# Applications of force feedback in medical and surgical robotics.

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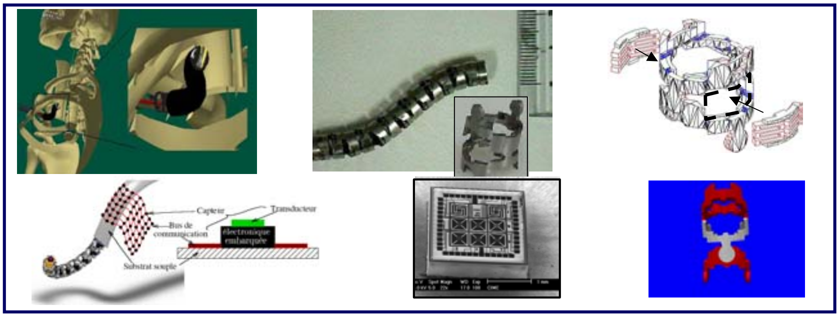
## Le Laboratoire de Robotique de Paris

- Institutions: Univ. Pierre et Marie Curie (Paris 6), CNRS.
- Location: Fontenay-aux-Roses, in the close suburb of Paris.
- 13 permanent researchers, 15-25 PhD students, 2-5 postdocs.
- 4 research groups:
  - Micromanipulation
  - Mobile Robotics for rough terrain exploration
  - Assistive devices
  - Interventional robotics for medicine and surgery
- We are encouraging applications for:
  - Short stays (1-3 months) of PhD students from other labs;
  - PostDocs

# Main projects of the *interventional robotics for medicine and surgery* group

## 1. Dexterous Instruments for Minimally Invasive Surgery [26, 27]



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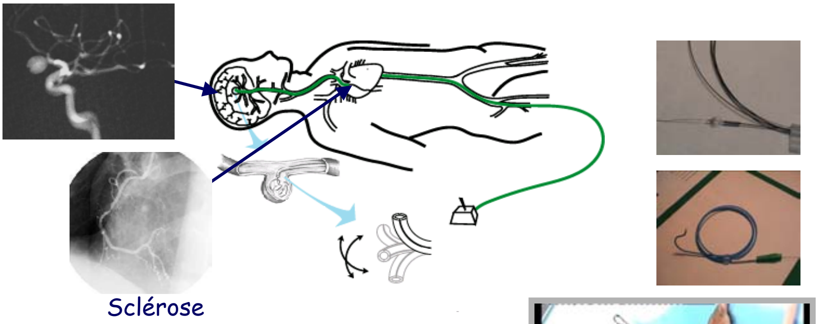
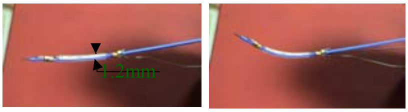
# Main projects of the *interventional robotics for medicine and surgery* group

## 2. Active Catheterism

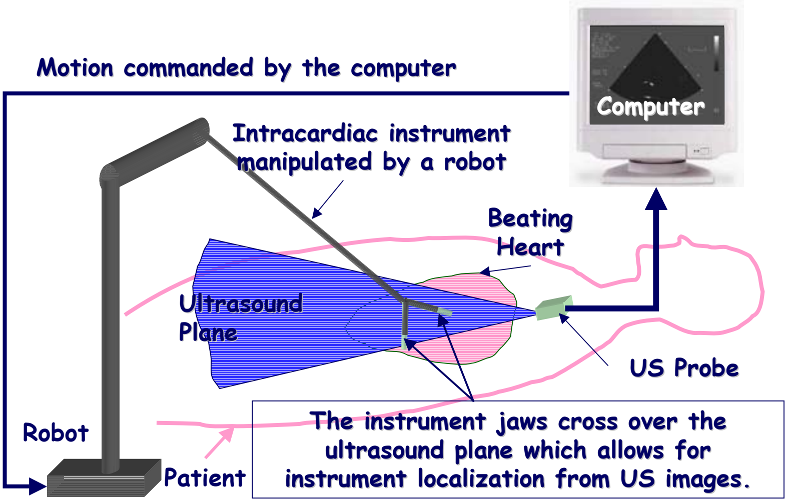


First attempt : active SMA based catheter



# Main projects of the *interventional robotics for medicine and surgery* group

## 3. Automatic Instrument Guidance from Ultrasound Imaging [23]



**Motion commanded by the computer**

**Computer**

**Intracardiac instrument manipulated by a robot**

**Beating Heart**

**Ultrasound Plane**

**US Probe**

**Robot**

**Patient**

**The instrument jaws cross over the ultrasound plane which allows for instrument localization from US images.**

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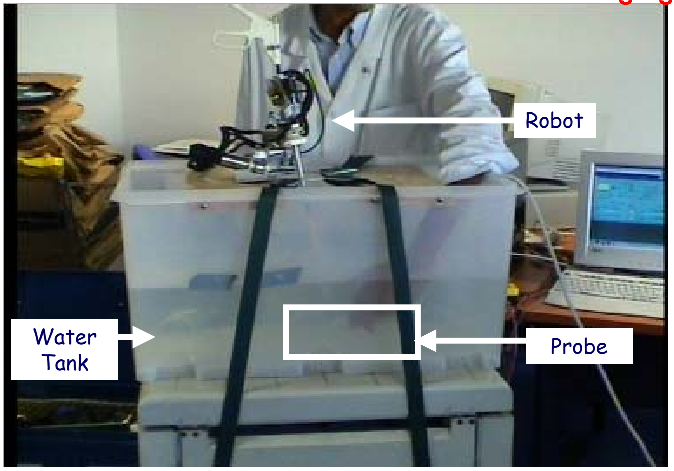
# Main projects of the *interventional robotics for medicine and surgery* group

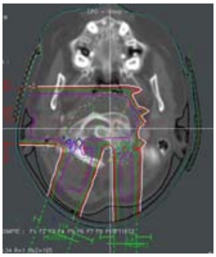
## 3. Automatic Instrument Guidance from Ultrasound Imaging [23]

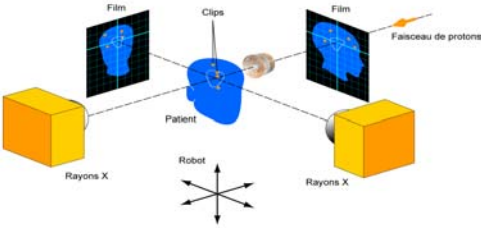


Experiences realized at the Hôpital de la Pitié Salpêtriére (*in vitro*) and at the Surgical School of Paris - APHP (*in vivo*).

# Main projects of the *interventional robotics for medicine and surgery* group

## 4. Automatic Patient Positionning for Protontherapy from Xray Images [4]





**Samuel Pinault**, who started his PhD about 1 year ago on this topic, is an attendee of this summer school. Ask him for details.

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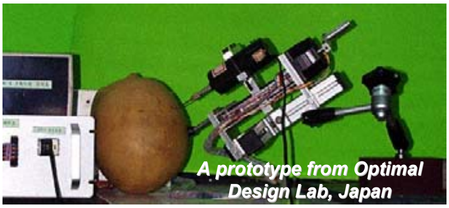
# Main projects of the *interventional robotics for medicine and surgery* group

## 5. Force feedback control in Minimally Invasive Surgery [25]

(to be detailed later in the talk)

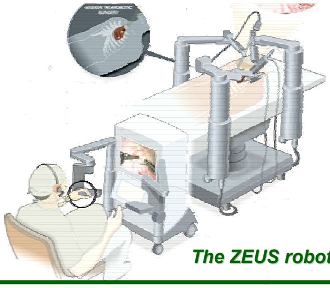
# Back to today's topic:
# Three paradigms of force feedback

1.“Autonomous” force control of robots.



*A prototype from Optimal Design Lab, Japan*

2. Telemanipulated systems



*The ZEUS robot*

3. Comanipulated robots

*The ACROBOT system*

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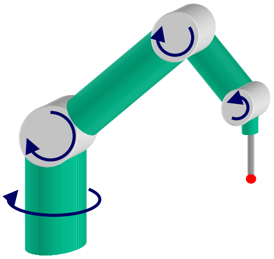
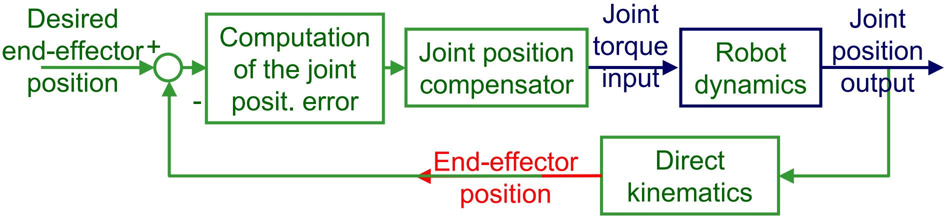
# Organization of the talk

1. Force feedback closed-loop control for an “autonomous” robot.
    1. A simplistic introduction to force feedback control in Robotics.
    2. Applications to robotics for medicine.
    3. Limitations and open problems.
2. Telemanipulation.
    1. Master-slave position coupling.
    2. Force feedback telemanipulation.
    3. Position-force coupling in telemanipulation
    4. Potential benefits
3. Comanipulation.
    1. Principle
    2. Comanipulation without force sensors
    3. Active force feedback for comanipulation
4. Conclusions

# 1.1 Basics of force feedback control

**a) Position control**





Desired end-effector position

+

-

Computation of the joint posit. error

Joint position compensator

Joint torque input

Robot dynamics

Joint position output

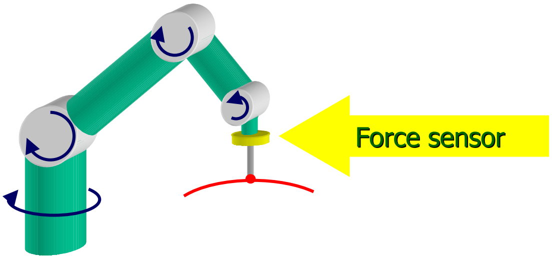
Direct kinematics

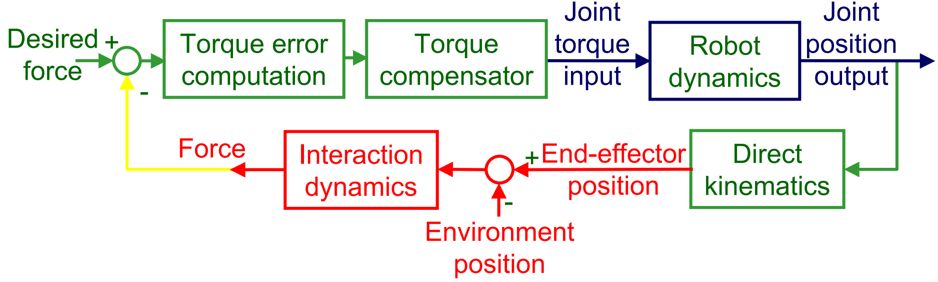
End-effector position

---

# 1.1 Basics of force feedback control

**b) Direct force control**





Desired force

+

-

Torque error computation

Torque compensator

Joint torque input

Robot dynamics

Joint position output

Direct kinematics

End-effector position

+

-

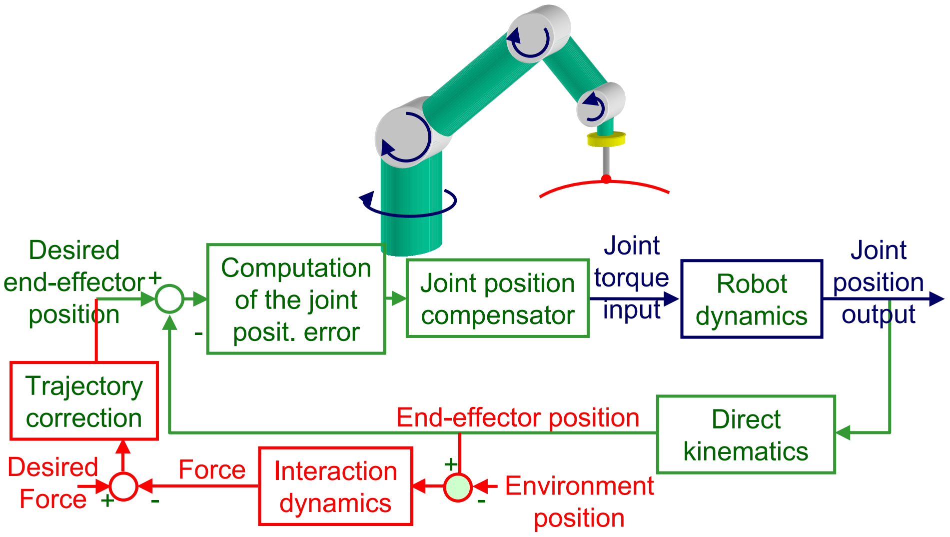
Environment position

Interaction dynamics

Force

# 1.1 Basics of force feedback control

**c) Indirect Force Control**



Desired end-effector position

\+

\-

Computation of the joint posit. error

Joint position compensator

Joint torque input

Robot dynamics

Joint position output

Trajectory correction

End-effector position

Direct kinematics

Desired Force

\+

\-

Force

Interaction dynamics

\+

\-

Environment position

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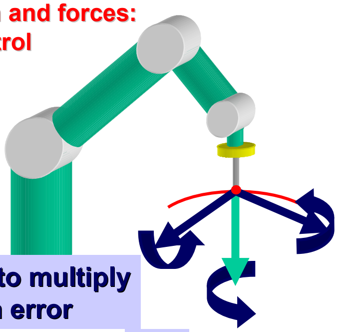
# 1.1 Basics of force feedback control

**d) Simultaneous control of position and forces:**
**Hybrid position/force control**



Principle = decompose the task into two subtasks :

- **Force control for some DoFs**
- **Position control for the remaining DoFs**

**A selection matrix to multiply the force error**

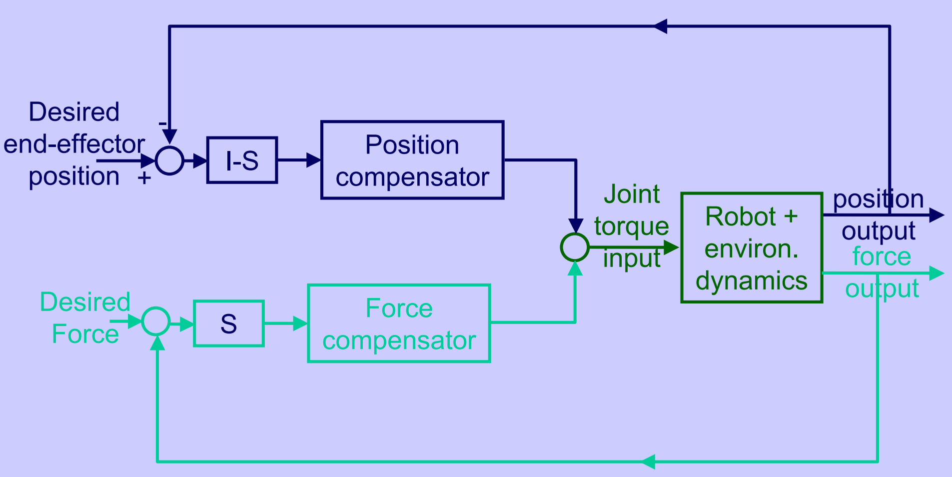
**Its complement to multiply the position error**

$$\boldsymbol{S} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{array}{l} \leftarrow \varepsilon F_x \\ \leftarrow \varepsilon F_y \\ \leftarrow \varepsilon F_z \\ \leftarrow \varepsilon M_x \\ \leftarrow \varepsilon M_y \\ \leftarrow \varepsilon M_z \end{array}$$

$$\boldsymbol{I} - \boldsymbol{S} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{array}{l} \leftarrow \varepsilon_x \\ \leftarrow \varepsilon_y \\ \leftarrow \varepsilon_z \\ \leftarrow \varepsilon\theta_x \\ \leftarrow \varepsilon\theta_y \\ \leftarrow \varepsilon\theta_z \end{array}$$

# 1.1 Basics of force feedback control

## d) Simultaneous control of position and forces: Hybrid position/force control



Desired end-effector position +

-

I-S

Position compensator

Joint torque input

Robot + environ. dynamics

position output

force output

Desired Force

S

Force compensator

---

# 1.2 Medical applications.

## a) Robotized skin harvesting [6]

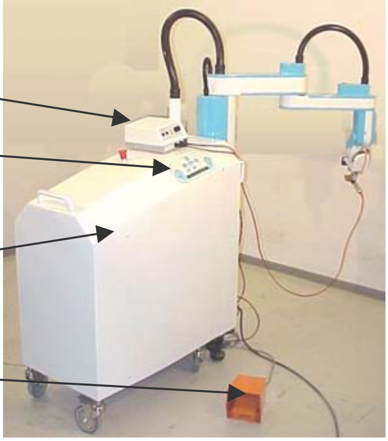
(LIRMM, Montpellier, Sinters, Lapeyronie Hosp.)

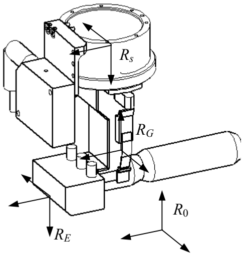
Dermatome controller

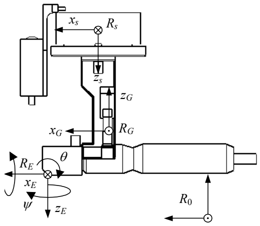
User interface

Control cabinet

DMS foot pedal



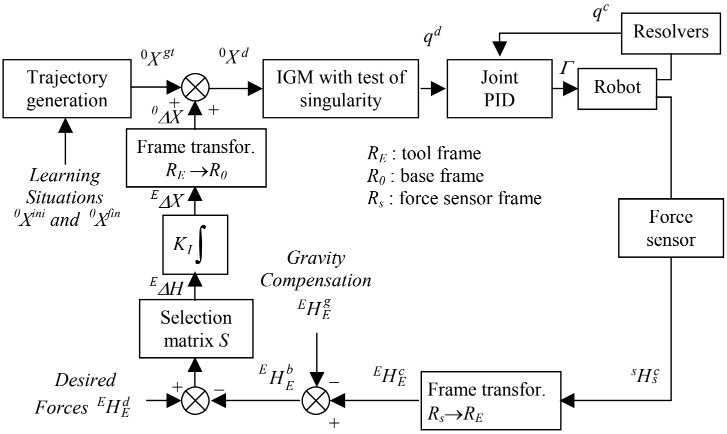




# 1.2 Medical applications.

## a) Robotized skin harvesting [6]

(LIRMM, Montpellier, Sinters, Lapeyronie Hosp.)



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# 1.2 Medical applications.

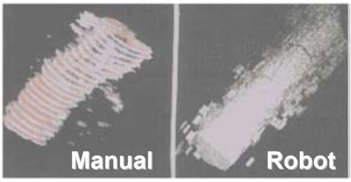
## a) Robotized skin harvesting [6]

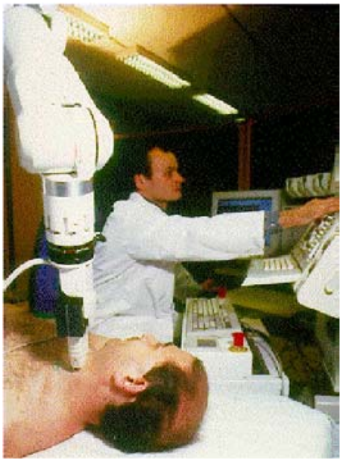
(LIRMM, Montpellier, Sinters, Lapeyronie Hosp.)

# 1.2 Medical applications.

## b) A similar application: ultrasound probe holder (Hippocrate) [15]

(LIRMM, Montpellier, et al.)





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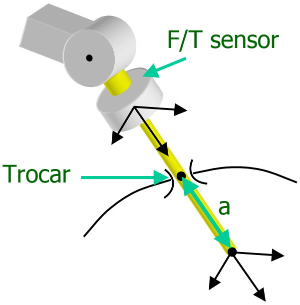
# 1.2 Medical applications.

## c) Hybrid Vision/Force Control for Laparoscopic Manipulation [11]

(LSIIT, Strasbourg)

Principle

- An approach to laparoscopic manipulation through a trocar:
  - A 6 dof robot + a force/torque sensor
  - a hybrid position/force controller :
    - The 2 constrained dof are force controlled
    - The 4 remaining dof are position controlled

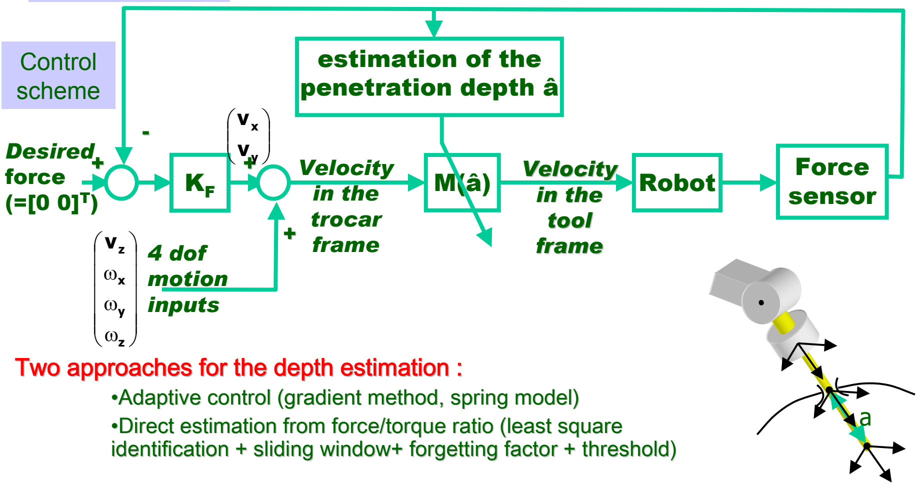


# 1.2 Medical applications.

## c) Hybrid Vision/Force Control for Laparoscopic Manipulation [11]

(LSIIT, Strasbourg)

Control scheme



Two approaches for the depth estimation :

- Adaptive control (gradient method, spring model)
- Direct estimation from force/torque ratio (least square identification + sliding window+ forgetting factor + threshold)

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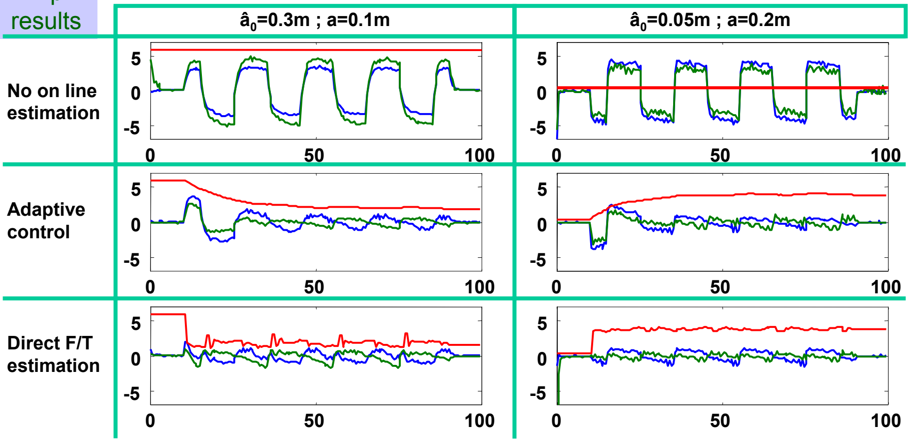
# 1.2 Medical applications.

## c) Hybrid Vision/Force Control for Laparoscopic Manipulation [11]

(LSIIT, Strasbourg.)

Exp. results

Fx(N), Fy(N), 20 â (m) vs time (s)



# 1.2 Medical applications.

**c) Hybrid Vision/Force Control for Laparoscopic Manipulation [11]**

(LSIIT, Strasbourg.)

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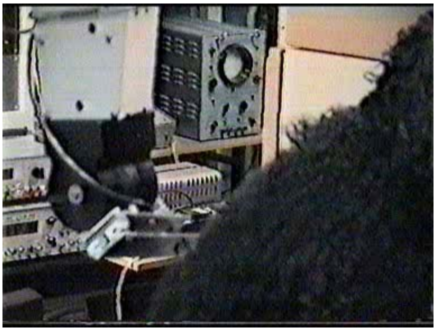
# 1.2 Medical applications.

**d) An alternative approach of F/P control: impedance control**

(Moscow State Industrial University &
Russian Science Center of
Rehabilitation and Balneology.)

Principle :
1) Program a 6 DoF trajectory
2) Program an impedance : ***V = Z. F***

**Application to a …. massage robot**



# 1.3 Benefits, limitations and open problems.

- **Main benefits:**
  - Fine and precise gesture (skin harvesting, US probe holding, …)
  - Compensation of small patient motions.
  - Safety issues: limitation of applied forces (manipulation through a trocar)
- **Main Limitations:**
  - Lack of dexterity: can perform only very simple tasks (simple enough to be specifiable in terms of forces / trajectories).
  - Safety issues: proof of stability either:
    - requires a contact/environment model.
    - is quite conservative (e.g. passivity analysis).
  - Cost / sterilization;
  - Technical problems inherent to force sensing (bias, etc…).

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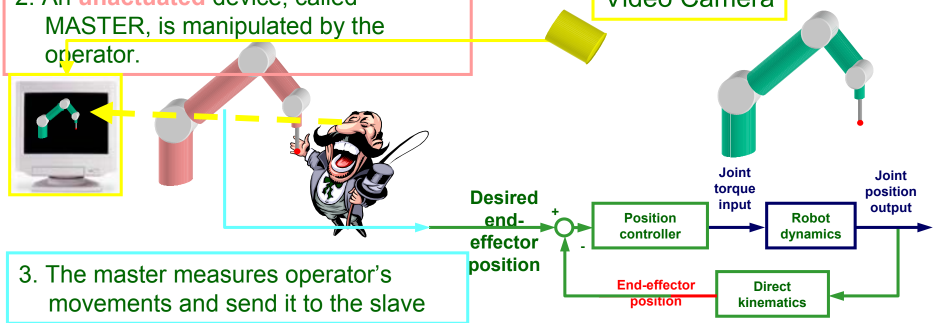
# 2.1 Master-slave position coupling

## a) Basic principle



2. An unactuated device, called MASTER, is manipulated by the operator.

3. The master measures operator's movements and send it to the slave

4. The loop is closed thanks to a visual feedback of the operation scene provided to the operator.

1. A position controlled robot, performing the gesture is called SLAVE

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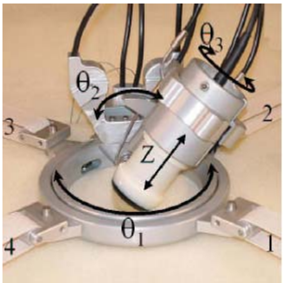
# 2.1 Master-slave position coupling

## b) Applications to medical robotics : tele-echography

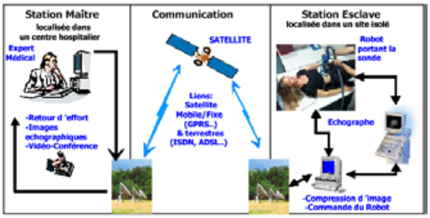
(IMAG, Grenoble & partners)



(LVR, Bourges & partners)

TER2 [22]

OTELO PROJECT [3]

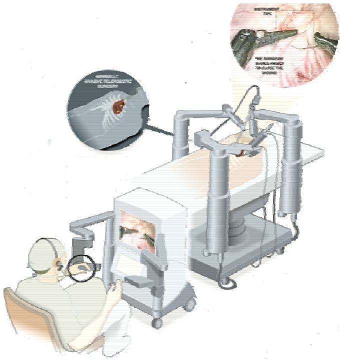


# 2.1 Master-slave position coupling

**c) Applications to medical robotics : Minimally invasive surgery**

Zeus

Da Vinci



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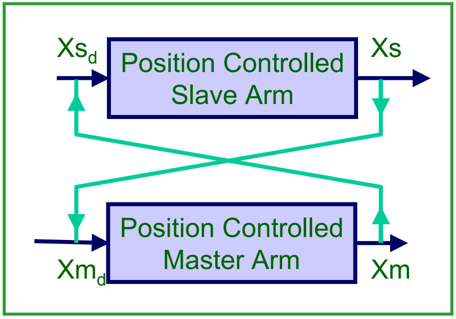
# 2.1 Master-slave position coupling

- Main benefits:
  - « Telepresence »
    - Long distance between the patient and the doctor [14].
    - Virtually getting « inside » a patient in a minimally invasive way.
  - Precision: a direct effect of the position scale factor.
  - Surgeon’s comfort: direct access to a patient may be quite tiring, specially for long procedures.
  - Safety/Insurance issues: the whole operation can be recorded.
- Main Limitations:
  - Lack of dexterity: restoring the dexterity of a direct acces with hands seems to be out of range.
  - Lack of force feedback => towards force feedback teleoperation.

# 2.2 Force feedback teleoperation

- In force feedback teleoperation, the master arm is actuated and can apply forces on the operator. Ultimately, the operator can « feel » the forces applied by the slave arm to its environment.
- Mainly two techniques can be used:

Bilateral position coupling.


$Xs_d$

Position Controlled Slave Arm

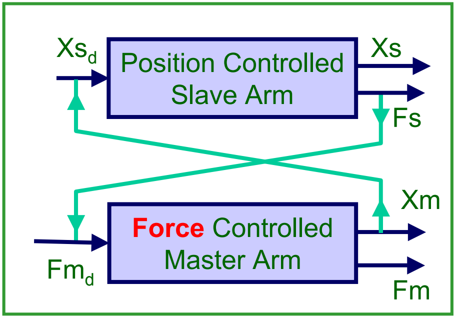
Xs

Position Controlled Master Arm

$Xm_d$

Xm

Force-position coupling.


$Xs_d$

Position Controlled Slave Arm

Xs

Fs

Xm

**Force** Controlled Master Arm

$Fm_d$

Fm

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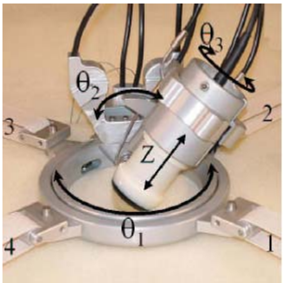
# 2.2 Force feedback teleoperation

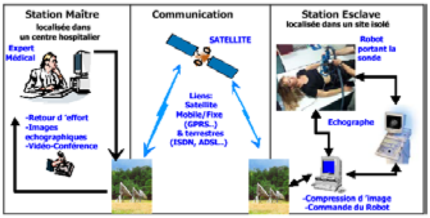
**Applications of bilateral P-P teleoperation to Tele-echography**

Tele-echography



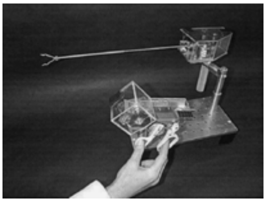
TER2 [22]

OTELO PROJECT [3]

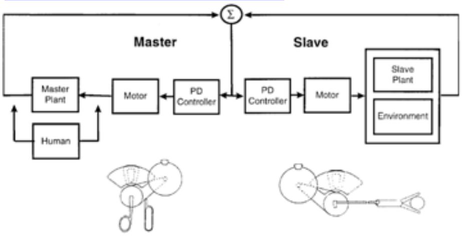


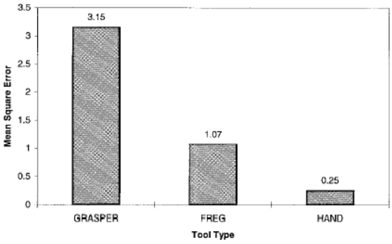
# 2.2 Force feedback teleoperation

## Application of bilateral P-P teleoperation to MIS [16]



(Univ. Washington, Seattle)





Mean square error of ranking the stiffness of 6 different materials

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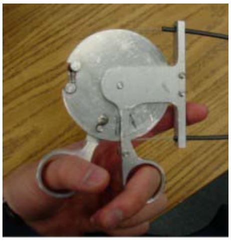
# 2.2 Force feedback teleoperation

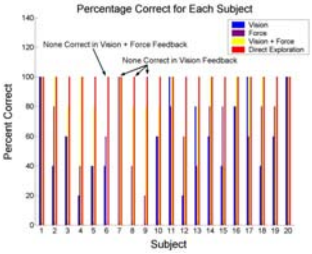
## Application of bilateral P-P teleoperation to MIS [8]



(PRISM, Drexel Univ.)

**Tissue characterization with the grasper :**

- **52% correct with vision only**
- **67% correct with FF only**
- **83% correct with vision + FF**



## 2.2 Force feedback teleoperation

- Main advantage of bilateral position-position teleoperation
  - Does not require any force sensor.
  - Allows for a better perception.
- Main drawbacks:
  - Requires a fine, transparent mechanical design.
  - Reflects all the forces exerted on the slave robot (e.g. trocar).

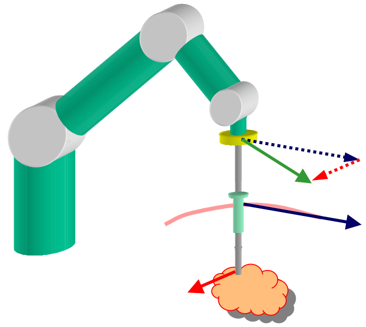
⇨ Can not be applied to MIS.

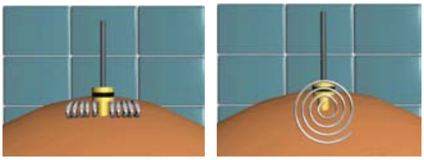
---

## 2.3 Force-Position coupling for TMIS

**The measurement problem**

- Usually, the force sensor is placed between the robot end-effector and the « tool » (i.e. instrument)
- In laparoscopic surgery, this solution leads to a corruption of the measure due to trocar disturbances

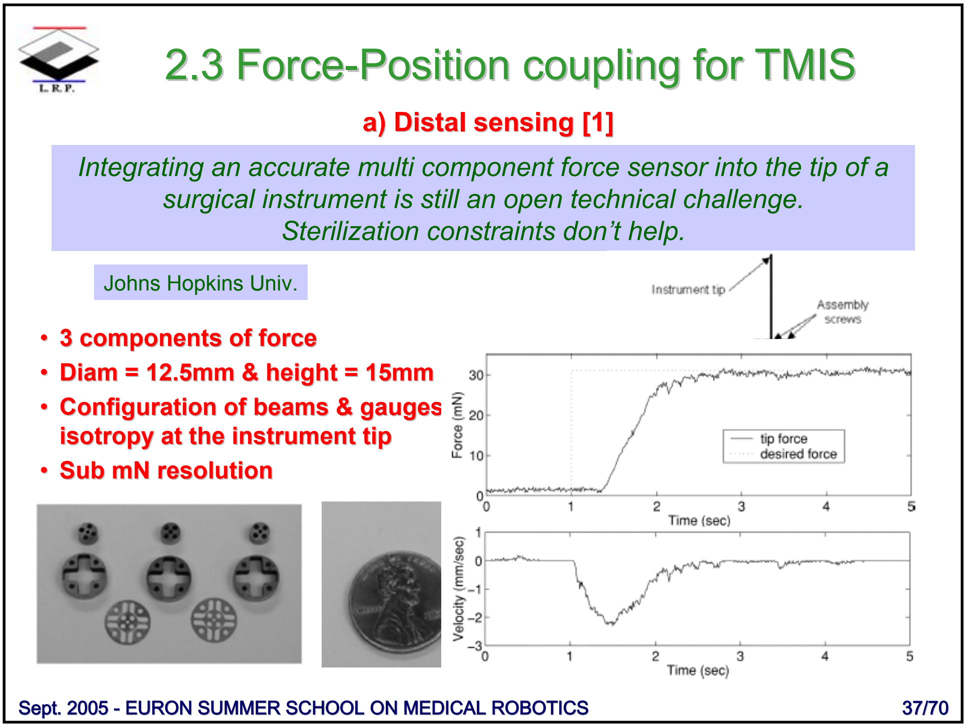




Trocar disturances also include a significant amount of friction, see [7]

**3 solutions:**

a) Distal sensing.
b) Sensorless force feedback.
c) Trocar mounted sensor.



# 2.3 Force-Position coupling for TMIS

## a) Distal sensing [1]

*Integrating an accurate multi component force sensor into the tip of a surgical instrument is still an open technical challenge.*
*Sterilization constraints don't help.*

Johns Hopkins Univ.

- **3 components of force**
- **Diam = 12.5mm & height = 15mm**
- **Configuration of beams & gauges isotropy at the instrument tip**
- **Sub mN resolution**

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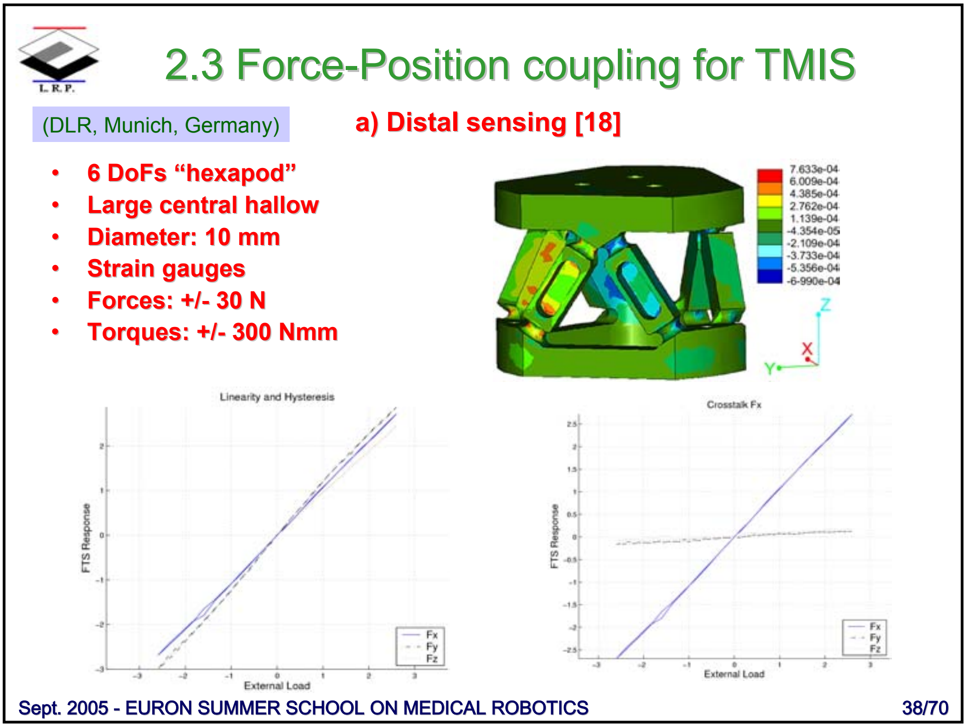

# 2.3 Force-Position coupling for TMIS

(DLR, Munich, Germany)

## a) Distal sensing [18]

- **6 DoFs "hexapod"**
- **Large central hallow**
- **Diameter: 10 mm**
- **Strain gauges**
- **Forces: +/- 30 N**
- **Torques: +/- 300 Nmm**

# 2.3 Force-Position coupling for TMIS

(DLR, Munich, Germany)

## a) Distal sensing [18]

### Integration into a Scalpel

- **Rigid instrument**
- **Standardized serial interface (RS 485)**
- **Diameter: 10 mm**
- **Sample rate of forces / torques: 800 Hz**
- **Resolution: approx. 9 bits**

### Integration into actuated forceps

- **Actuated instrument**
- **Standardized serial interface (RS 485)**
- **Full mobility (2 DoF + 4 DoF)**
- **Satisfactory Manipulability**
- **Prototype diameter: 10 mm**

---

# 2.3 Force-Position coupling for TMIS

(DLR, Munich, Germany)

## a) Distal sensing [18]

Video of a force feedback teleoperation experiment

# 2.3 Force-Position coupling for TMIS

## b) Sensorless Force Feedback [10]

Trick: Reproducing what the surgeon does, i.e. ***estimate the force from the deformation observed by vision***.

*First attempts in a vision based haptic feedback*

(PRISM, Drexel Univ.)

This aparatus involves :
- A deformable membrane
- A FEM model
- A vision algorithm that track points
- An estimation algorithm that compute forces from displacement

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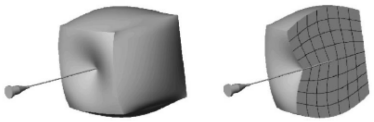
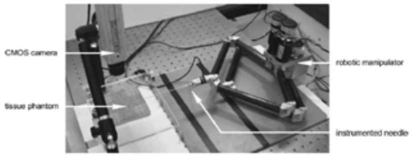
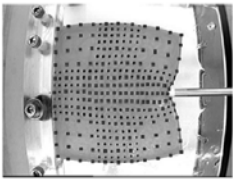
# 2.3 Force-Position coupling for TMIS

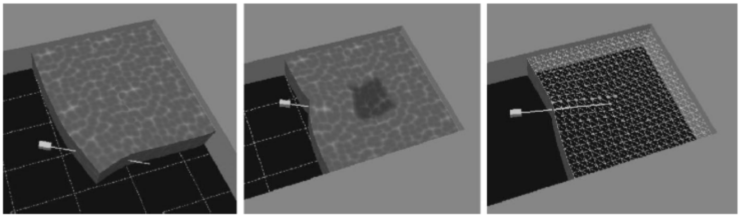
Related work : modelling of needle penetration in a tissue [5]

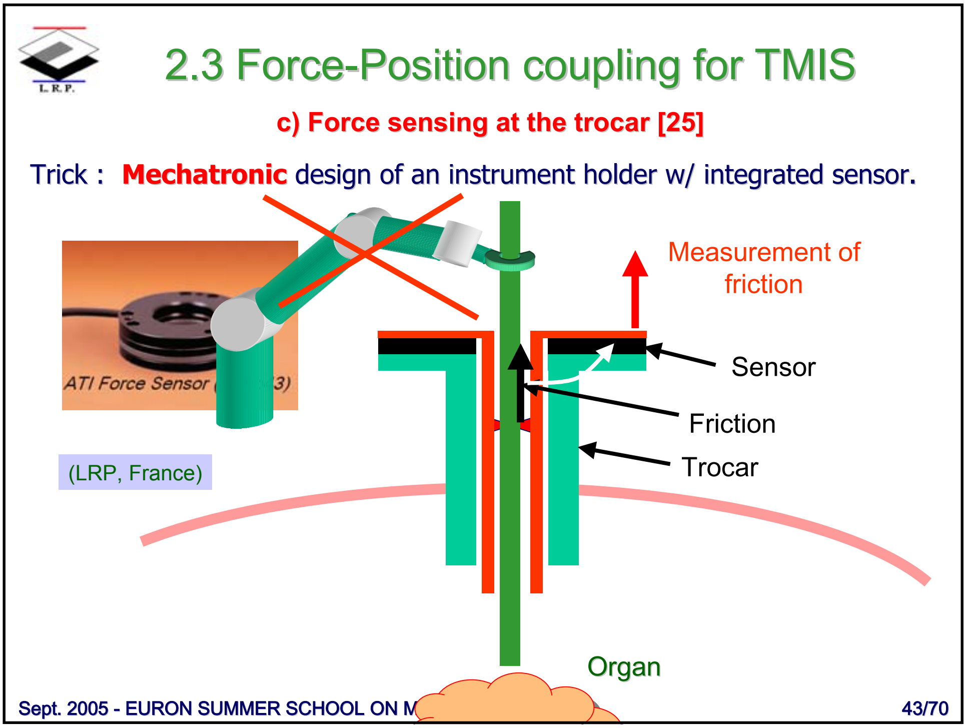


(Univ. British Columbia, Canada)









## 2.3 Force-Position coupling for TMIS

**c) Force sensing at the trocar [25]**

Trick : **Mechatronic** design of an instrument holder w/ integrated sensor.

(LRP, France)

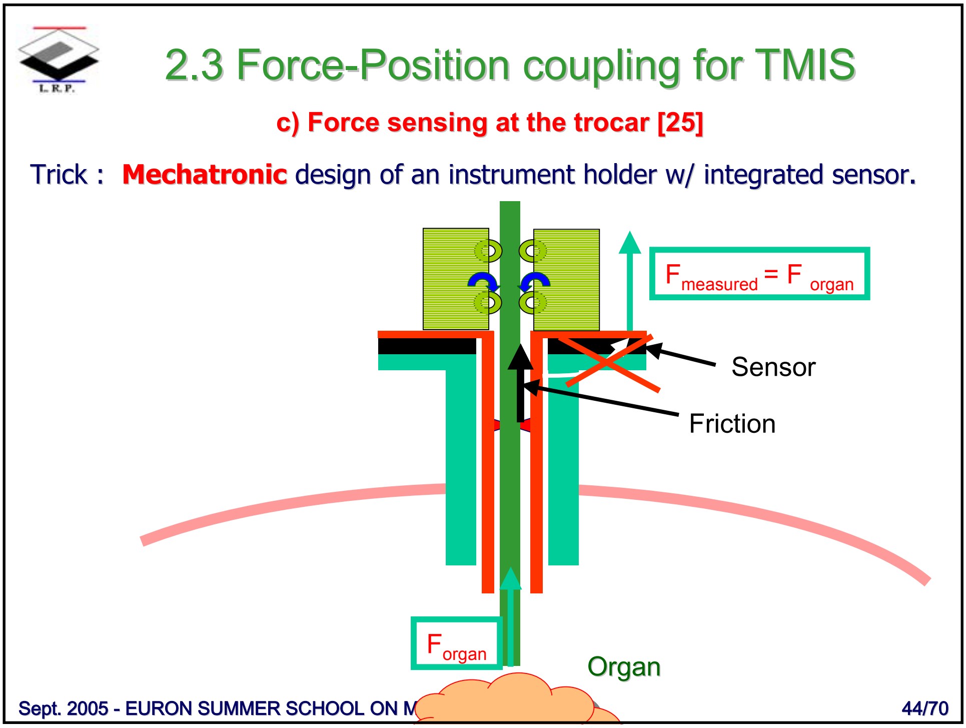
Measurement of friction

Sensor

Friction

Trocar

Organ



## 2.3 Force-Position coupling for TMIS

**c) Force sensing at the trocar [25]**

Trick : **Mechatronic** design of an instrument holder w/ integrated sensor.

$F_{measured} = F_{organ}$

Sensor

Friction

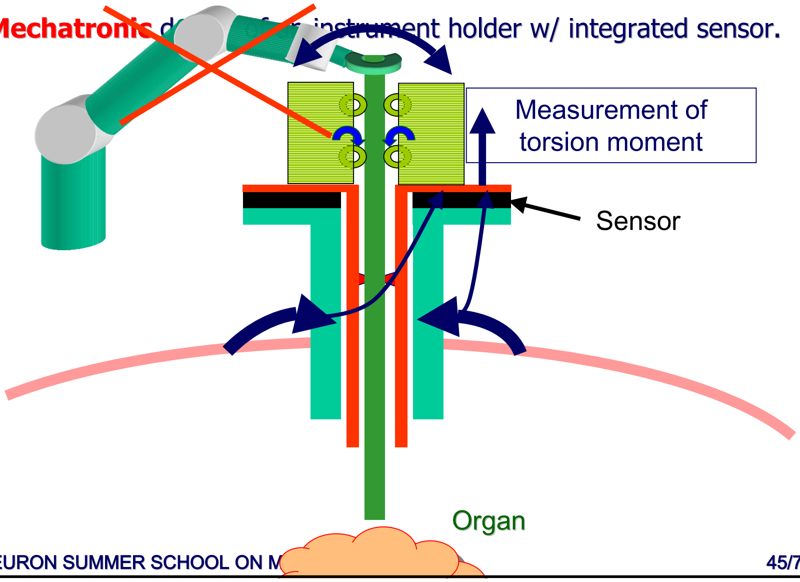
$F_{organ}$

Organ

# 2.3 Force-Position coupling for TMIS

## c) Force sensing at the trocar [25]

Trick : **Mechatronic** design of an instrument holder w/ integrated sensor.



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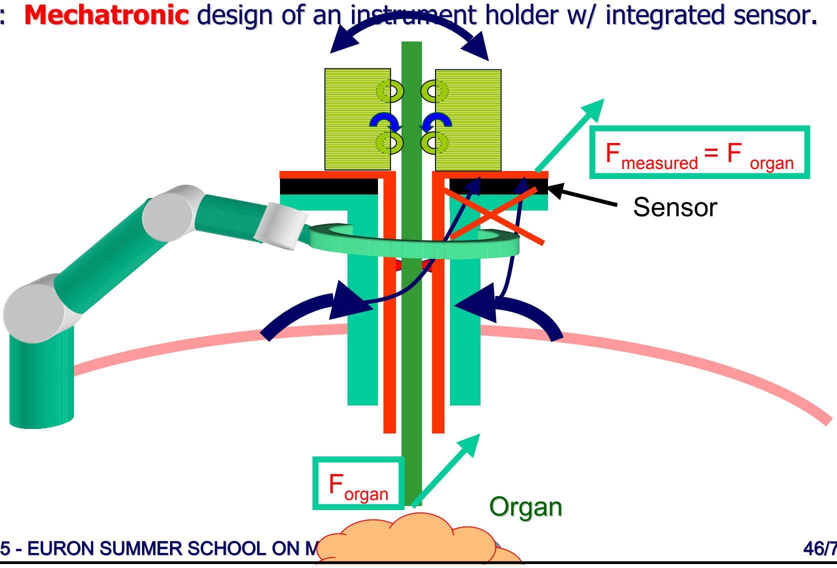
# 2.3 Force-Position coupling for TMIS

## c) Force sensing at the trocar [25]

Trick : **Mechatronic** design of an instrument holder w/ integrated sensor.



# 2.3 Force-Position coupling for TMIS

## c) Force sensing at the trocar [25]

Trick : **Mechatronic** design of an instrument holder w/ integrated sensor.

Video w/ in vitro and in vivo experiments

---

# 2.3 Force-Position coupling for TMIS

## c) Force sensing at the trocar [25]

Trick : **Mechatronic** design of an instrument holder w/ integrated sensor.

Video w/ in vitro experiments of force-position coupling telemanipulation

# 2.4 Potential benefits

Read in [24] : *ask a surgeon if force feedback is needed for robotic surgery, and the answer is predictably « yes ».*

- I would be less affirmative.
  - A number of surgeons seem to think that force estimation from tissue deformation is enough.
  - For medical devices, benefits are evaluated in terms of direct consequences on patient’s health and/or costs.
  - As the technology is still under development, who knows how better the system will be once equipped with force feedback.
  - A great deal of work is to be done for the intuitive interfacing of force feedback teleoperated systems.

- Only a few studies can be found in the literature.

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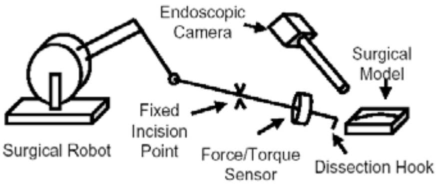
# Force feedback teleoperation reduces forces applied to the organs [24]



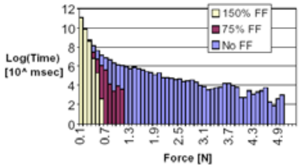
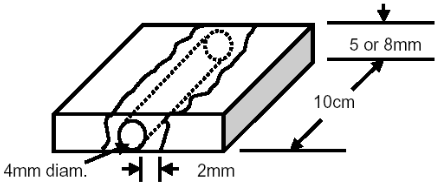


**Figure 3.** Histogram of forces applied during visible artery trials



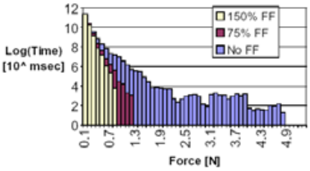
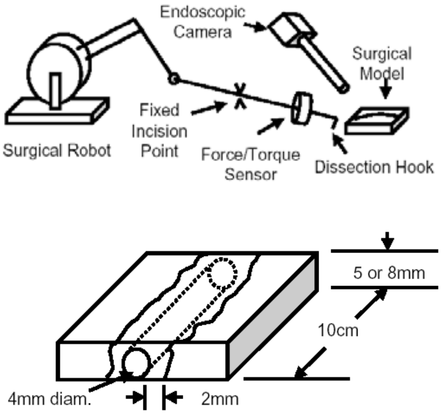


**Figure 4.** Histogram of forces applied during obscured artery trials

# Force feedback teleoperation has low influence on the operational speed [24]



Blunt dissection trials, with a given time

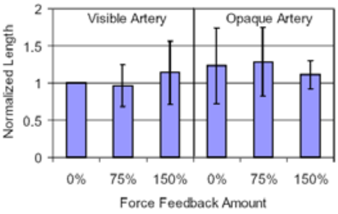


**Figure 8. Normalized length dissected vs. trial types**

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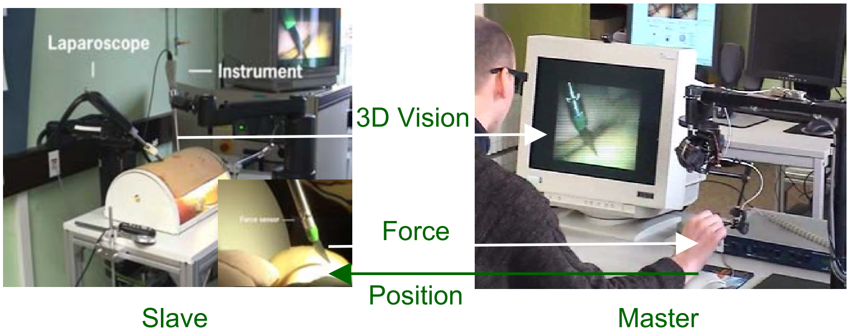
# The DLR Experimental Evaluation of Force Feedback in MIRS

(DLR, Munich, Germany)

## Experimental Setup



3D Vision

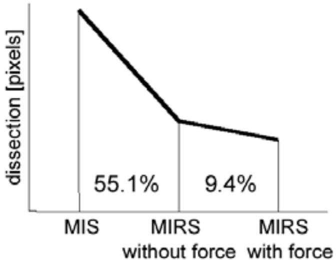
Force

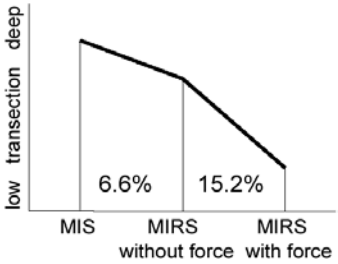
Position

Slave

Master

# Task and Results





Task:
- Dissect blood vessel

Modes:
- MIS
- MIRS without force feedback
- MIRS out force feedback

(DLR, Munich, Germany)

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# Organization of the talk

1. Force feedback closed-loop control for an "autonomous" robot.
    1. A simplistic introduction to force feedback control in Robotics.
    2. Applications to robotics for medicine.
    3. Limitations and open problems.
2. Telemanipulation.
    1. Master-slave position coupling.
    2. Force feedback telemanipulation.
    3. Position-force coupling in telemanipulation
    4. Potential benefits
3. Comanipulation.
    1. Principle
    2. Comanipulation without force sensors
    3. Active force feedback for comanipulation
4. Conclusions

# 3.1 Principle of comanipulation

- The tool (medical instrument) is held by both an operator (doctor) and a robot.
- A number cooperation paradigms can be implemented:
  - Degrees of freedom sharing : the robot controls the motions of the tool along some DoF only, while the operator controls the motion along the other DoF.
  - Space sharing : in a “free space”, the robot does not constrain the tool motion, while it blocks the tool motion in a “forbidden space”.
  - Motion filtering : a kind of “frequency domain sharing”.
  - Gravity compensation: the robot only compensates for the tool mass, which is then felt as “free-floating” by the operator.
  - Active guidance: the robot applies active (by opposition to resistive) forces to indicate to the operator where he should go.
  - Etc.

---

# 3.1 Principle of comanipulation

- Two main classes of comanipulation techniques:
  - <u>Without force sensing</u>: resistive forces can be applied by the robot by modulating its apparent stiffness.
    - Binary stiffness (very hard or very soft): use of controllable brakes.
    - Continuously variable stiffness (requires a transparent robot design and a position controller with variable gains)
  - <u>With force sensing</u>: one can directly control the interaction forces between the robot and the tool.
    - Example: a force controlled robot with a zero desired force is said to be in a transparent mode. It can compensate for gravity.

# 3.2 Comanipulation without force sensor

## a) Application to stereotactic neurosurgery [13]

(IMAG, Grenoble, France)

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

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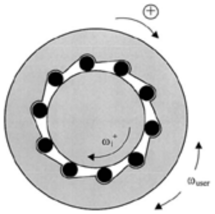
# 3.2 Comanipulation without force sensor

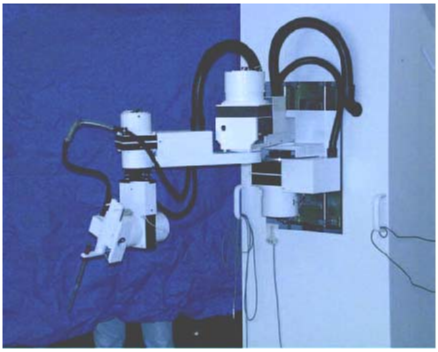
## b) An evolution of the previous one: PADyC [17]



Principle: two freewheels connected and mounted in opposite directions.
Two motors rotating at $\omega_i^+$, $\omega_i^-$.
The « user velocity » is mechanically limited by:

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

Main advantage : safety, dynamic constraints.



(IMAG, Grenoble, France)

# 3.2 Comanipulation without force sensor

## c) An application to maxilofacial surgery [2]

Principle :

1) Thanks to a transparent design, the robot (a haptic device, in fact) can be programmed with a desired apparent stiffness within a quite wide range.
2) In the region to be removed, the stiffness is low, while it's very large in the region to be left.

Main advantage : no force sensor, dynamic constraints. Less intrinsicly safe than PADyC

(CEA, Fontenay aux Roses, France)

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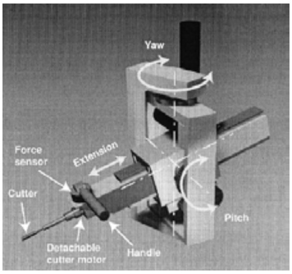
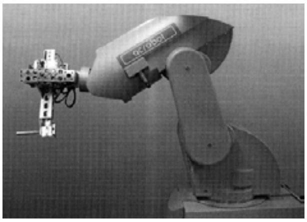
# 3.3 comanipulation w/ active force feedback

## a) Application to oethopeadic surgery : Acrobot [9]





Clinical application to knee surgery

(Imperial College of Science, Technology and Medicine, London)

## 3.3 comanipulation w/ active force feedback

### a) Acrobot [9]

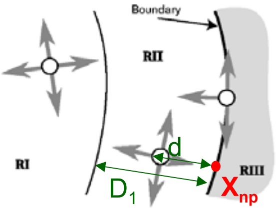
*The basic idea behind active constraint control is to gradually increase the stiffness of the robot as it approaches the predefined boundary.*

Low level control law:

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

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

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



| Region RI | Region RII | Region RIII |
|---|---|---|
| $\boldsymbol{X_d} = \boldsymbol{X}$<br>$\dot{\boldsymbol{X}}_{\boldsymbol{d}} = A\boldsymbol{F_G}$<br>$\boldsymbol{F_C} = 0$ | $\dot{\boldsymbol{X}}_{\boldsymbol{d}} = A_N\boldsymbol{F_{GN}} + A\boldsymbol{F_{GT}} \quad A_N = \frac{d}{D_1}A.$<br>$\boldsymbol{F_C} = -\frac{D_2 - d}{D_2}\boldsymbol{F_{GN}}.$ | $\dot{\boldsymbol{X}}_{\boldsymbol{d}} = A\boldsymbol{F_{GT}}$<br>$\boldsymbol{F_C} = -\boldsymbol{F_{GN}}.$ |

(Imperial College of Science, Technology and Medicine, London)

---

## 3.3 comanipulation w/ active force feedback

### b) Dermarob [6]

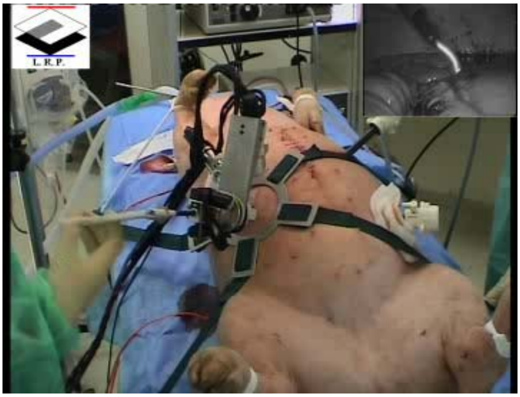
*In order to provide an easy and intuitive mean for the registration of points, Dermarob can be programmed in a transparent mode for comanipulation.*

(LIRMM, Montpellier)

# 3.3 comanipulation w/ active force feedback

## c) MC²E [25]

*When MC2E is force controlled with a zero desired force, the surgeon can feel the forces exerted inside the patient without being corrupted by the trocar forces.*



(LRP, Paris)

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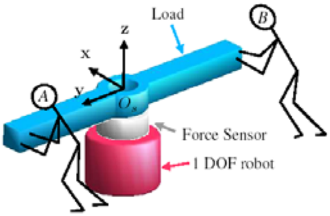
# 3.3 comanipulation w/ active force feedback

## c) MC²E [25]

A technical issue about force control:

Kinematically Constrained Manipulators (KCMs) cannot be force-controlled like others.

In particular, force component selection is quite dangerous (kinematic instability).



(LRP, Paris)

Passivity analysis showed that the only possible solution for stable control of the most general class of KCMs is to project measured and desired wrenches in the joint space without selecting force components:

If $\varepsilon_{\mathcal{T}} = \mathbf{J}(\mathbf{q})^T \varepsilon_{\mathbf{w}}$. with $\varepsilon_{\mathbf{w}} = \mathbf{w}_d - \mathbf{w}$.

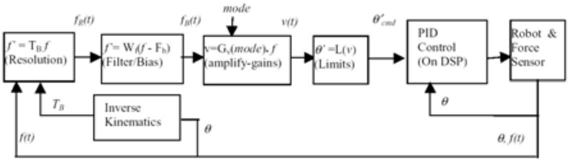
Then $\varepsilon_{\mathcal{T}} = 0$. $\Rightarrow$ $\mathbf{J}^T(\mathbf{q})\ (\mathbf{w}_d - \mathbf{w}) = 0$.

# 3.3 comanipulation w/ active force feedback

## d) Microsurgical Augmentation [19]

*Goal = scaling of interaction forces, with tool tip forces ranging from 0.001 N to 0.01 N and human interaction forces ranging from 0.03N to 3N.*

A main difference with previous examples is that the system uses 2 force sensors:
- one for measuring the interaction with human
- one for measuring the interaction with patient



(Johns Hopkins Univ.)

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# Conclusions

- Although Force Control has been studied for over 25 years, its application to Minimally Invasive Surgery is still an open problem.
- Sensing solutions are not ready yet for the Operating Room in MIS.
- Interaction Modeling is probably the toughest issue; a significant help in this field comes from the virtual reality / simulation community.
- Full scale, dexterous, in vivo experiments are still to be programmed as they are required to evaluate clearly what force feedback can effectively help the surgeon.
- Active compensation of physiological motion in a teleoperation system is one of the great technical challenges of the future years.
- Comanipulation offers a wide variety of possible interactions that has been only partially explored.

- I'm now ready for questions.
- I just want to add that:
  - Tobias Ortmaier
  - Nabil Zemiti
  - Marie-Aude Vitrani

  helped a lot to prepare that talk. Thanks.
- Thanks to Etienne and Philippe too for the invitation(1) and the great organization.

(1)"*September is a great time for staying at Montpellier*", they said; "*all the tourists are gone the weather is so nice*".

---

# A few references used for this talk

[1] Berkelman, P. J., Whitcomb, L. L., Taylor, R. H., and Jensen, P. A miniature microsurgical instrument tip force sensor for enhanced force feedback during robot-assisted manipulation. *IEEE Transactions on Robotics and Automation*, 19(5) :917-922, october 2003.

[2] Bonneau, E., Taha, F., Gravez, P., and Lamy, S. Surgicobot : Surgical gesture assistance cobot for maxillo-facial interventions.In *Proc. of MRNV 2004 : Medical Robotics, Navigation and Visualization*. Remagen, Allemagne, march 2004.

[3] Courrèges, F., Poisson, G., Vieyres, P., Gourdon, A., Szpieg, M., and Mérigeaux, O. Real time exhibition of a simulated space tele-echography using an ultralight robot.In *Proc. of ISAIRAS - 6th International Symposium on Article Intelligence, Robotics and Automation in Space*. Montréal, Canada, june 2001.

[4] Desblancs, C., Mazal, A., R.Ferrand, and Habrand, J. Use of robots for patient positioning at the Orsay protontherapy center. *To appear in Medical Image Analysis*.

[5] DiMaio, S. P. and Salcudean, S. Needle insterion modeling and simulation. *IEEE Transactions on Robotics and Automation*, 19(5) :864-875, october 2003.

[6] Dombre, E., Duchemin, G., Poignet, P., and Pierrot, F. Dermarob : a safe robot for reconstructive surgery. *IEEE Trans. on Robotics and Automation*, 19(5) :876-884, 2003.

[7] Dubois, P., Thommen, Q., and Jambon, A. In vivo measurement of surgical gestures. *IEEE Trans. on Biomedical Engineering*, 49(1) :49-54, 2002.

[8] Hu, T., Tholey, G., Desai, J. P., and Castellanos, A. E. Evaluation of a laparoscopic grasper with force feedback. *Surgical Endoscopy*, 18(5) :863, 2004.

[9] Jakopec, M., y Baena, F. R., Harris, S., Gomes, P., J. Cobb, J., and Davies, B. The hands-on orthopaedic robot "acrobot" : Early clinical trials of total knee replacement surgery. *IEEE Transactions on Robotics and Automation*, 19(5) :902-911, 2003.

[10] Kennedy, C. and Desai, J. P. Force feedback using vision.In *International Conference on Advanced Robotics*. Coimbra, Portugal, 2003.

[11] Krupa, A., Morel, G., and de Mathelin, M. Achieving high precision laparoscopic manipulation through adaptive force control. *Advanced Robotics*, 18(9) :905-926, 2004.

[12] Kuchenbecker, K. J. and Niemeyer, G. Cancelling induced master motion in force reflecting teleoperation.In *Proc. ASME Int. Mech. Eng. Congress and Exposition*. november 2004.

[13] 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.

[14] Marescaux, J., Leroy, J., Gagner, M., Rubino, F., Mutter, D., Vix, M., Butner, S., and Smith., M. Transatlantic robot-assisted telesurgery. *Nature*, 413 :379-380, 2001.

[15] Pierrot, F., Dombre, E., Dégoulange, E., Urbain, L., Caron, P., Boudet, S., Gariépy, J., and Mégnien, J.-L. Hippocrate : A safe robot arm for medical applications with force-feedback. *Medical Image Anal.*, 3(3) :285-300, 1999.

[16] Rosen, J., Hannaford, B., Farlane, M. M., and Sinanan, M. Force controlled and teleoperated endoscopic grasper for minimally invasive surgery. *IEEE Transactions on Biomedical Engineering*, 46(10), 1999.

[17] Schneider, O. and Troccaz, J. A six-degree-of-freedom passive arm with dynamic constraints (padyc) for cardiac surgery application : preliminary experiments. *Computer Aided Surgery*, (6) :340-351, 2001.

[18] Seibold, U., Kuebler, B., Weiss, H., and Hirtzinger, T. O. G. Sensorized and actuated instruments for minimally invasive surgery.In *Proc. of 4th International Conference EuroHaptics*. Munich, Allemagne, june 2004.

[19] Taylor, R., Jensen, P., Whitcomb, L., Barnes, A., Kumar, R., Stoianovici, D., Gupta, P., Wang, Z., de Juan, E., and Kavoussi, L. A steady-hand robotic system for microsurgical augmentation. *International Journal of Robotics Research*, 18 :1201-1210, 1999.

[20] Taylor, R. H., Funda, J., Eldridge, B., Gomory, S., Gruben, K., Larose, D., Talamini, M., Kavoussi, L., and Anderson., J. A telerobotic assistant for laparoscopic surgery. *IEEE Engineering in Medicine and Biology Magazine Special Issue on Robotics in Surgery*, 14(3) :279-291, 1995.

[21] Troccaz, J., Lavallée, S., and Hellion, E. A passive arm with dynamic constraints : a solution to safety problems in medical robotics ?In *Proc. of IEEE SMC : Systems, Man and Cybernetics*, pages 166-171. 1992.

[22] Vilchis, A., Troccaz, J., Cinquin, P., Masuda, K., and Pelissier, F. A new robot architecture for tele-echography. *IEEE Transactions on Robotics and Automation*, 19(5) :922-926, 2003.

[23] Vitrani, M. A., Morel, G., and Ortmaier, T. Automatic guidance of a surgical instrument with ultrasound based visual servoing.In *Proc. of the IEEE International Conference on Robotics and Automation*, pages 510-515. Barcelona, Spain, april 2005.

[24] Wagner, C. R., Stylopoulos, N., and Howe, R. D. The role of force feedback in surgery : Analysis of blunt dissection.In *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. march 2002.

[25] Zemiti, N., Ortmaier, T., Vitrani, M., and Morel, G. A force controlled laparoscopic surgical robot without distal force sensing.In *Proc. of ISER'04 : The international symposium on experimental robotics*. 2004.

[26] Sallé, D., Bidaud, Ph. and Morel (G.) – *Optimal Design of High Dexterity Modular MIS Instrument for Coronary Artery Bypass Grafting.* In Proc. of ICRA'04: IEEE International Conference on Robotics and Automation, New Orleans, LA, USA, May 2004.

[27] de Sars, V., Szewczyk J. and Bidaud, Ph. – *Force and Position Control of an SMA Actuated Endoscope,* Proc. Of ROMANSY'02 : 14th CISM-IFTOMM Symposium on Theory and Practice of Robots and Manipulators, pp.527-536, Udine, Italie, Juillet 2002.