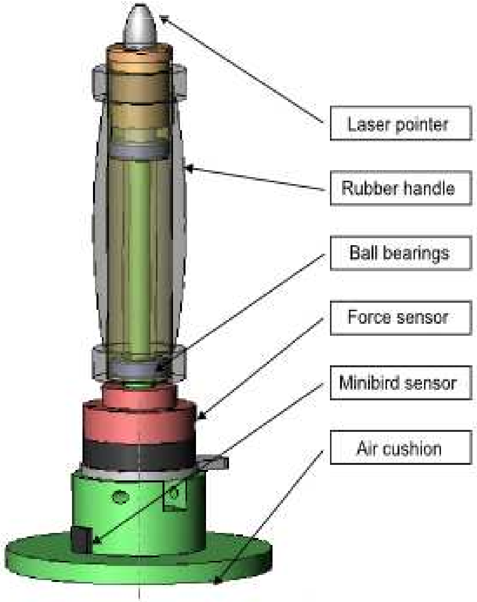
Assuming one has a prediction of the human movements, how to use it in a direct force control scheme ?



Accounting for human movement prediction with direct force control



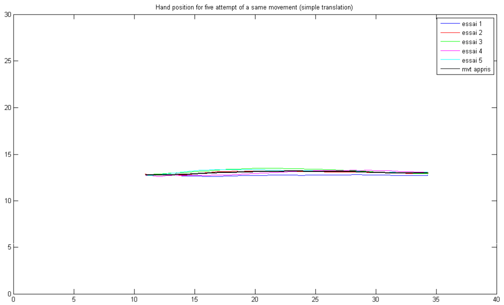


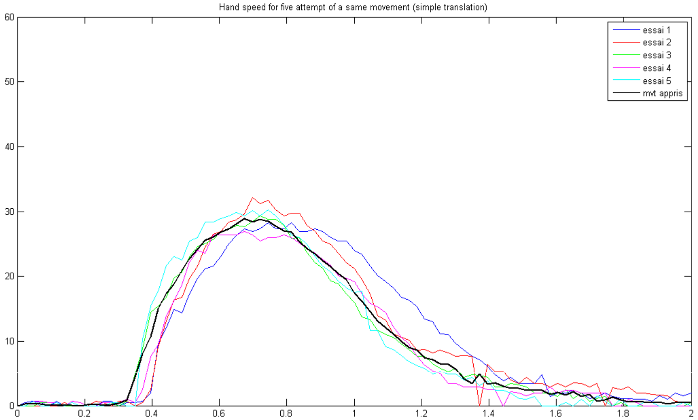


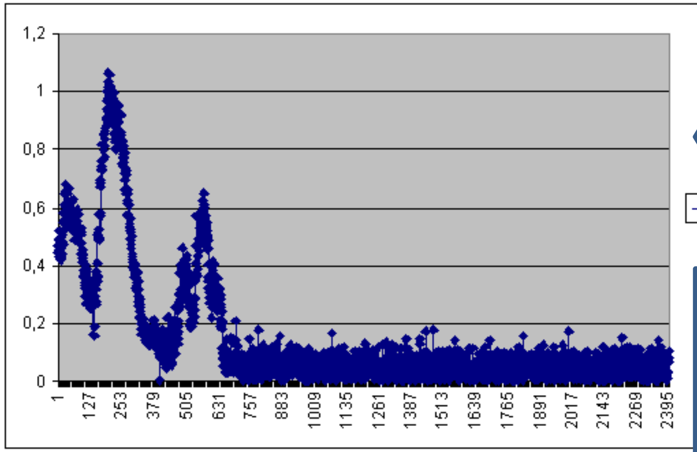
Credit: N. Jarrassé

Accounting for human movement prediction with direct force control

- First results

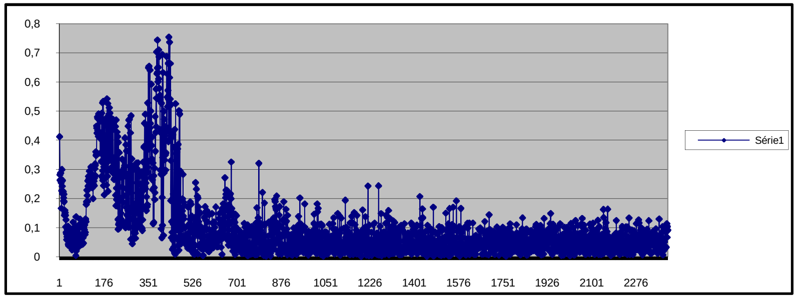






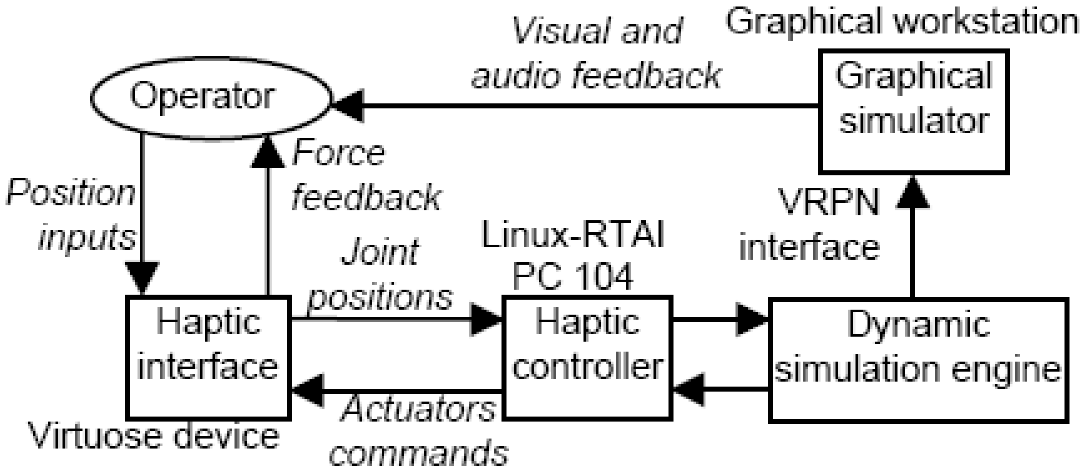
With force feedback only

With force feedback + Feedforxard



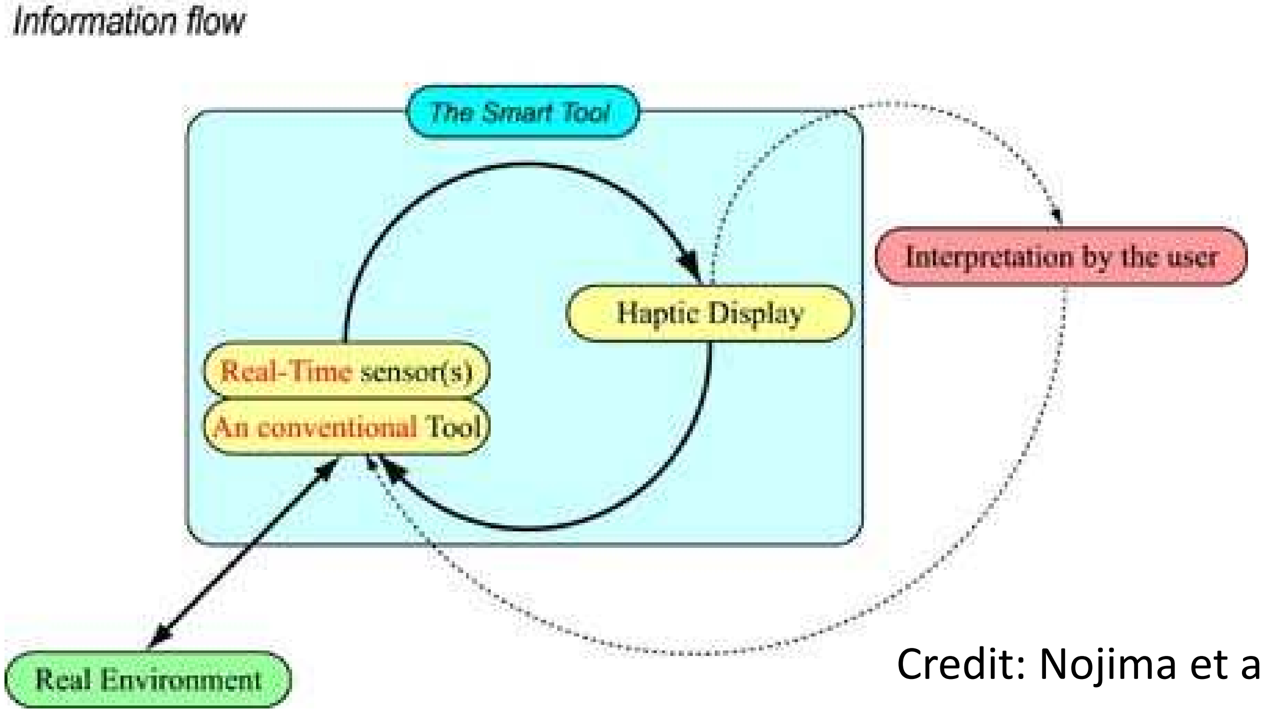
I.5. Geometrical guidance from a sensor-based reference

- 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

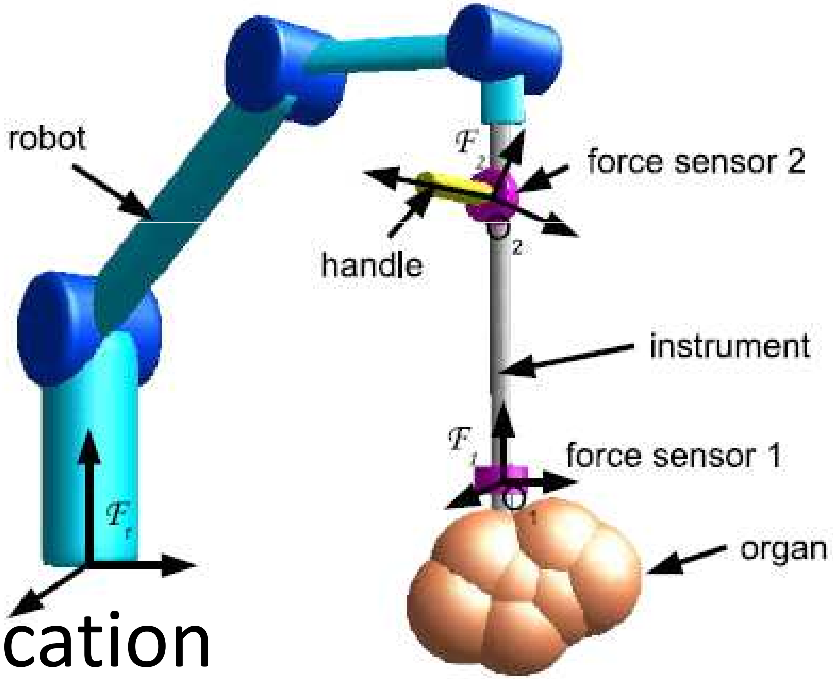
I.6. Force amplification

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

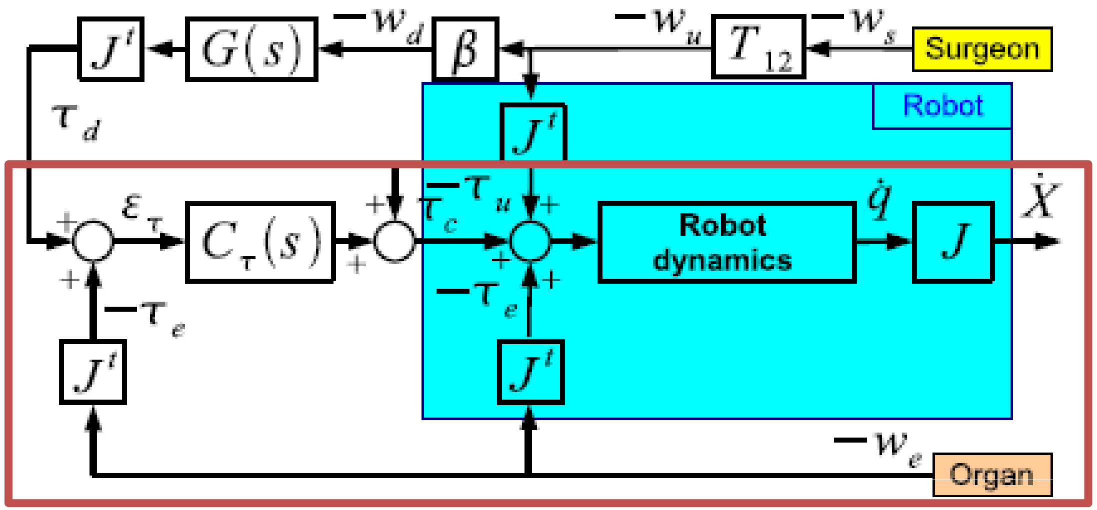
We want :

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

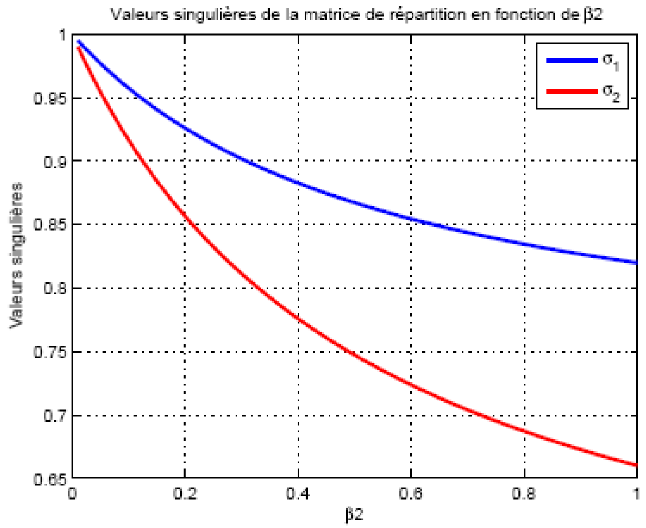
- Low β = high force amplification



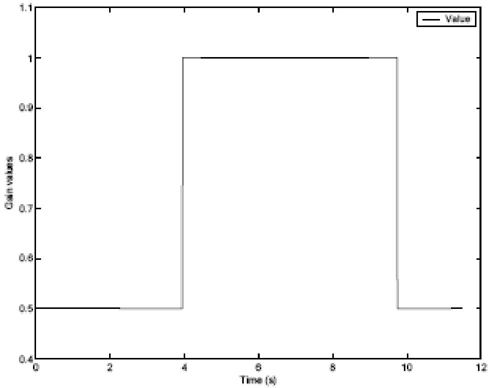
Control scheme

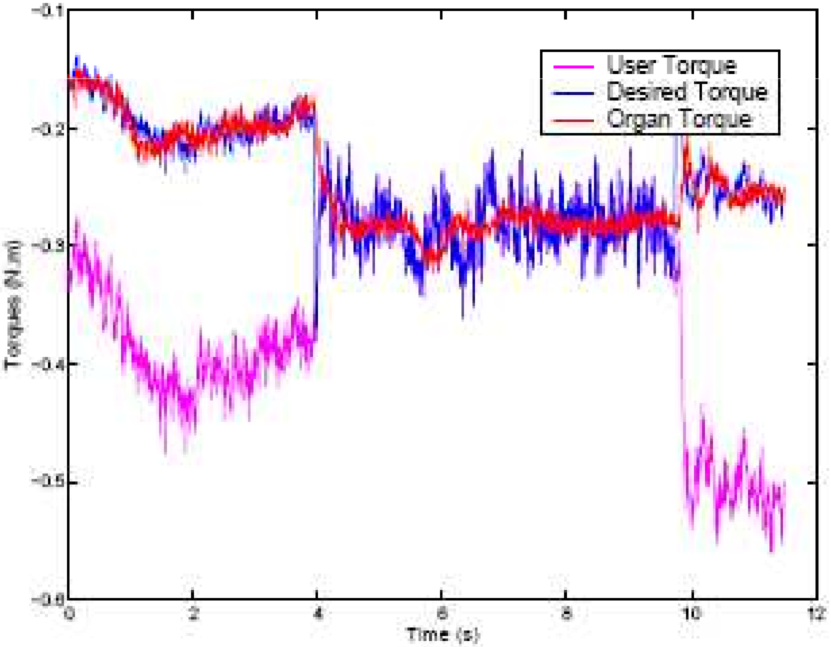


The passivity is kept even for β<<1



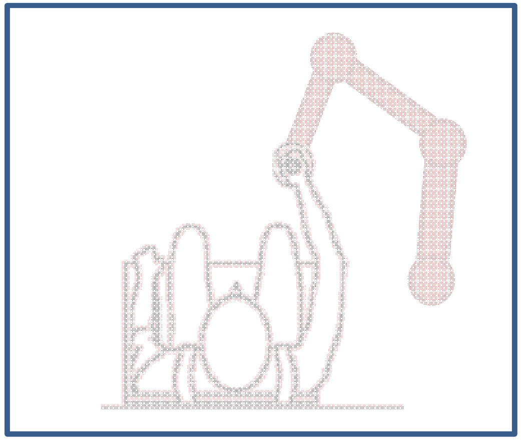
Results


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

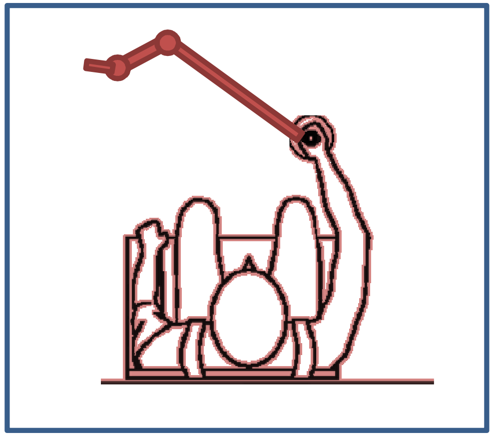

User Torque
Desired Torque
Organ Torque
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
Torques (N.m)
0
2
4
6
8
10
12
Time (s)

PART II: SERIAL COMANIPULATION

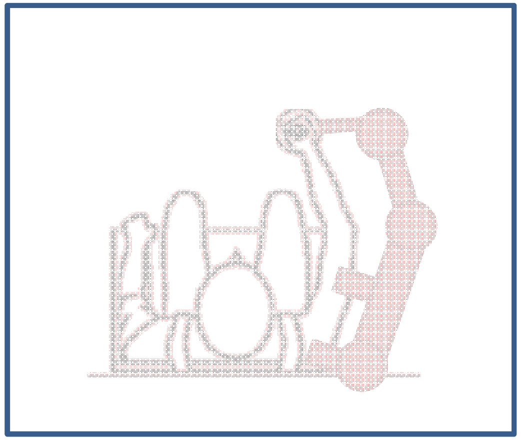
Parallel Comanipulation: summing operational forces



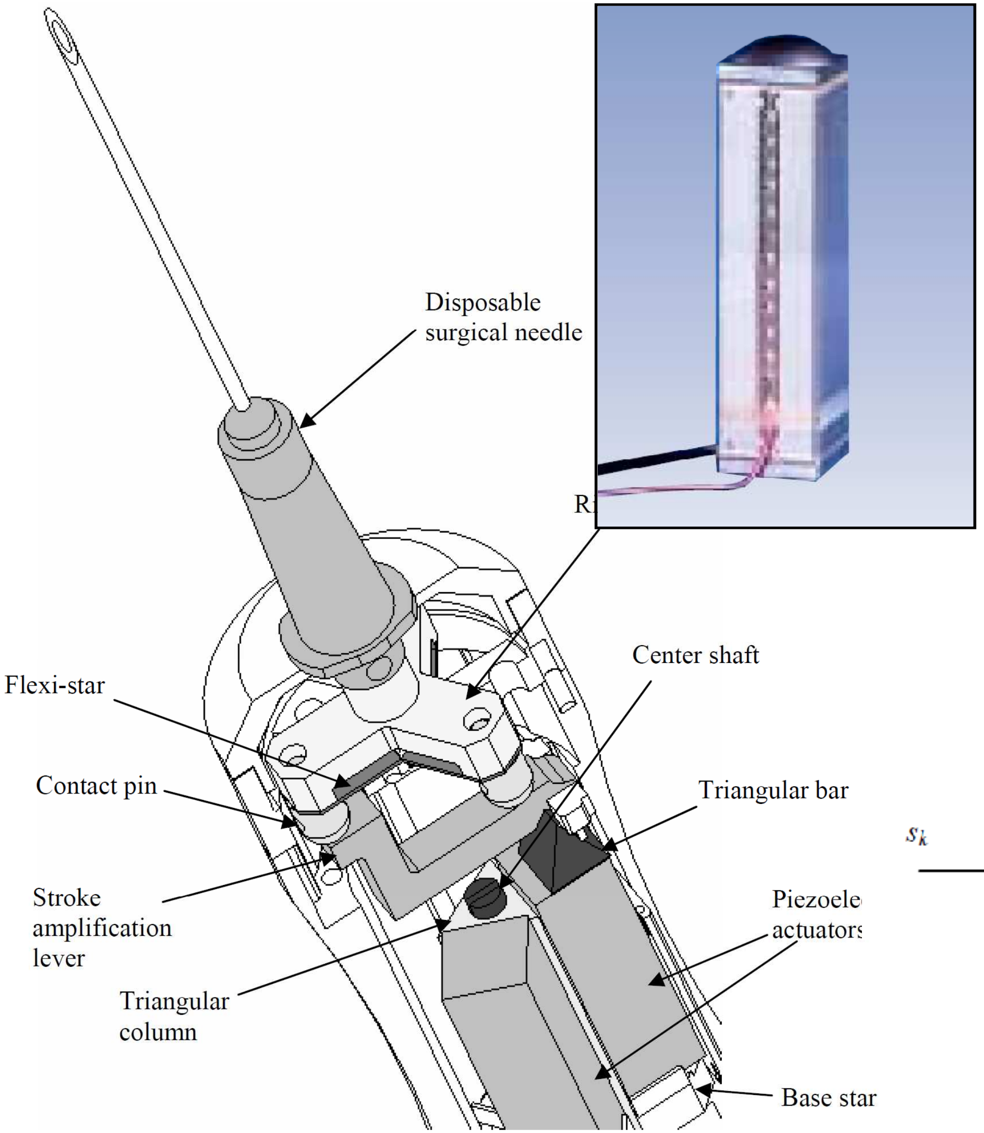
Serial Comanipulation: summing operationnal velocities

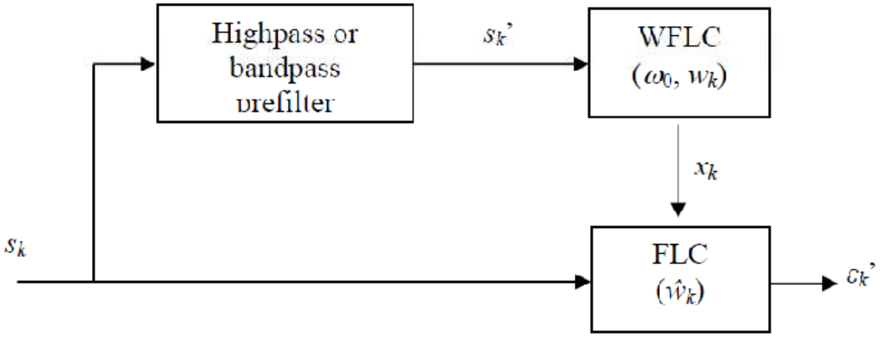


Orthotic Comanipulation : summing joint torques



II.1 Microsurgery

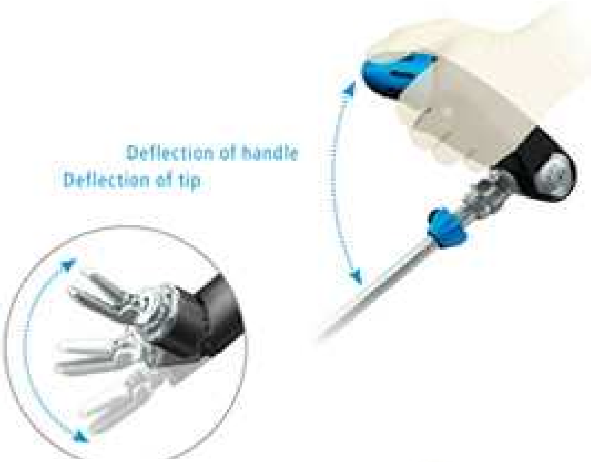

Disposable
surgical needle
Ri
Flexi-star
Center shaft
Contact pin
Triangular bar
Stroke
amplification
lever
Piezoele
actuators
Triangular
column
Base star


Highpass or
bandpass
prefilter
s_k'
WFLC
(ω_0, w_k)
x_k
s_k
FLC
$(\hat{w}_k)$
ε_k'

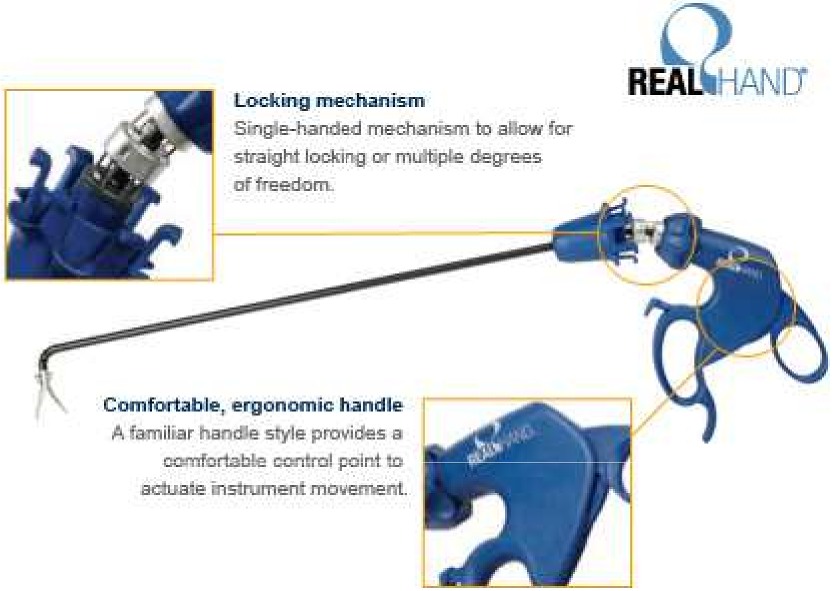
Exploiting external sensors

- Using fast visual servoing to stabilize the tip
- Problem: drift/range of motions
- Solution: visual clues (ICRA2009 video)

II-2 Laparoscopic surgery

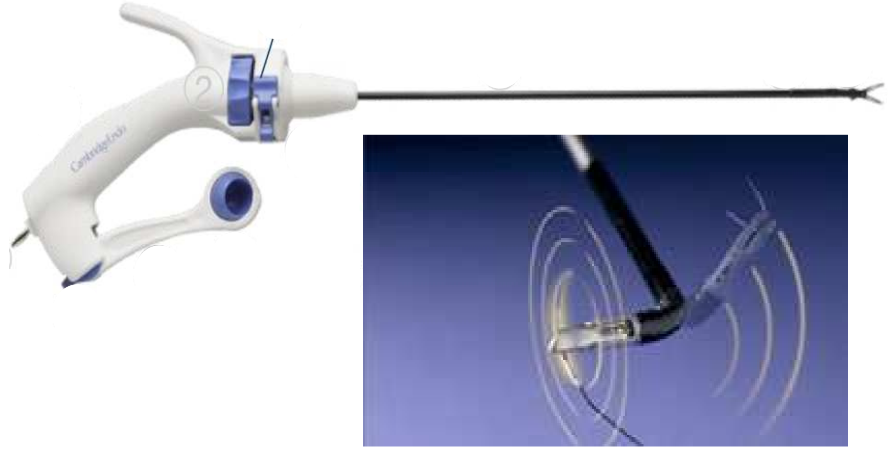


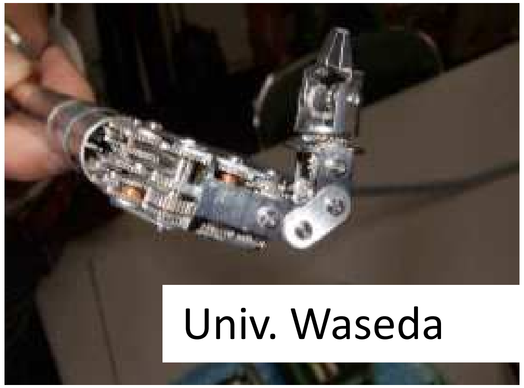
RADIUS



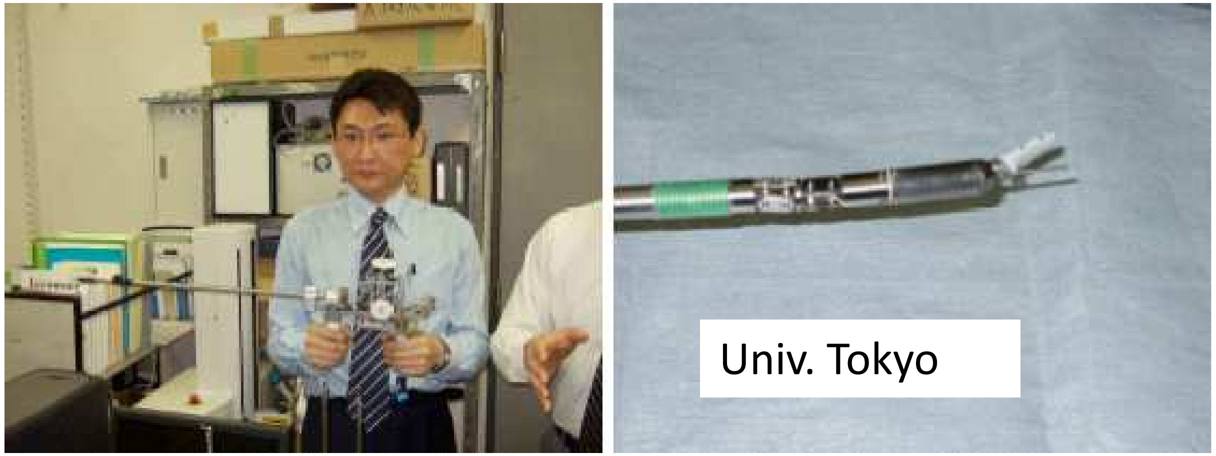
Locking mechanism
Single-handed mechanism to allow for straight locking or multiple degrees of freedom.

Comfortable, ergonomic handle
A familiar handle style provides a comfortable control point to actuate instrument movement.

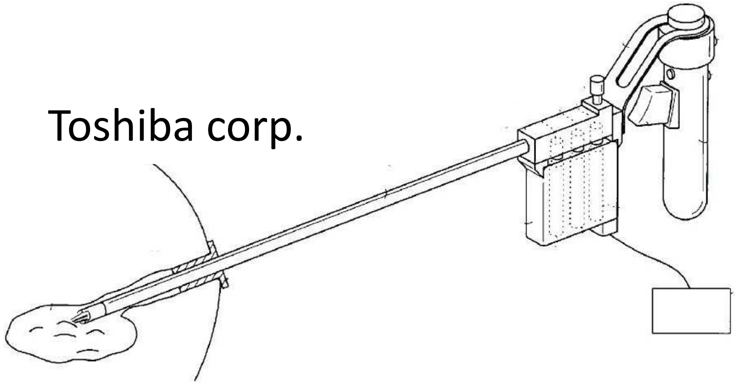




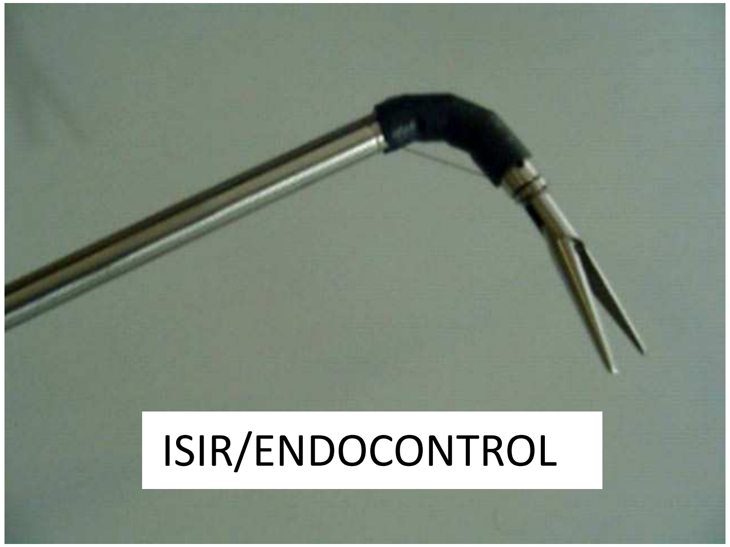
Univ. Waseda



Univ. Tokyo



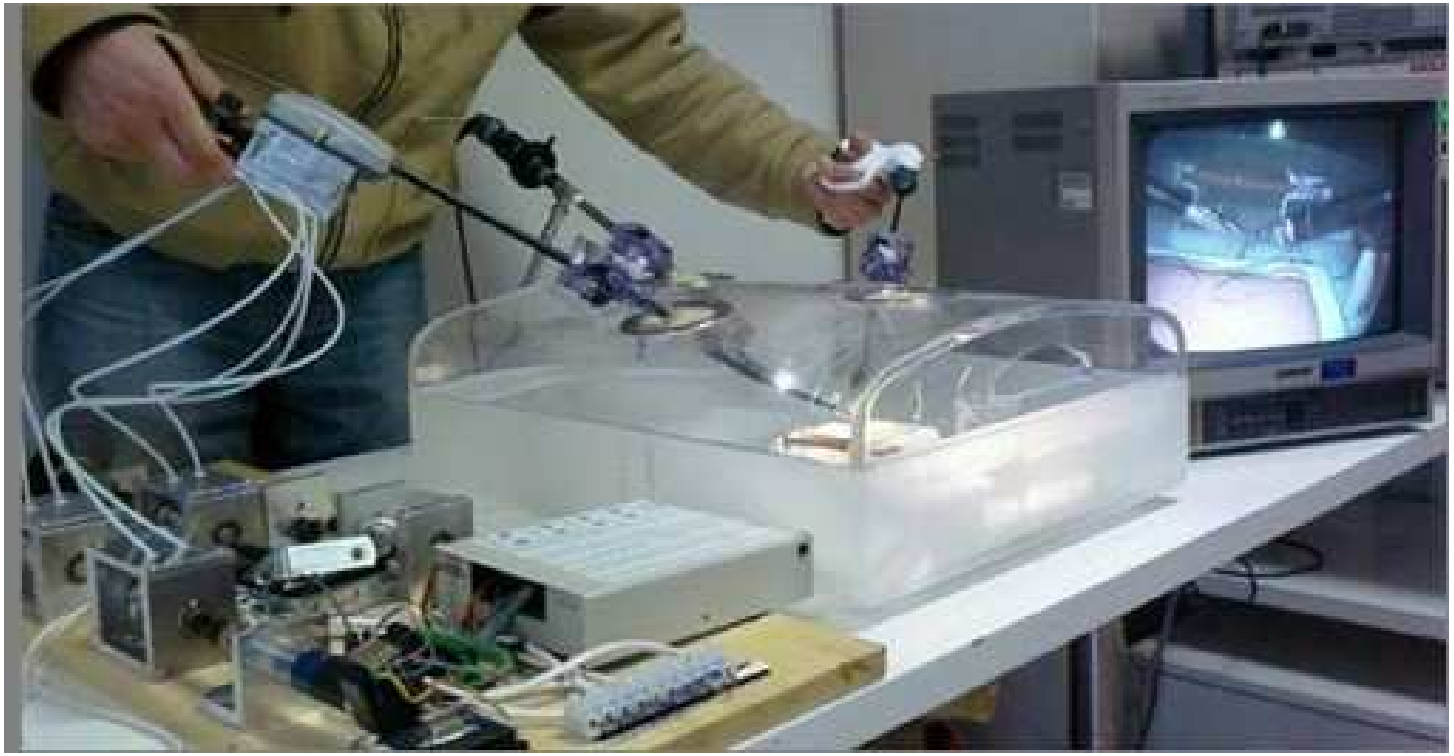
Toshiba corp.



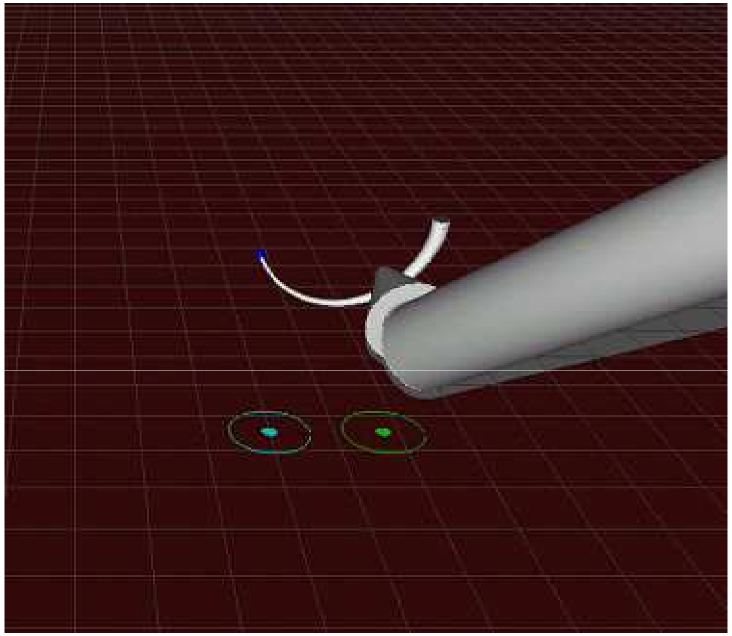
ISIR/ENDOCONTROL

Pictures from : La robotique chirurgicale au Japon, http://www.bulletins-electroniques.com/rapports/smm08_047.htm
Authors: DOMBRE Etienne - GANGLOFF Jacques - MOREL Guillaume - POUCHELLE Marie-Christine

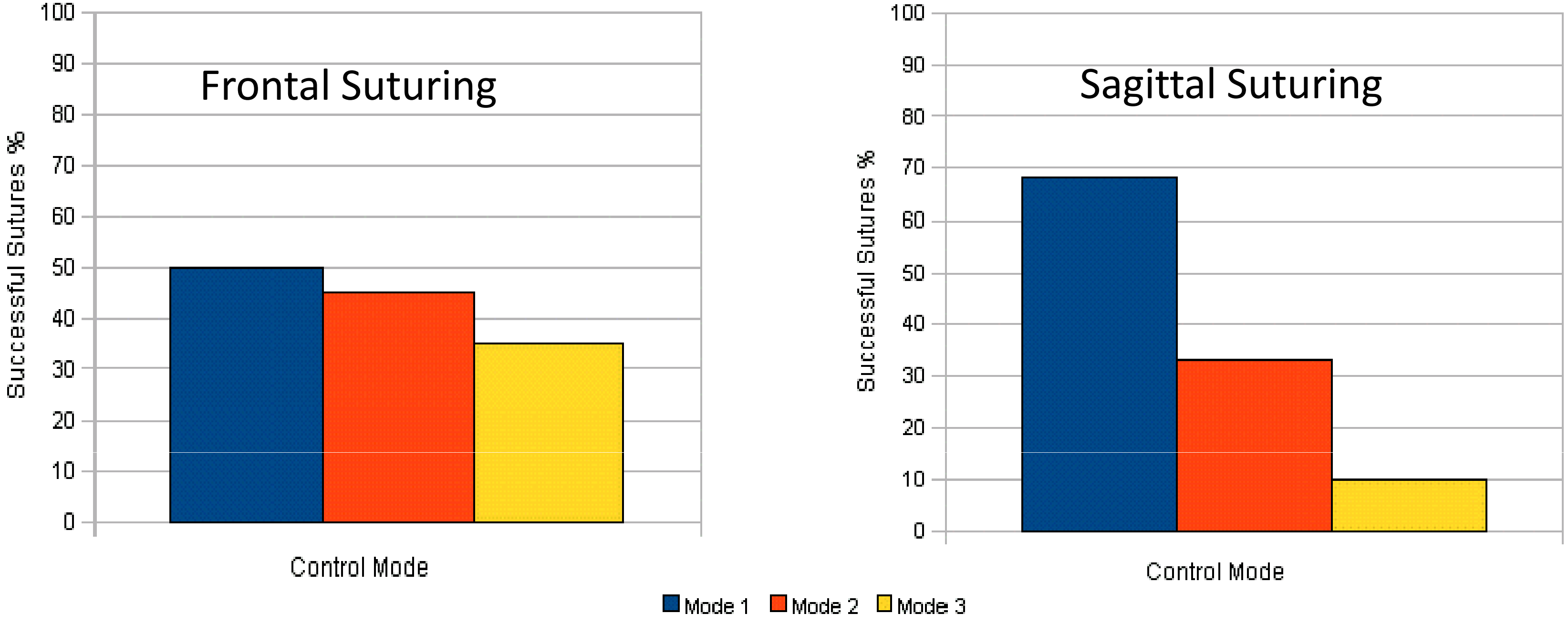
An experiment with daVinci instruments in Pisa



Ongoing work (ALI): evalulating control modes

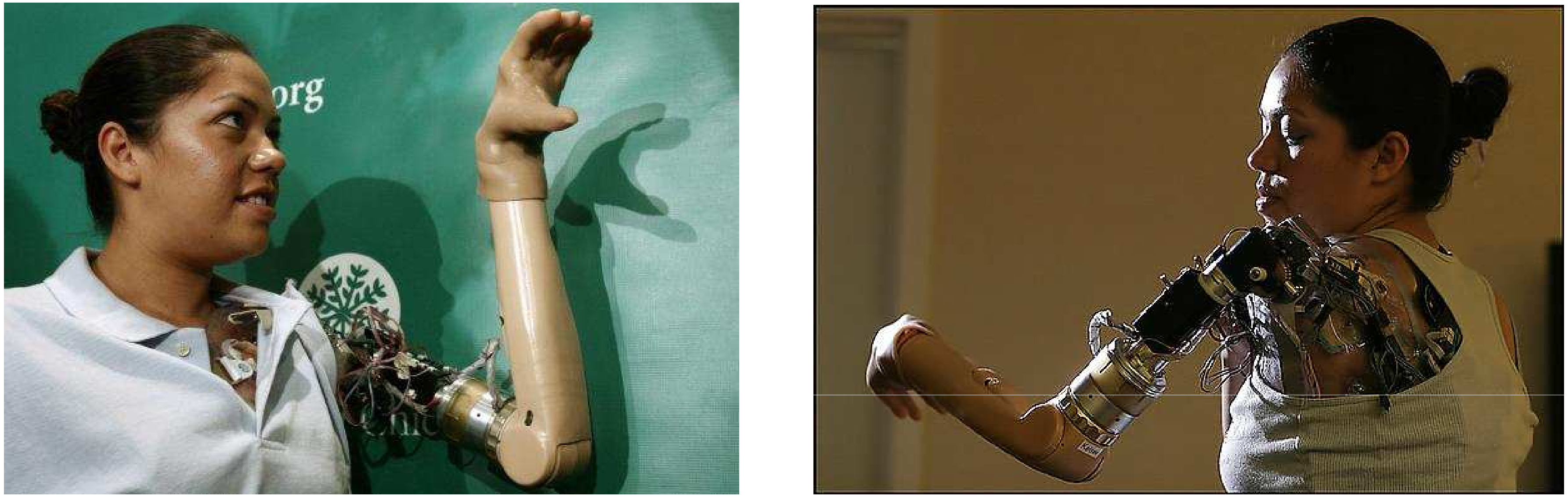


Preliminary results



- Mode 1: inverse coupling between the handle's orientation and the end effector's orientation. The end effector's orientation can also be locked.
- Mode 2: inverse coupling like in mode 1. But the end effector's orientation can not be locked.
- Mode 3: direct coupling between the handle's orientation and the end effector's orientation. The end effector's orientation can not be locked.

II.3Towards prosthetics

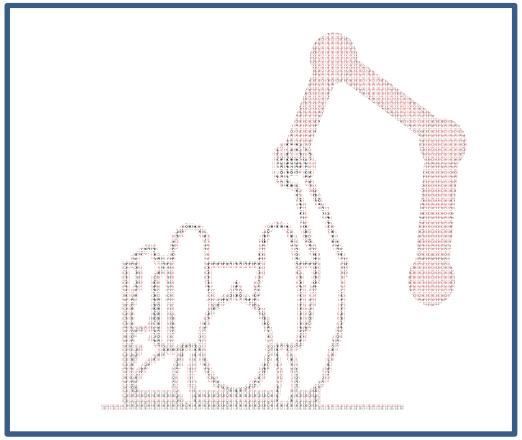


- Connect nerve termination of the missing arm in the pectoral muscles
- Use surface electrodes to interface with them
- Both motor and sensing capabilities are recovered
- Learning is very long.

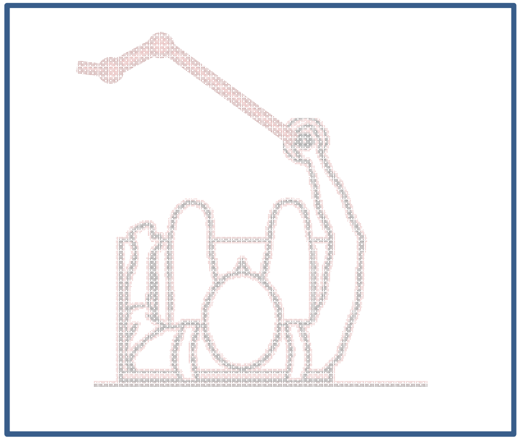
Chicago Institute of Rehab.

PART III: ORTHOTIC COMANIPULATION

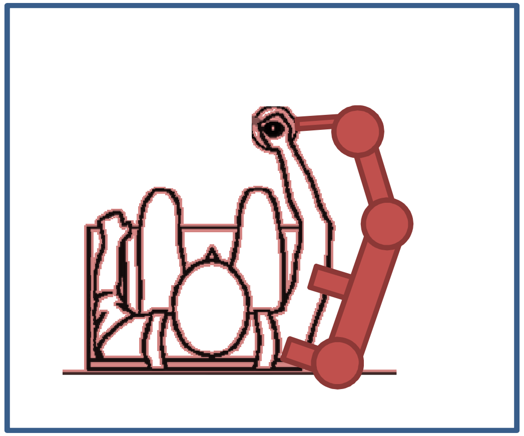
Parallel Comanipulation: summing operational forces



Serial Comanipulation: summing operationnal velocities



Orthotic Comanipulation : summing joint torques



Upper limb rehabilitation exoskeletons


ARMinII


Rupert


MAHI


L-Exos


Washington Univ.


iMoveReacher

ABLE exoskeleton (CEA List)

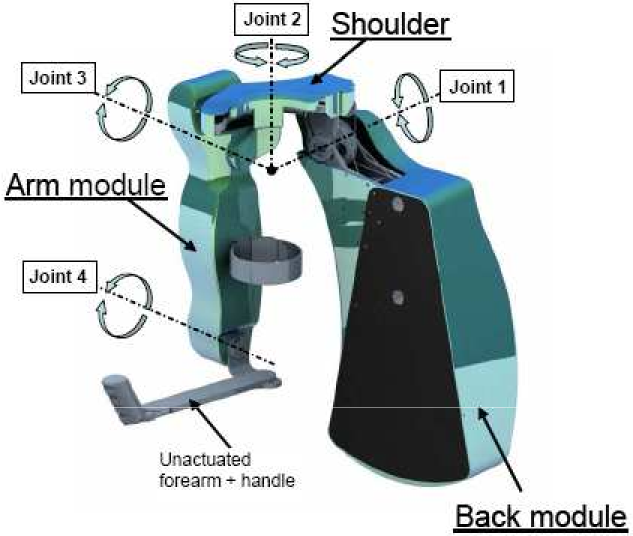
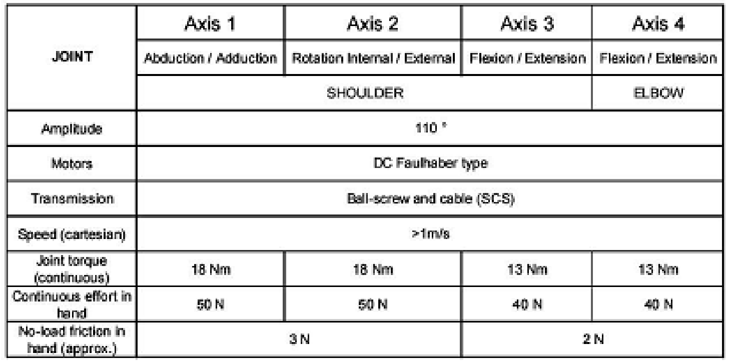


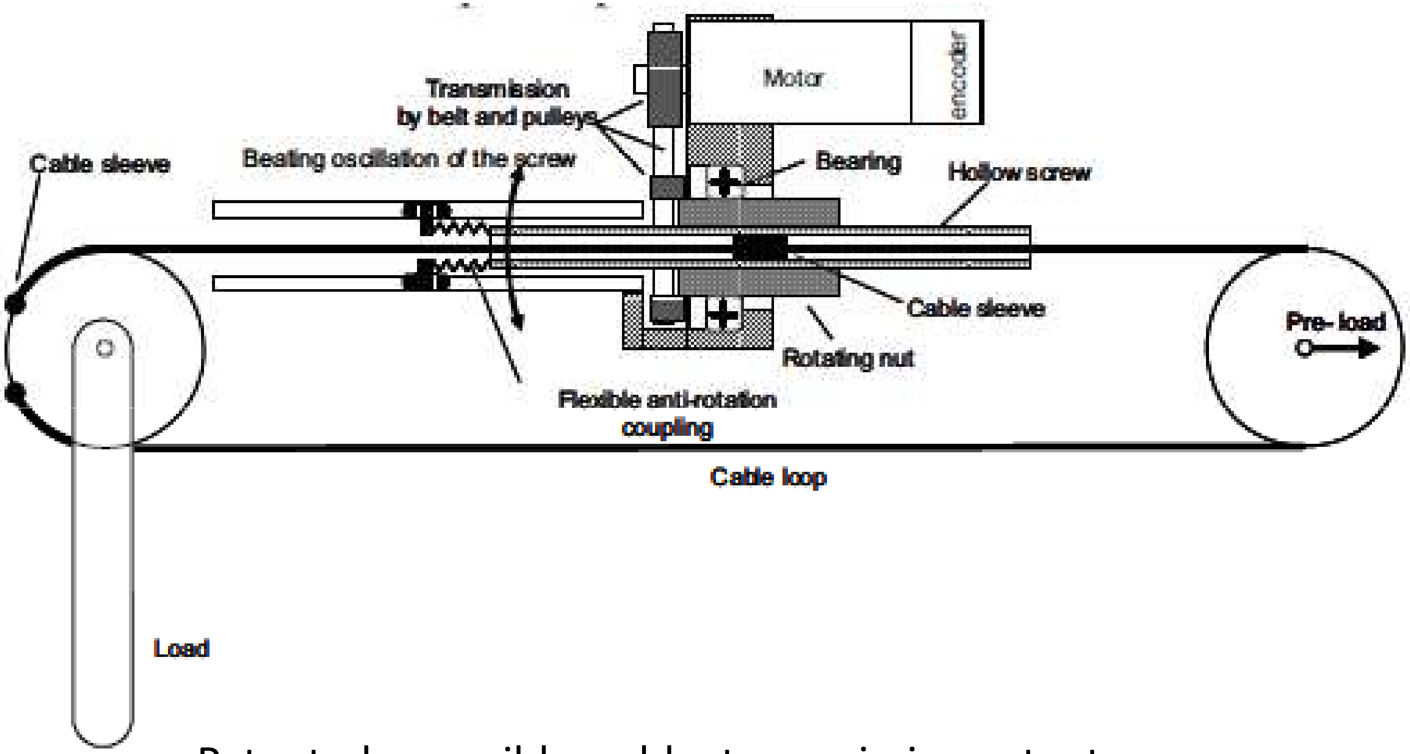
Fig 6. General view of ABLE



JOINT	Axis 1	Axis 2	Axis 3	Axis 4
	Abduction / Adduction	Rotation Internal / External	Flexion / Extension	Flexion / Extension
	SHOULDER			ELBOW
Amplitude	110 °			
Motors	DC Faulhaber type			
Transmission	Ball-screw and cable (SCS)			
Speed (cartesian)	>1m/s			
Joint torque (continuous)	18 Nm	18 Nm	13 Nm	13 Nm
Continuous effort in hand	50 N	50 N	40 N	40 N
No-load friction in hand (approx.)	3 N		2 N	

Joint	% of human range
1. Abduction	50%
2. Shoulder Rotation	76%
3. Flexion/extension	61%
4. Elbow flexion	80%

ABLE exoskeleton (CEA List)



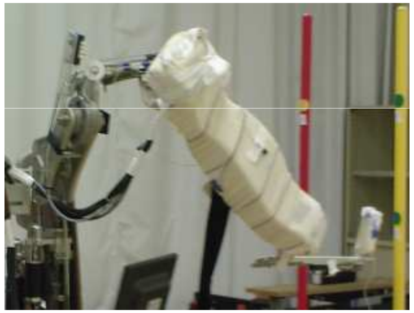
Patented reversible cable transmission actuator

- High transmission ratio
- Reduced friction
- High reversibility

ABLE exoskeleton (CEA List)

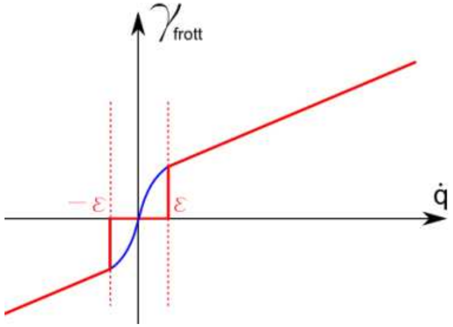
Control:

- Exploits incremental encoder only
- Orthosis gravity compensation



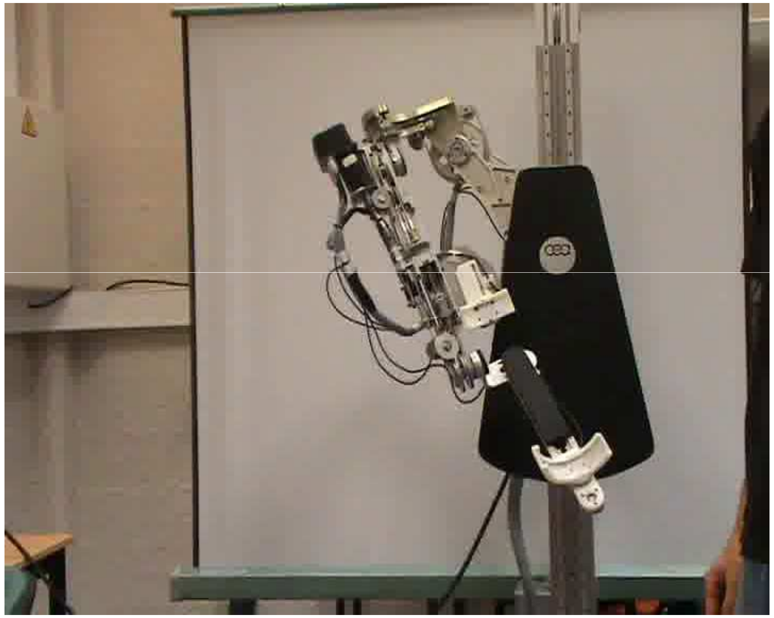
$$\Gamma_{Masse,\ i} = \sum_{j=i}^{4} \left(\overrightarrow{G_j O_i} \times m_j \vec{g}\right) . \vec{z}_i$$

- Simplistic friction model

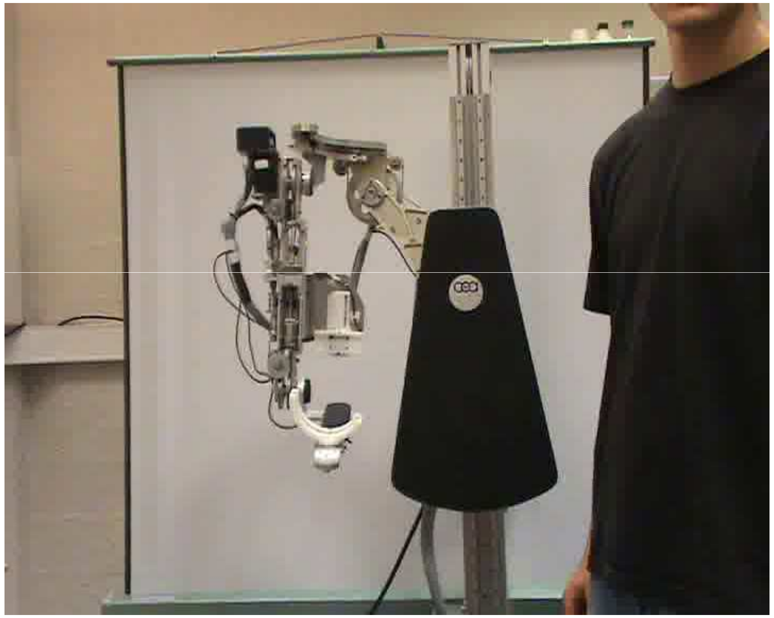


$$\Gamma_{frottement,\ i} = a_i * sgn(\dot{\theta}_i) + b_i * \dot{\theta}_i + c_i$$

ABLE exoskeleton (CEA List)

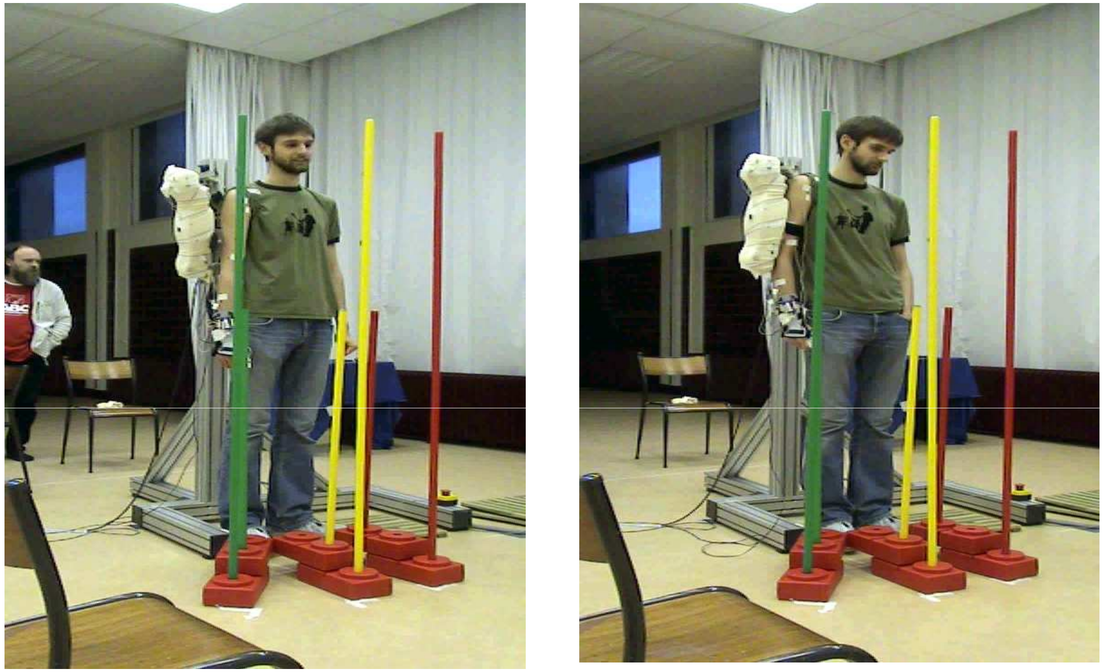


Gravity compensation only



Gravity + friction compensation

Preliminary evaluations



Subjects with similar morphology were chosen. Randomized pointing of 3D targets:

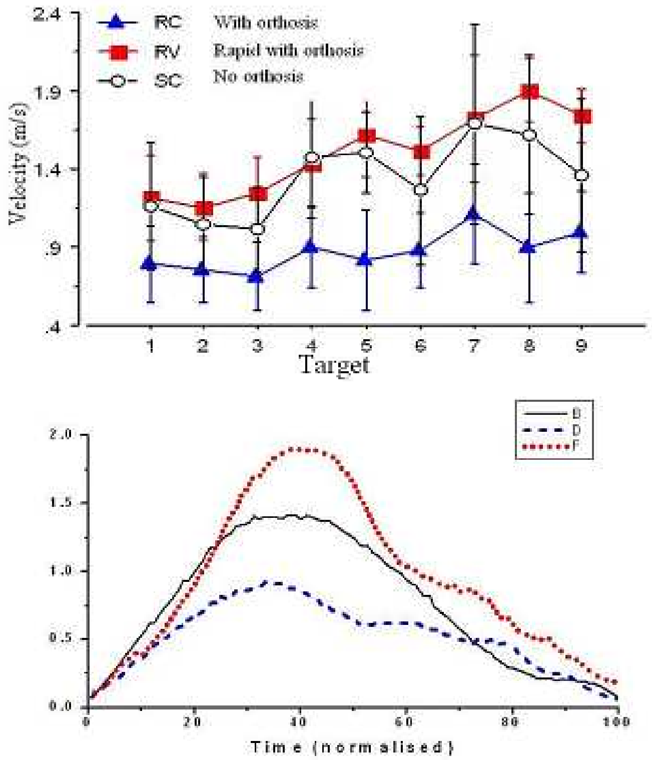
- Without robot (without speed indication)

- With robot (without speed indication)

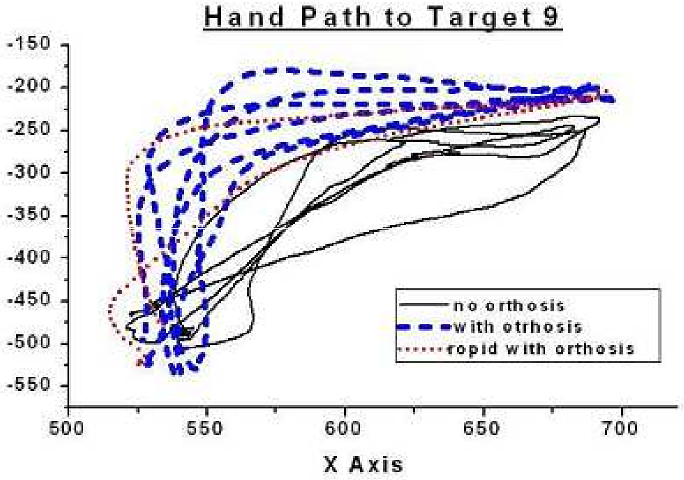
- With robot (with speed indication)

Preliminary evaluations

Speed profiles analysis



Path analysis



Important movement alteration with the exoskeleton

What is missing at this stage that could increase transparency?

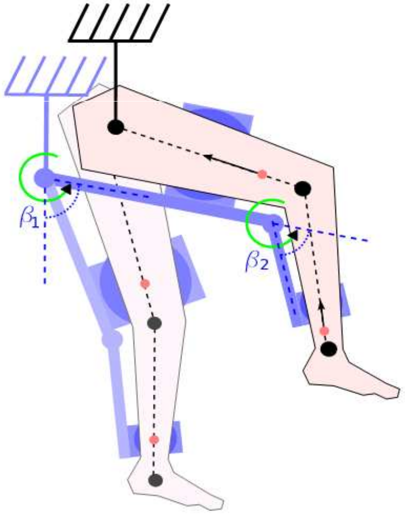
⇒ **The kinematics of the two chains do differ.**

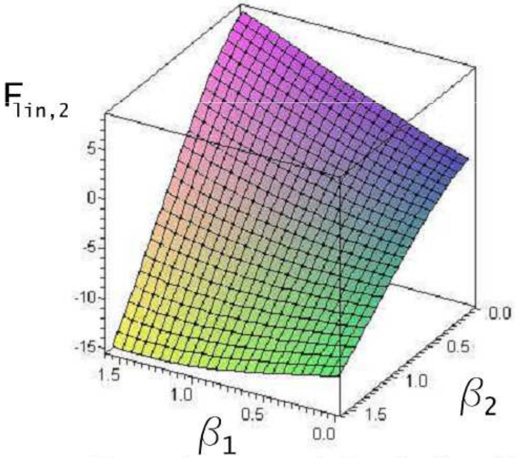
- **By definition, exoskeleton kinematics is aimed at imitating those of the human member.**
- Most published research focuses on designing the kinematics of the exoskeleton and on the technical problem of actuation.
- Some of the existing designs are rather complex in order to reproduce as well as possible the human kinematics.
- However:
  - **Complexity of human joint kinematics** resulting from bone local geometry
  - **Intra subject large variability** in geometrical parameters
  - **Matching** between human joint axis instantaneous axis of rotation and exosqueleton axis of rotation is **hard to obtain**.

Why is this a problem?

- Is this kinematic mismatch a problem?

⇒ Yes, because **either no motion is possible, or forces appear** at the fixations.





Linear Force generated on fixation n°2

- Is the appearance of forces at the fixations a problem?

⇒ Yes, because **transparency** is required.

Defining a new approach

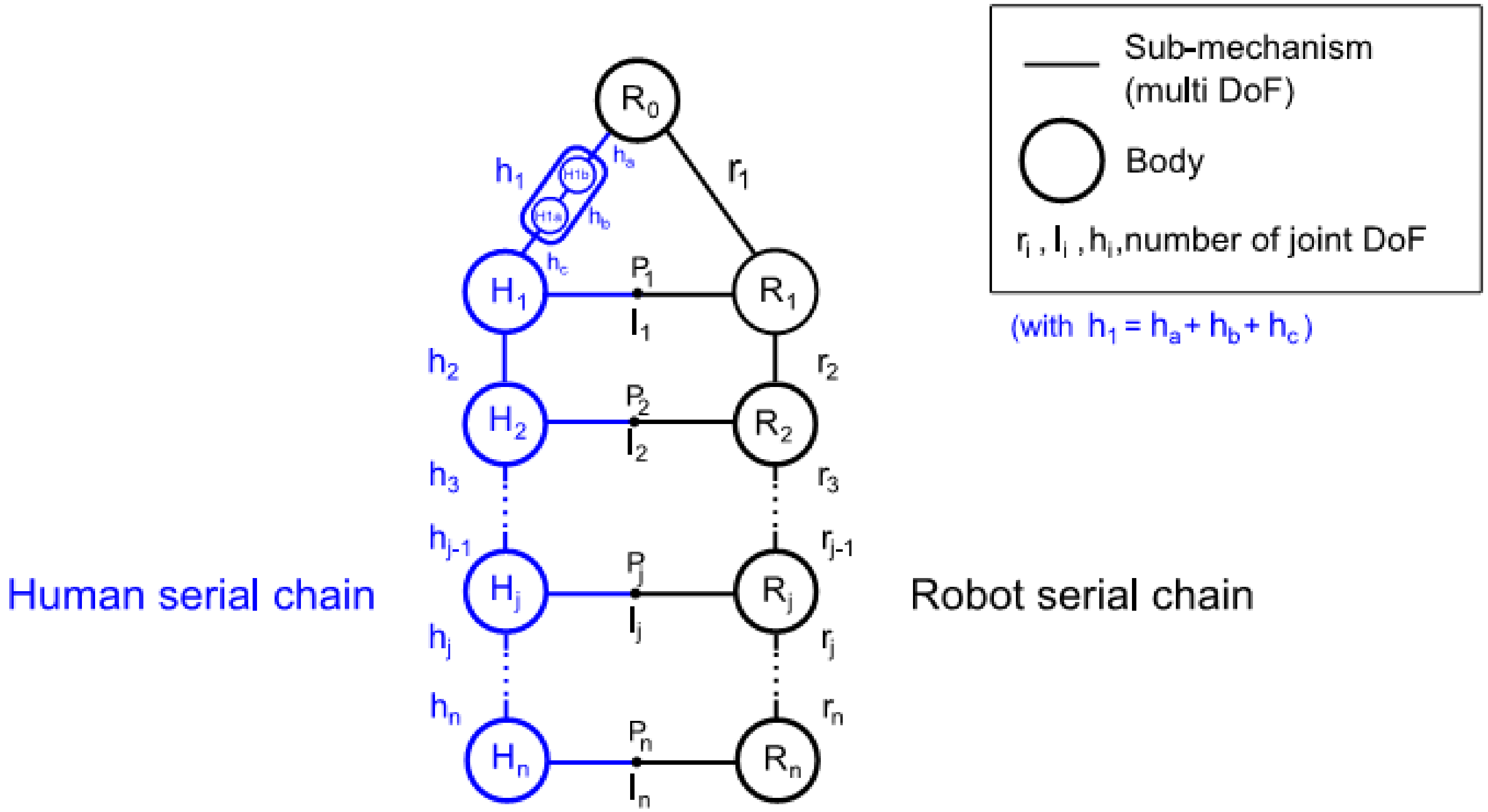
1. We **quit searching perfect match** between the two kinematic chains: **it’s a no-can-do**.
2. We focus on the **force transmission problem**: what are the forces that are controllable?

   ⇒ Statics point of view
3. Given an orthosis kinematics (similar to the human member kinematics), how can we attach it to the human member ?

   ⇒ Fixations design

⇒ A general method to **design fixations with passive DOFs** for coupling a human member with an orthosis

Studied problem

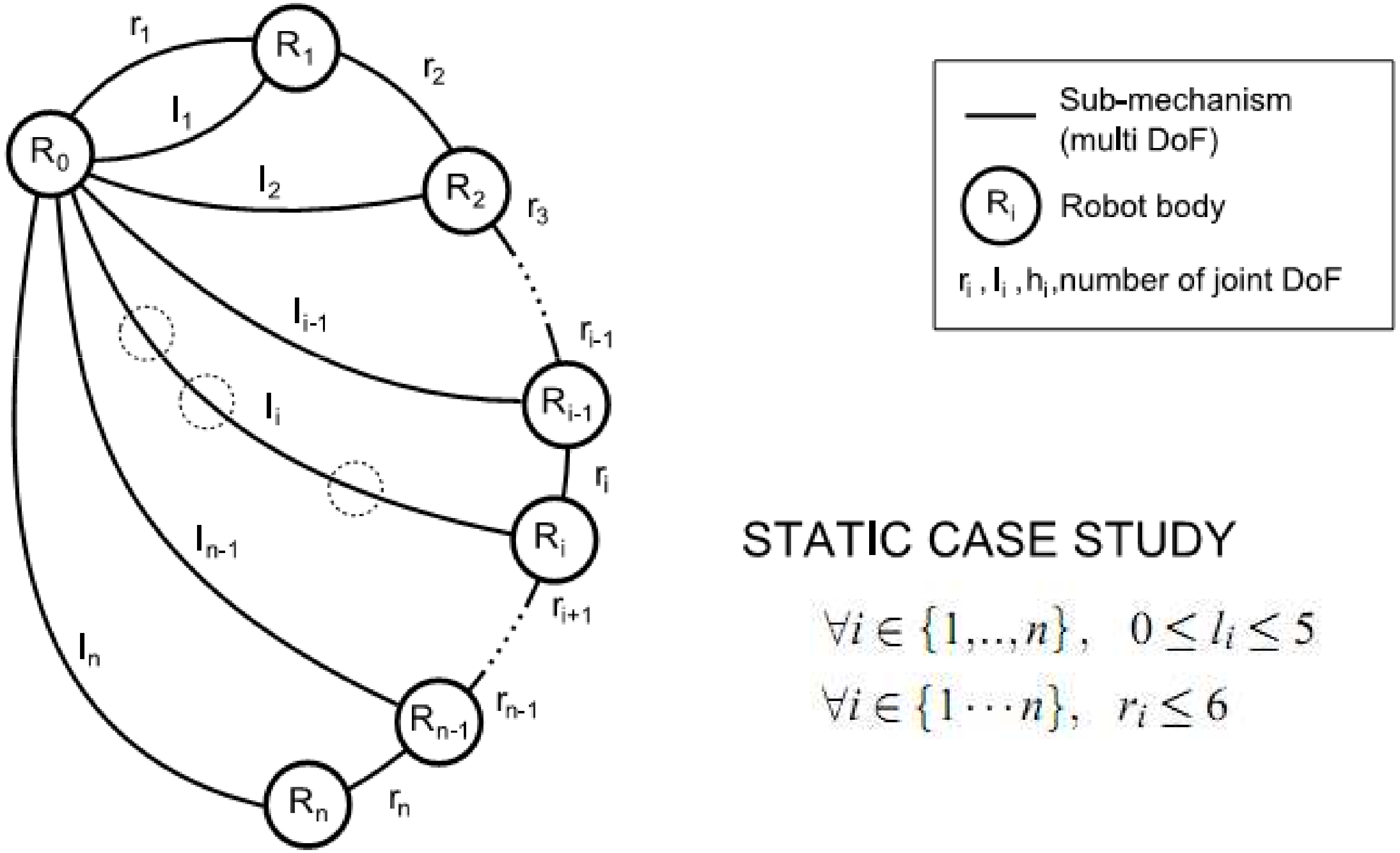


TYPICAL CASE STUDY

Schematic of two serial chains parallel coupling

Statics formulation

The human body is supposed to stay still



STATIC CASE STUDY

$$\forall i \in \{1,..,n\}, \quad 0 \leq l_i \leq 5$$

$$\forall i \in \{1 \cdots n\}, \quad r_i \leq 6$$

Important notice : it's a recursive structure

Preventing hyperstaticity

Goal : to select DoF in **Li** with i ∈ {1, ..,n} in such a way that there is

- no uncontrollable forces generated by the exoskeleton on the human limb
- no possible motion for the exoskeleton when the human limb is still.

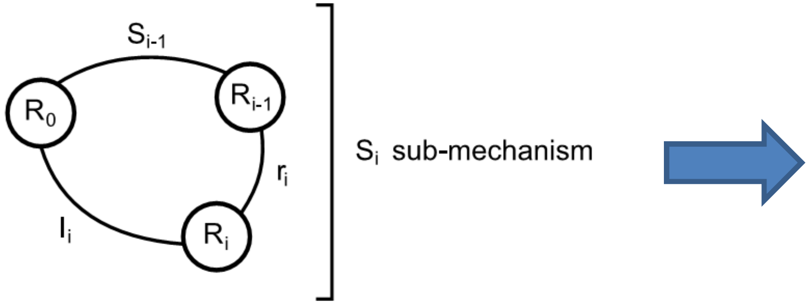
$$\boxed{\begin{array}{ll} \forall i \in 1 \cdots n, \quad {}^{S_n}T_i = 0 \quad & and \\ \forall i \in 1 \cdots n, \quad {}^{S_n}W_{li\rightarrow 0} = 0 \quad & , \end{array}}$$

With:

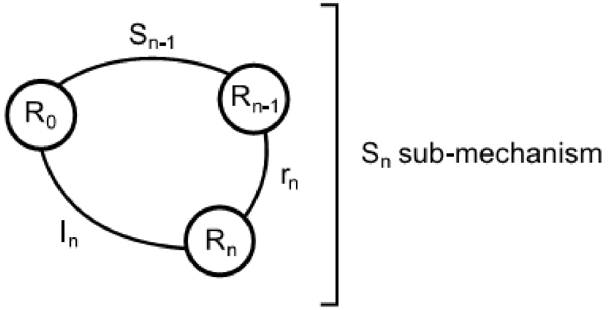
${}^{S_n}T_i$ the space of twists describing the velocities from robot body $\mathscr{R}_i$ relative to $\mathscr{R}_0$ in the S_n mechanism and ${}^{S_n}W_{li\rightarrow 0}$ space of wrench statically admissible transmitted through the li chain on the reference body $\mathscr{R}_0$ (the blocked arm),

Preventing hyperstaticity

Considering the recursive structure of the system:



Recursive structure Si of the system



Reduced complete system Sn

N&S conditions of no hypserstaticity nor mobility can summarized in :

$$\forall i \in 1\cdots n,\quad dim(T_{S_{i-1}} + T_{r_i} + T_{l_i}) = 6 \quad and$$
$$\forall i \in 1\cdots n,\quad dim(T_{r_i} \cap T_{l_i}) = 0 \quad and$$
$$dim(T_{S_n}) = 0 \quad ,$$

Where T_{S_i}. is the space of twists describing the velocities from robot body $\mathscr{R}_i$ relative to $\mathscr{R}_0$ in the mechanism S_i.

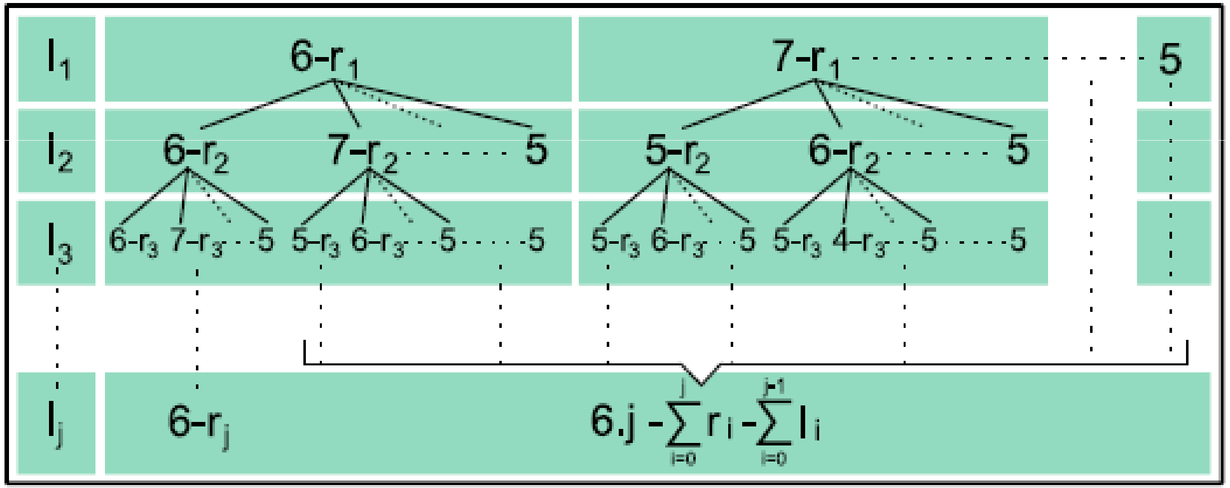
That leads to a simplified usable for design set of equations

$$\forall i \in 1\cdots n,\quad \sum_{j=1}^{i}(l_j + r_j) \geq 6.i \qquad \forall i \in 1\cdots n,\quad \sum_{j=1}^{i-1}(l_j + r_j) + r_i \leq 6.i \qquad \sum_{j=1}^{n}(l_j + r_j) = 6.n$$

Admissible solutions for l_i

$$\sum_{i=1}^{n}(r_i+l_i) = 6n$$

$$\forall 0<j<n \quad \sum_{i=1}^{j}(r_i+l_i) \geq 6j$$

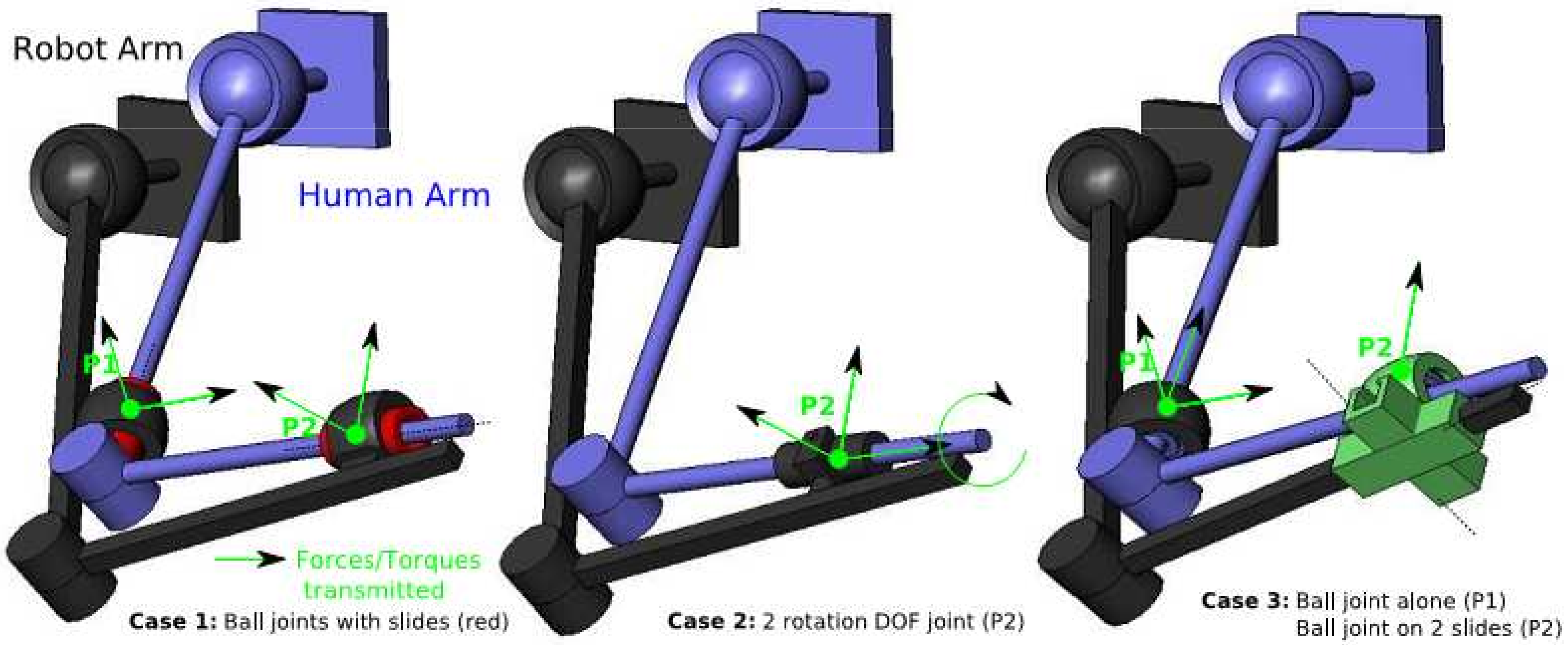


- ⇒A number of different possible solutions for l_i
- ⇒A number of different solutions to choose the DOFs w.r.t. human member geometry once l_i has been selected

Fixations kinematic design

	$l2=2$	$l2=3$	$l2=4$	$l2=5$
$l1=3$	$\sum l_i < 8$	$\sum l_i < 8$	$\sum l_i < 8$	**OK**
$l1=4$	$\sum l_i < 8$	$\sum l_i < 8$	**OK**	$\sum l_i > 8$
$l1=5$	$\sum l_i < 8$	**OK**	$\sum l_i > 8$	$\sum l_i > 8$

Catalog of solutions



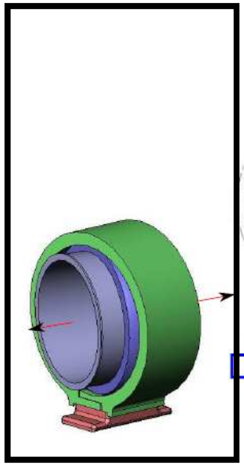
Case 1: Ball joints with slides (red)

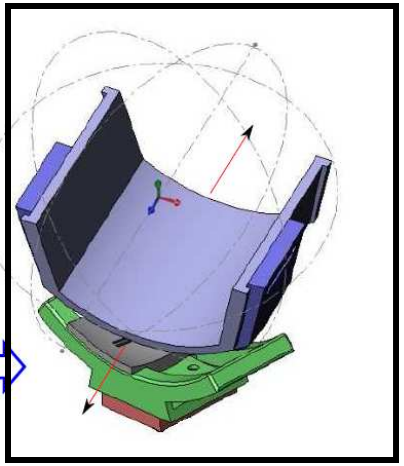
Case 2: 2 rotation DOF joint (P2)

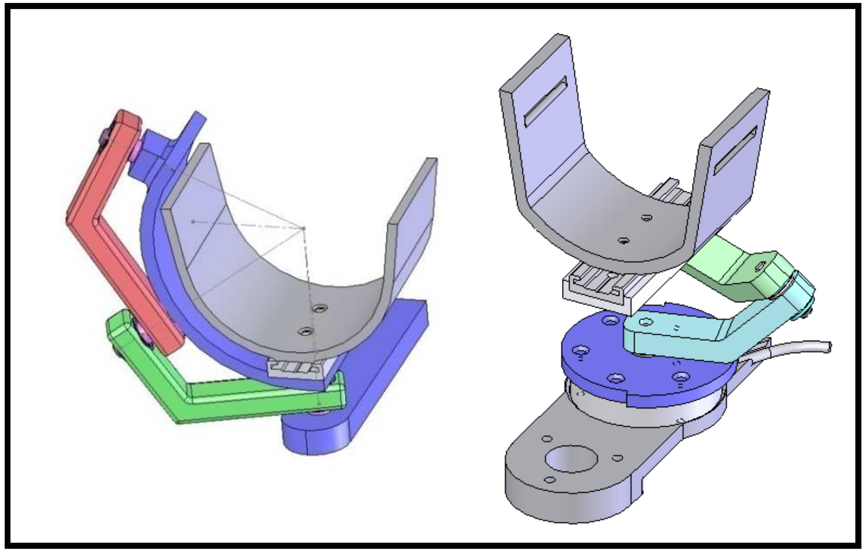
Case 3: Ball joint alone (P1)
Ball joint on 2 slides (P2)

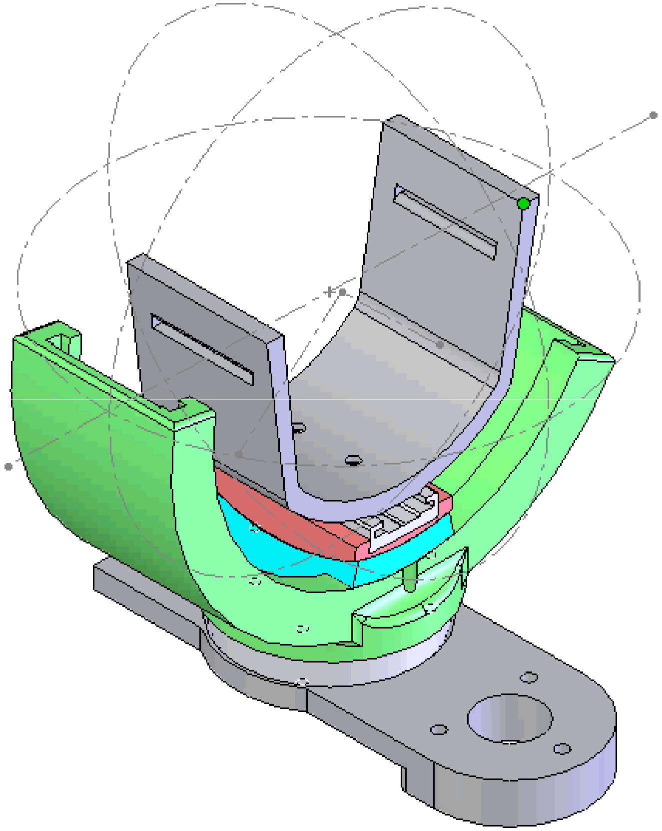
Schematic of possibilities given by the solution tree for coupling ABLE to an human arm. From left to right: Case 1 (l1 = 4, l2 = 4), Case 2 (l1 = 6-no fixations-, l2 = 2), Case 3 (l1 = 3, l2 = 5)

Practical realization

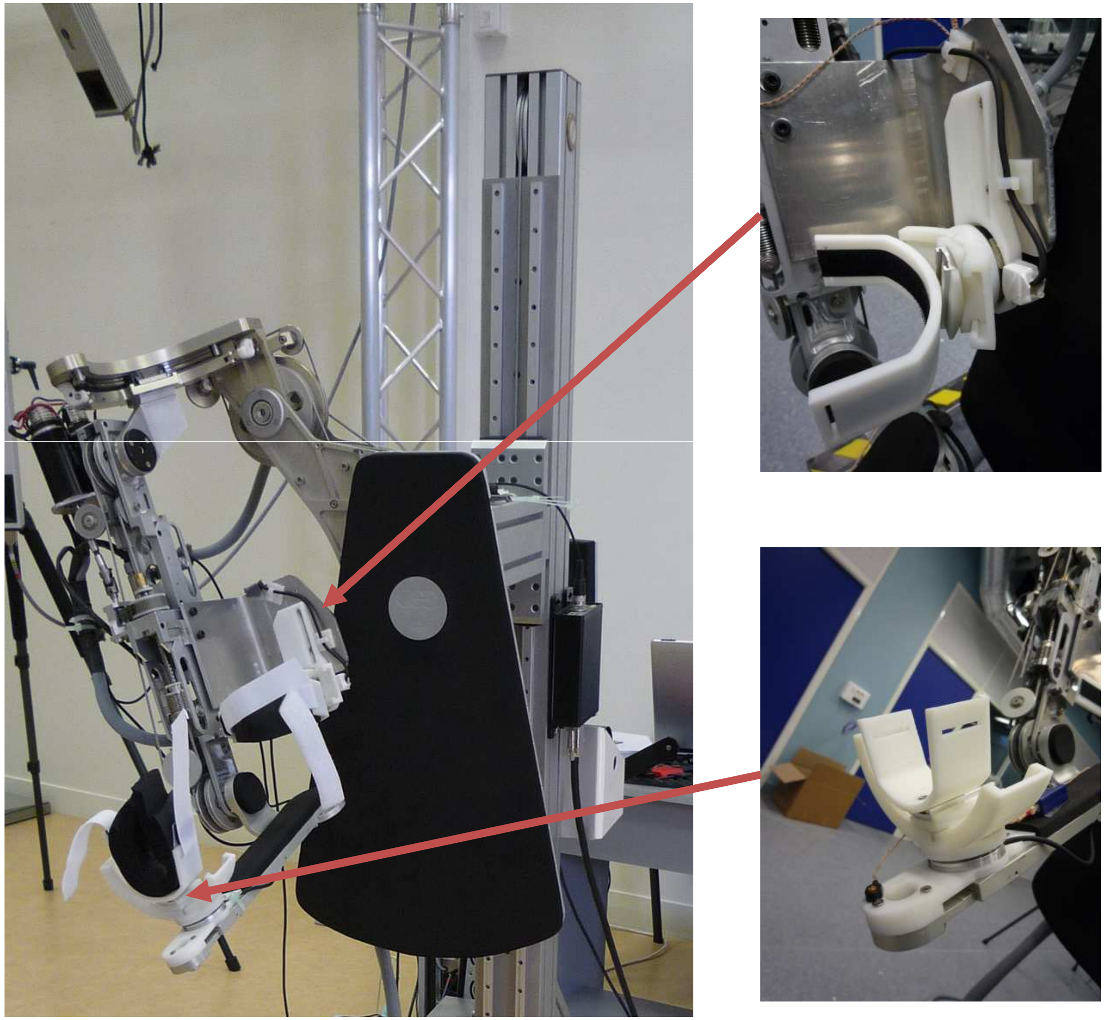

Simple solution

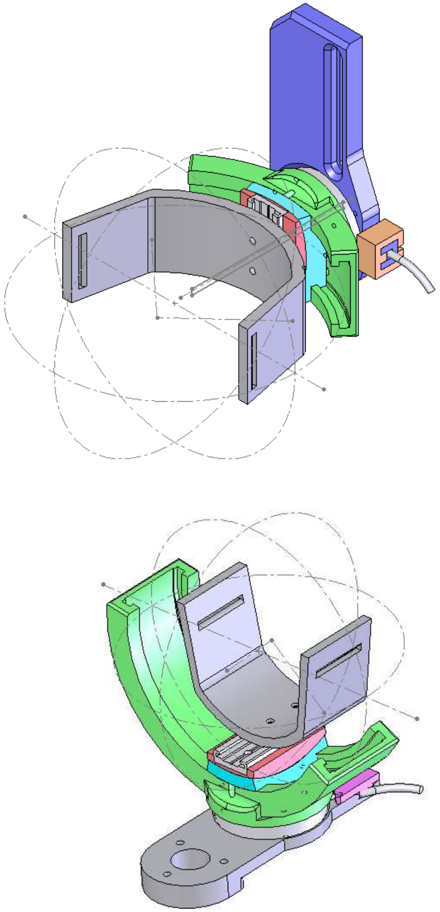

Chosen solution


Possibles solutions

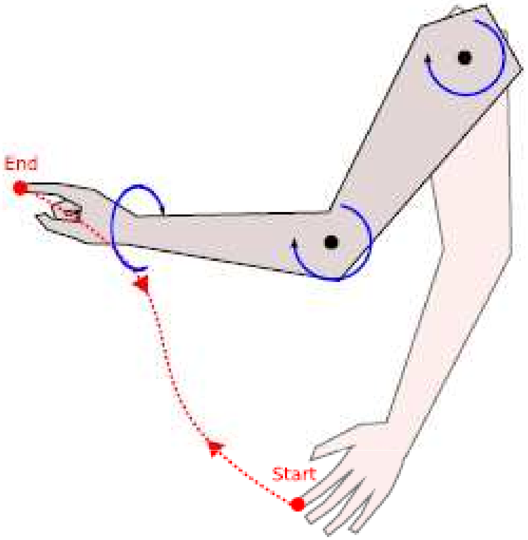


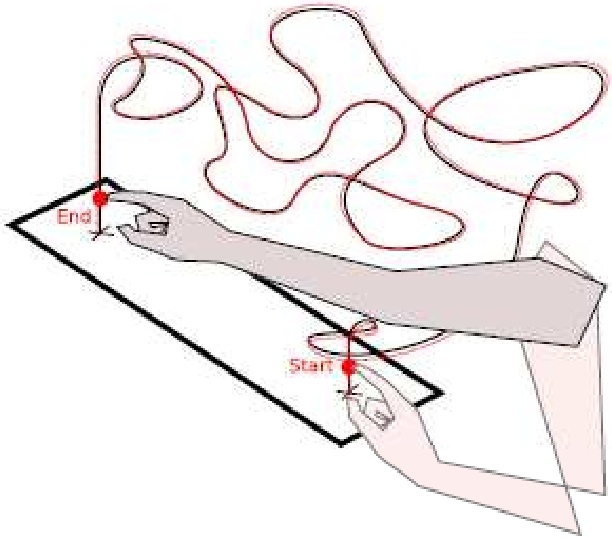
Practical realization

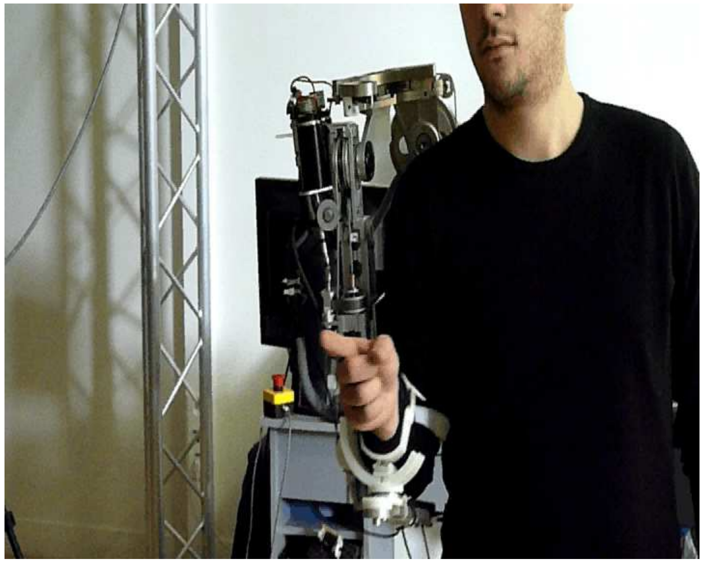




Experiments



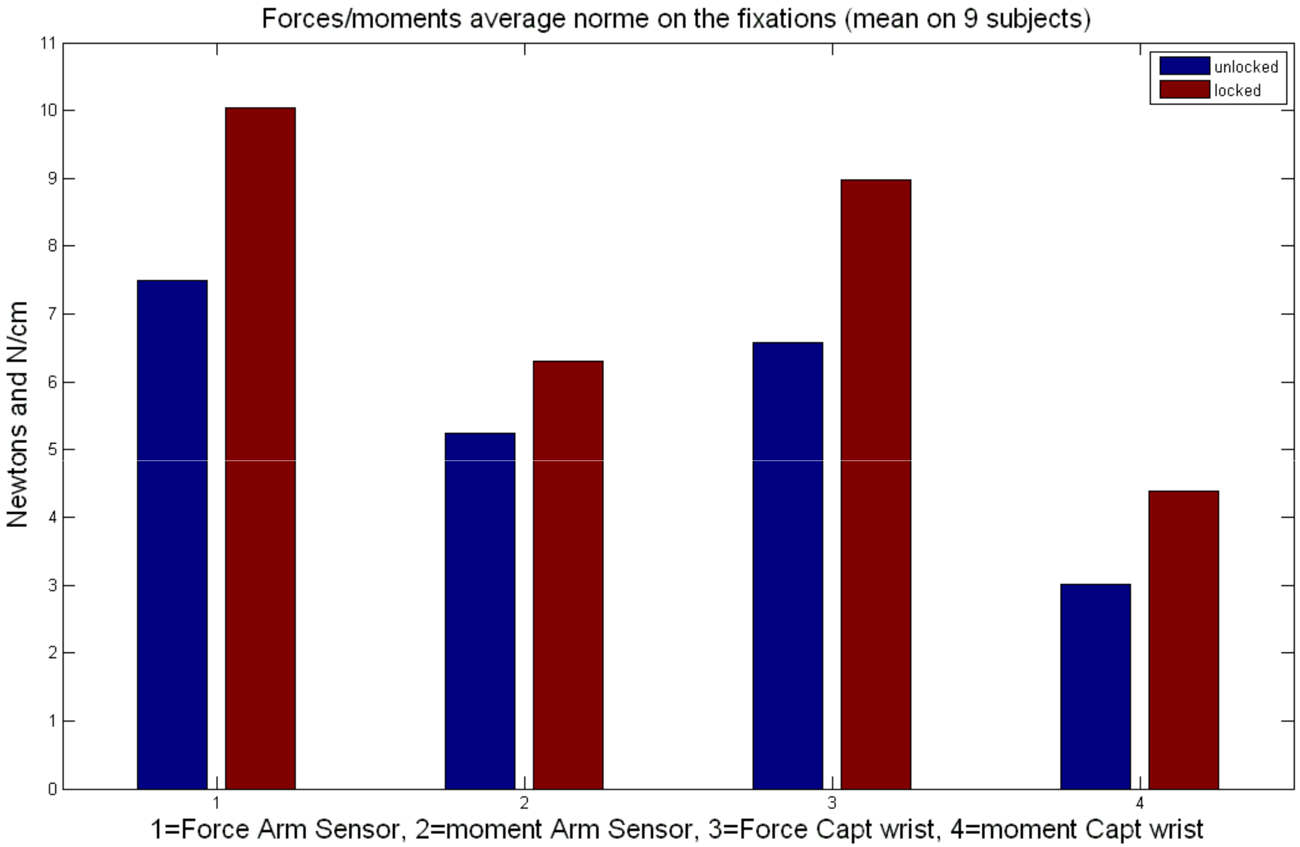




- **18 naive subjects**
- **2 tasks:**
  - 1 simple reaching task (only on 9 subjects)
  - 1 manipulation task (complex trajectory following)
- **Force measurement with the fixations freed or blocked.**

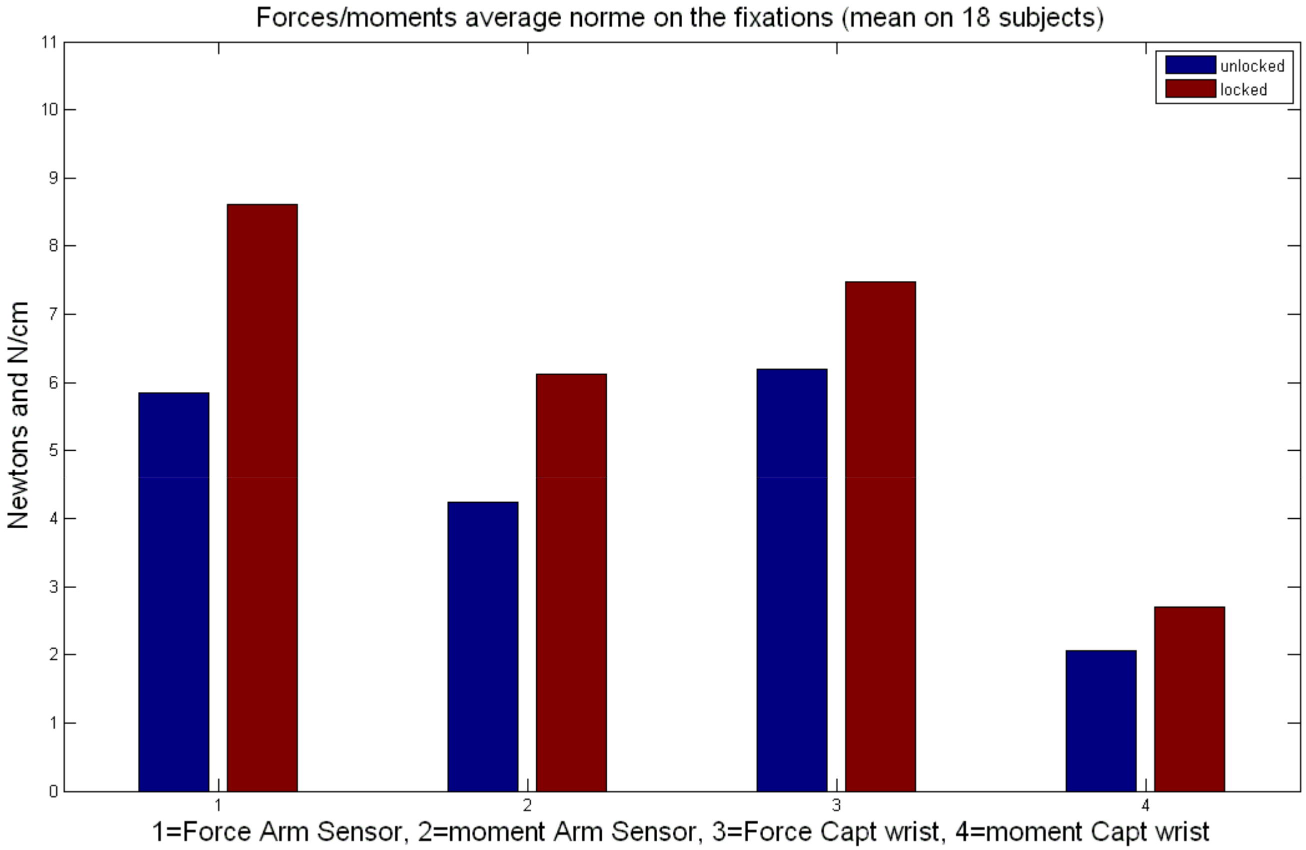
2x 6DoF F/T measurements

Assessing transparency



Average force measured for the 9 subjects with the fixations freed (blue) or blocked (red) for the **reaching experiment**

Assessing transparency

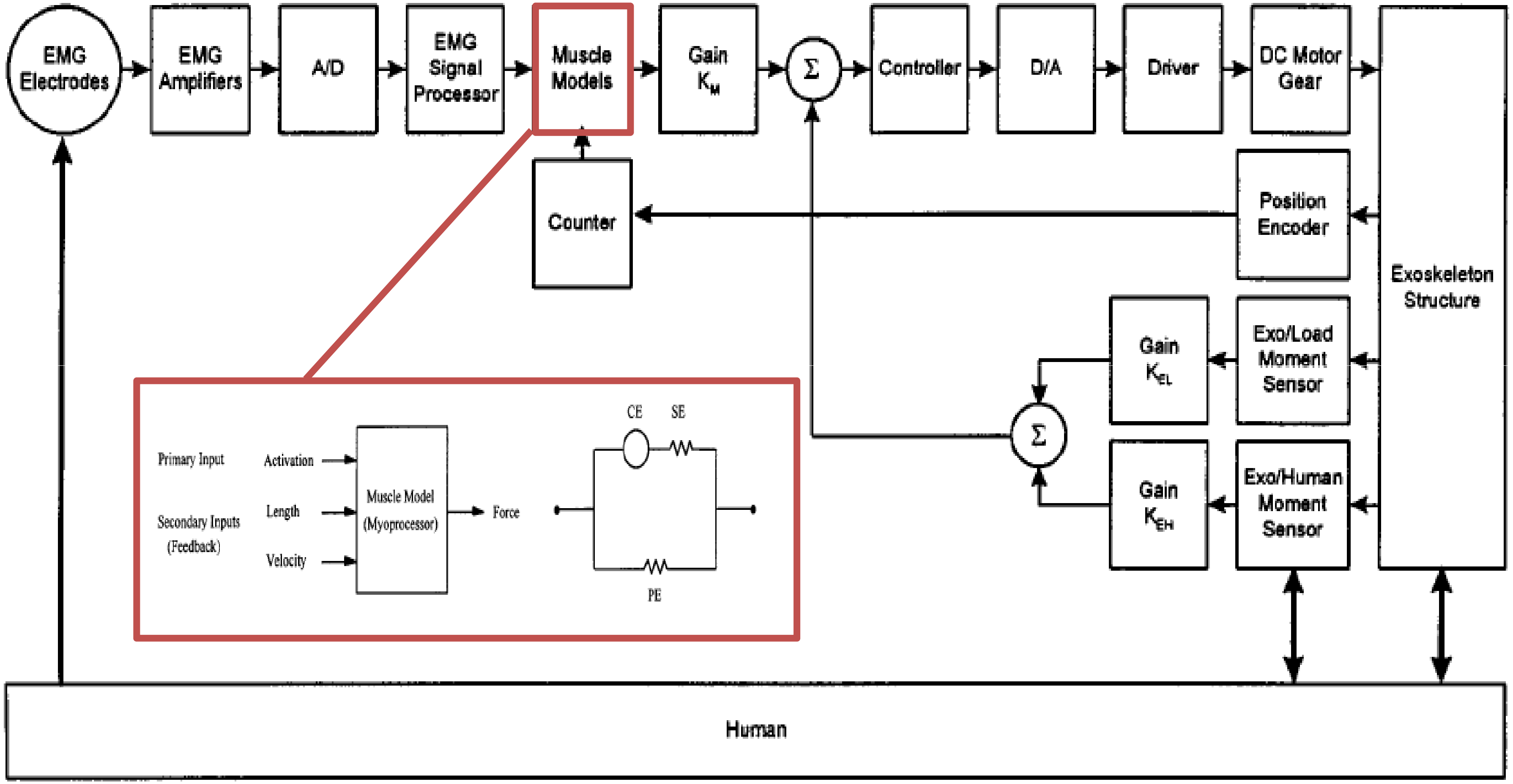


Average force measured for the 9 subjects with the fixations freed (blue) or blocked (red) for the **complex manipulation experiments**

II.2 – Using EMG signals in cooperation with contacts

- Force amplification for assistance to manipulation with an exosqueleton

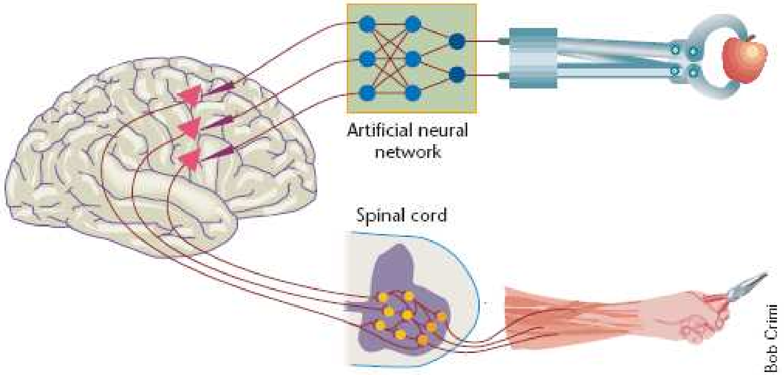
II.2 – EMG-based control



Please ask Blake Hannaford for details

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.

Thanks

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