Medical robot design and control

MICCAI'09 Tutorial
on
Medical Robotics and Computer Assisted Intervention

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LIRMM : Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier

- University of Montpellier and CNRS*
- Staff (01/01/2009): 366
  - 156 Faculty members (112 from University, 37 CNRS*, 7 INRIA**)
  - 14 Post-docs
  - 35 Technical and Administrative staffs (8 from University, 21 CNRS)
  - 161 PhD students

www.lirmm.fr

***CNRS: French National Center of Scientific Research**

**** INRIA: National Research Institute for Computer Sciences and Automatic Control**

Outline

- Future directions and technical challenges
  - Intra-body robotics
  - Beating heart surgery
- Some control issues in assisted MIS and cardiac surgery

- **Specifications**
  - lightweight, smaller, simpler, cheaper,
  - integration in the OR: plug-and-play systems
  - setup and skin-to-skin times as in conventional procedure
  - sensors: sterilizable or disposable
  - MMI: easy and friendly cooperation between Surgeon and Robot ("Hands-on" / Co-manipulation concept: the surgeon operates the device)…

- **Trends:**
  - Dedicated robotized instruments ("smart" insrument)
  - Autonomy

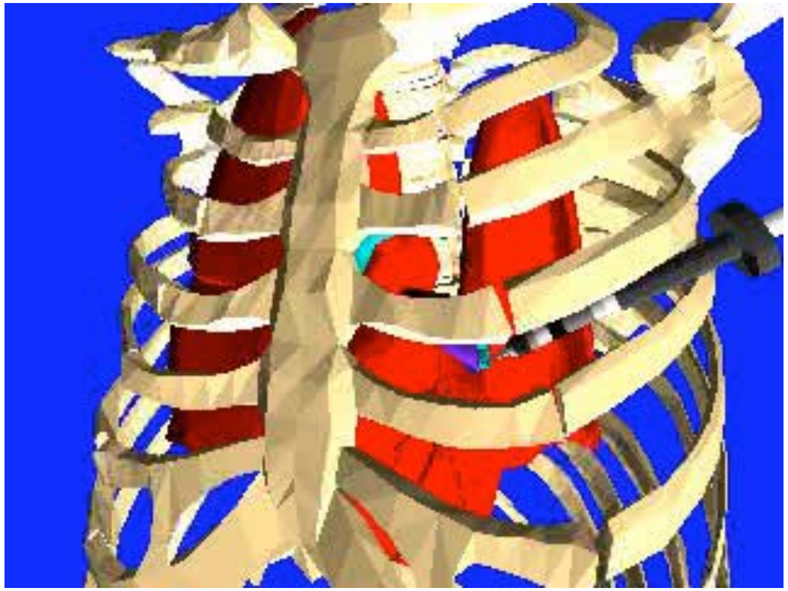
➔ Towards intra-body robotics

- Tele-operated mini-manipulators / instrument holders / surgical end-effectors
- Robotized colonoscopes and autonomous pills
- Active catheters

➔ Towards beating heart surgery

Toward intra-body robotics

- **Mini-manipulators "inside the body"**
  - could be a device fixed on the trocar or distal part of an instrument
  - high dexterity: they should compensate at most for the loss of mobility due to the trocar
  - size requirements : Ø < 10mm, L = a few cm, small radius of curvature
  - Force capabilities: a few Newtons (penetration force in a coronary artery = 1N), up to 50 N to grasp a needle



ISIR, Paris

Da Vinci (Intuitive Surgical)

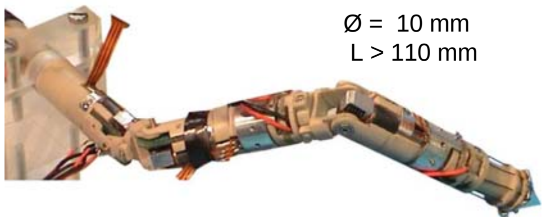
- **Mini-manipulators "inside the body"**

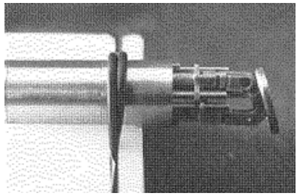
  2 design approaches:

Embedded actuators: mini-serial (or parallel) manipulators made of rigid bodies and discrete joints

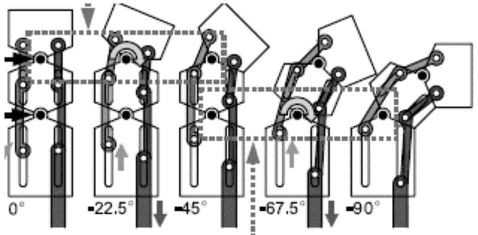
bulky, power limitation,
low reliability of actuators

DRIMIS (ISIR, Paris), 2002





MIPS (INRIA-Sophia), 2002



Dohi Lab., Univ. Tokyo

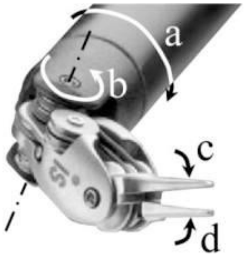
Remote actuators:

➔ Two approaches :

- **Rigid-linkage mechanisms:** *bulky, complexity*
- **Wire-driven mechanisms:**
  high dexterity but

  if cable-drives: backlash, limited reliability

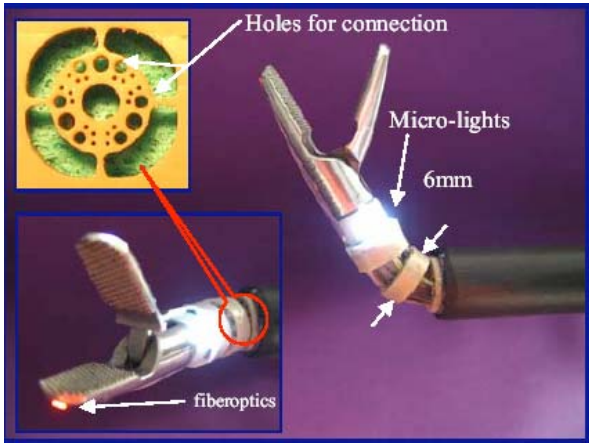
  if SMA wires (NiTi): large stroke length / weight ratio but limited bandwidth

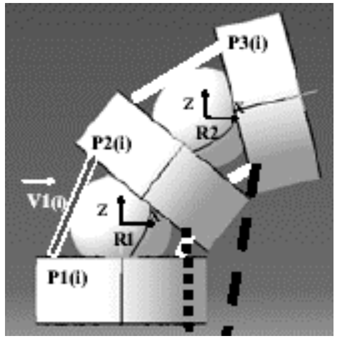


4-dof forceps (da Vinci, Intuitive Surgical)

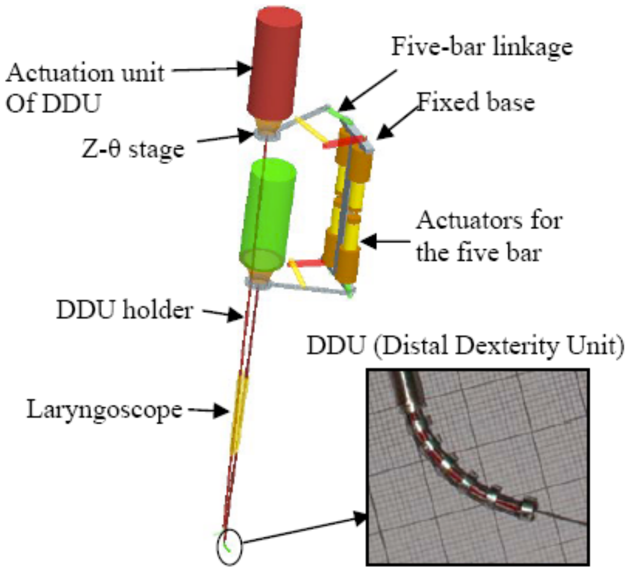
Toward intra-body robotics

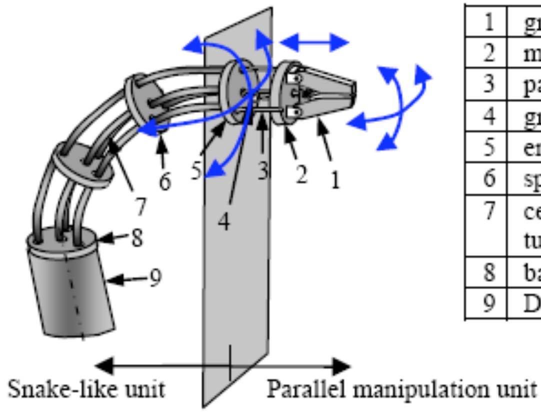
- discrete architecture (e.g. with ball joints)
- or "continuous" backbone ("snake-like")





Disposable plastic compact wrist (LAAS, Sinters 2004): plastic vertebra+balls and NiTi super-elastic wires





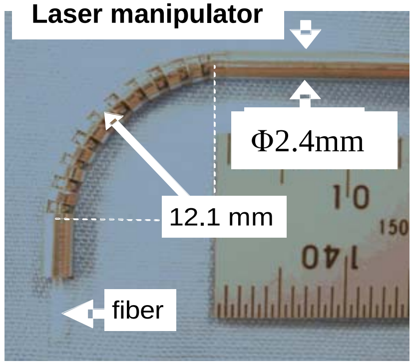
1	gripper
2	moving platform
3	parallel stage wires
4	gripper wire
5	end disk
6	spacer disk
7	central backbone tube
8	base disk
9	DDU holder

Ø=4.2
L=26
3 NiTi superelastic cables
+ 1 steel wire for rigidity

Telerobotic assistant for MIS of the upper airways (JHU & ARMA lab., Columbia Univ.), 2004

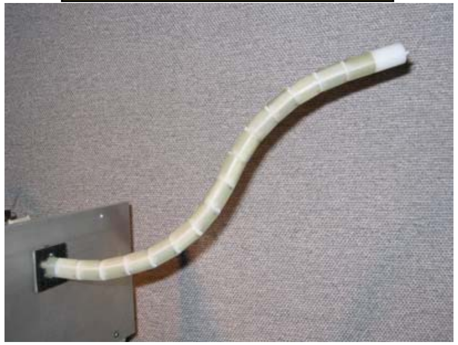
Toward intra-body robotics

Hydraulic // manipulator (KUL, Leuven), 2000



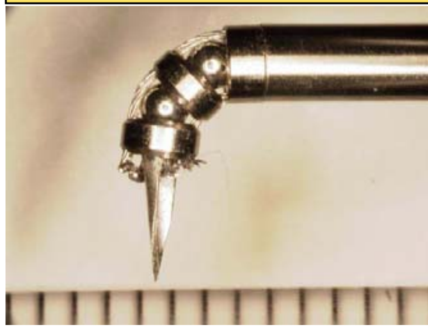
Fujie lab. (Waseda University, Tokyo)

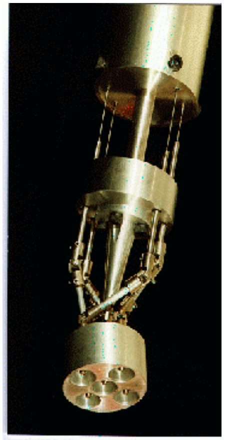
HARP (Robotics Institute, CMU, Pittsburg), 2006



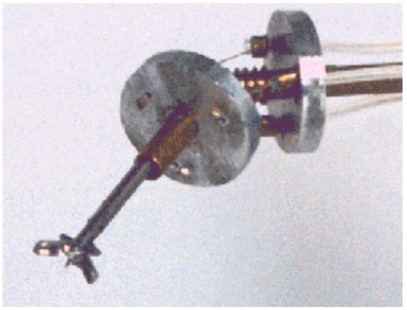
Bending forceps based on rigid linkage mechanism (Univ. Tokyo), 2003

Micro-manipulator for Intrauterine fetal surgery (Wasesa Univ., Japan), 2005



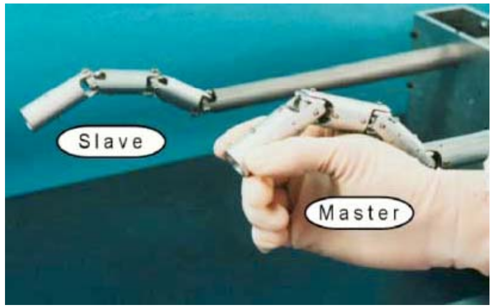


Reboulet's redundant wrist (CERT / ONERA, Toulouse), 1999



Endoscope (Univ. Berkeley)

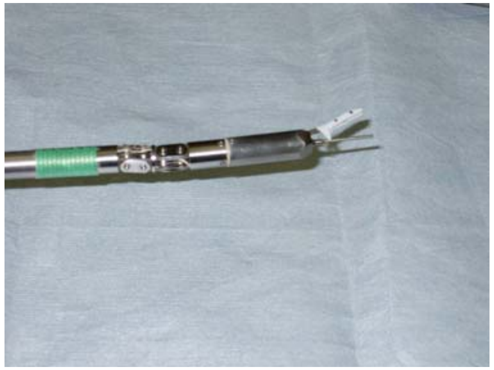
Bending US coagulator/cutter (Women's Medical Univ. Tokyo), 2004



HyperFinger (Nagoya Univ., Japan), 2003

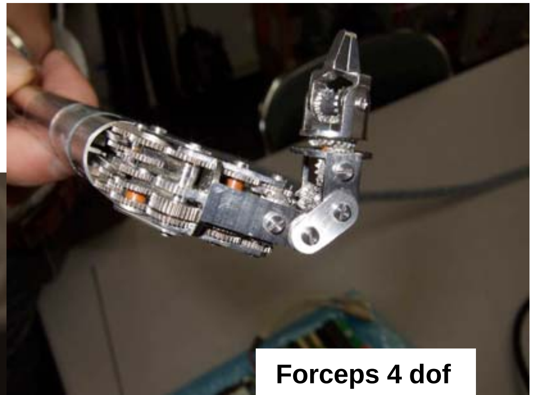
Toward intra-body robotics

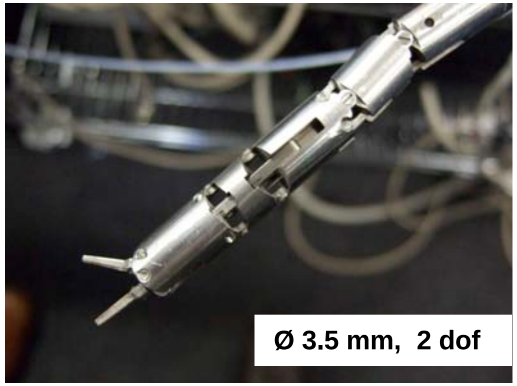
- **Rigid-linkage mechanisms**



Sakuma Lab. (Tokyo Univ.)

Fujie lab. (Waseda University, Tokyo)



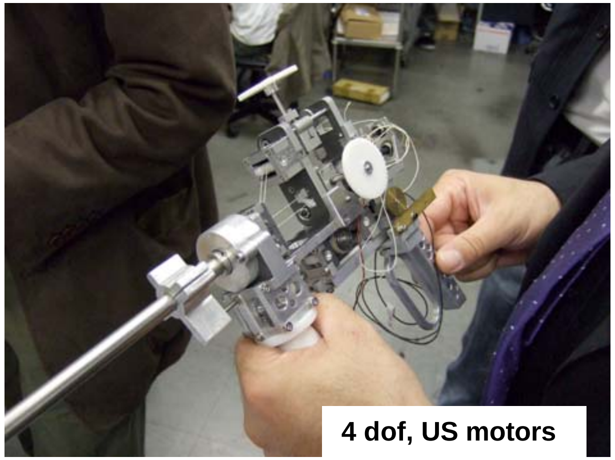


Dohi Lab. (Tokyo Univ.)

Mitsuishi Lab. (Tokyo Univ.)

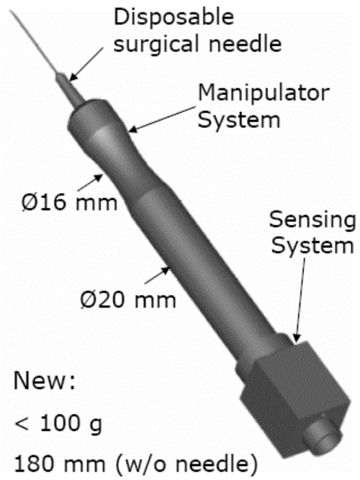
Ikuta Lab. (Nagoya Univ.)

Hand-held motorized instruments

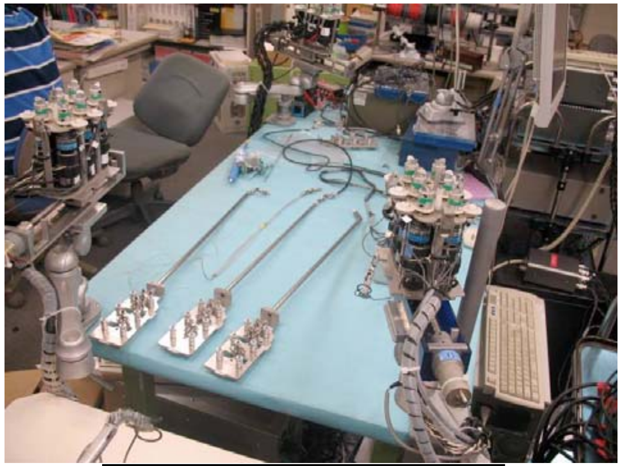


Sakuma Lab. (Tokyo University)

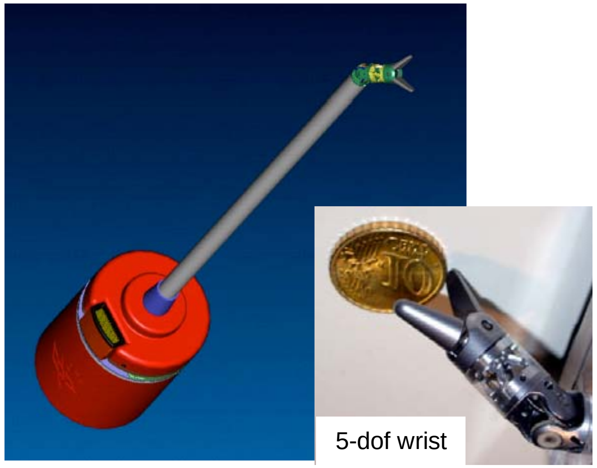
MICRON tremor cancelling instrument (CMU, Pittsburgh): eye surgery



Fujie lab. (Waseda University, Tokyo)



Ikuta Lab. (Nagoya University)

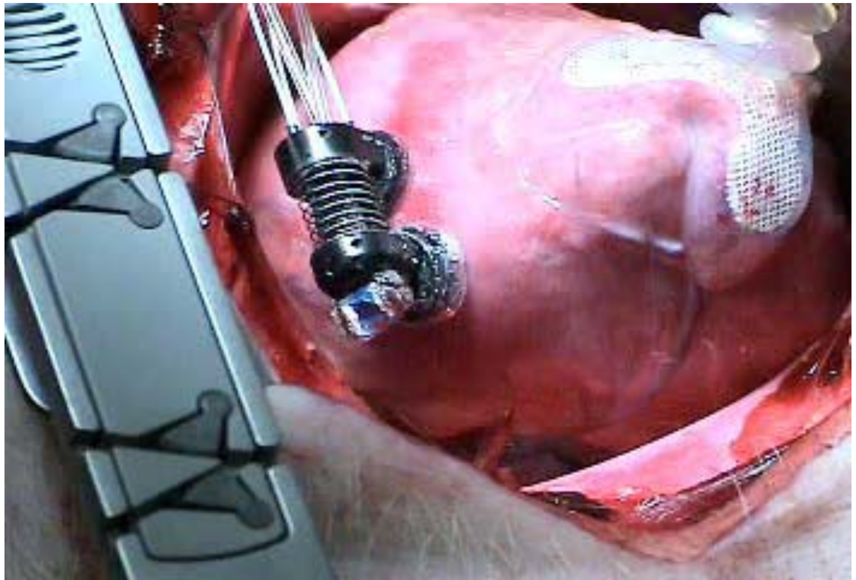


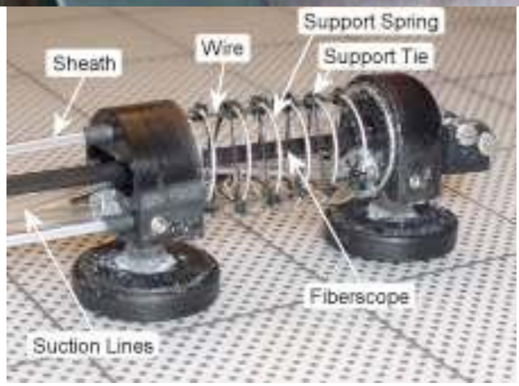
Forceps (German Aerospace center, DLR, Germany)

Toward intra-body robotics

HeartLander (The Robotics Institute, CMU, Pittsburgh)

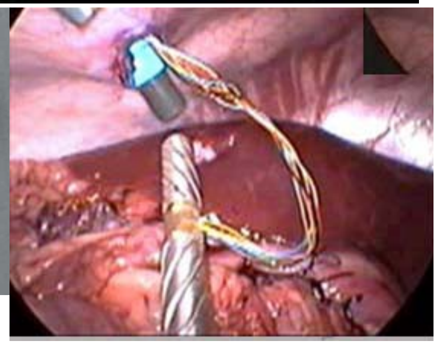
… an inchworm-like mobile robot for minimally-invasive beating-heart cardiac surgery



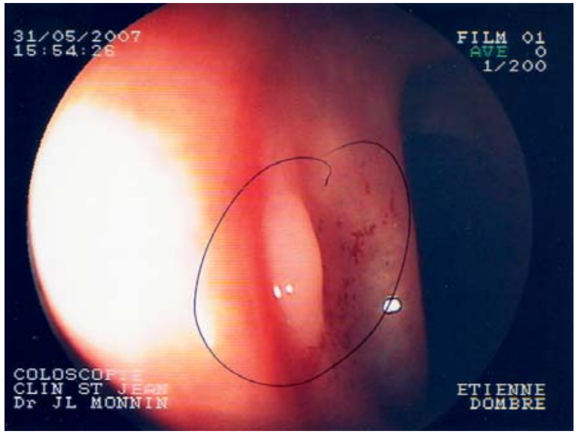


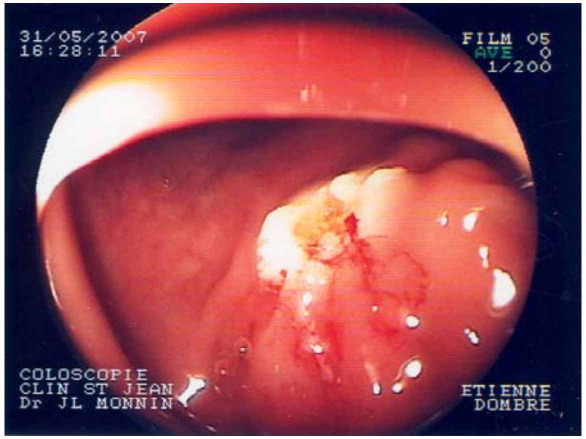
In vivo mobile robot (Robotics & Mechatronics Lab., Univ. Nebraska)

… a wheeled-driven mobile robot to be placed in the abdominal cavity

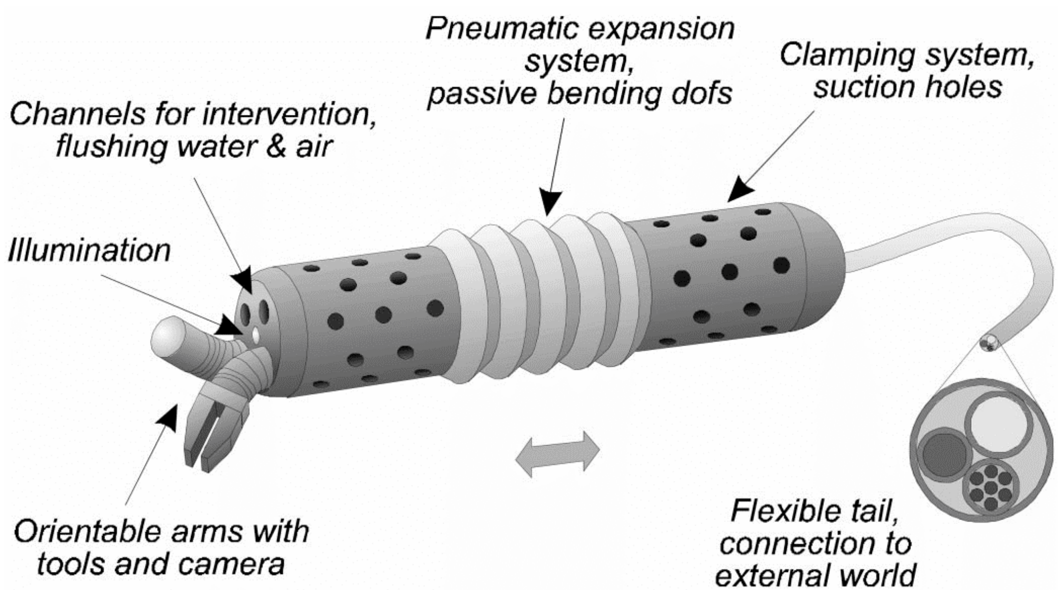


- **Robotized colonoscopes / autonomous pills**
  - Goal: Inspection of the gastrointestinal tract (small intestine, colon).
  - Colon cancer: one of the main causes of death in the industrialized countries
  - Detection and resection of polypus
  - Currently, manual colonoscopy: push-type flexible endoscope (up to Ø 2cm) with CCD camera, optical fiber for illumination, working channels (air, water, wire-actuated instruments for biopsy…)
  - Technically demandind for the coloscopiste, unpleasant for the patient





- **Solutions**
  - Semi-autonomous colonoscope: self propelling robot with a tether to transport fluids and energy

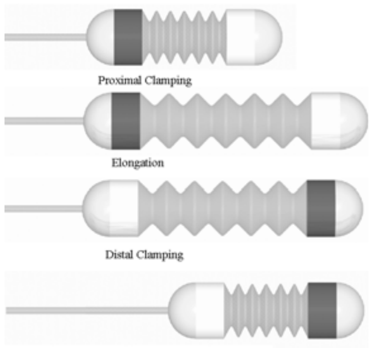


Katholieke Universiteit Leuven, Belgium

Toward intra-body robotics

Solutions

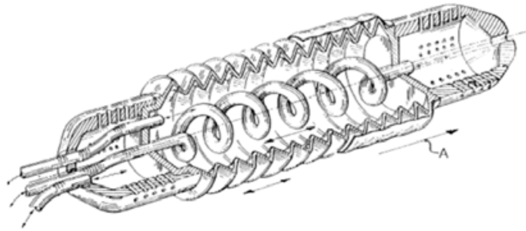
- Semi-autonomous colonoscope: self propelling robot with a tether to transport fluids and energy
- Autonomous untethered pill swallowed by the patient (thus, the whole tract may be inspected)



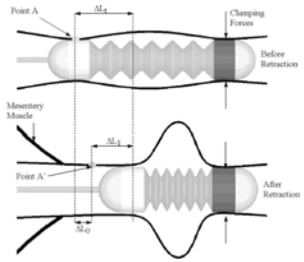
Propulsion based on inchworm locomotion

Ø = 12 mm
Lmin = 115
Lmax = 195

EMIL (SSSA, ARTS Lab., Pise)



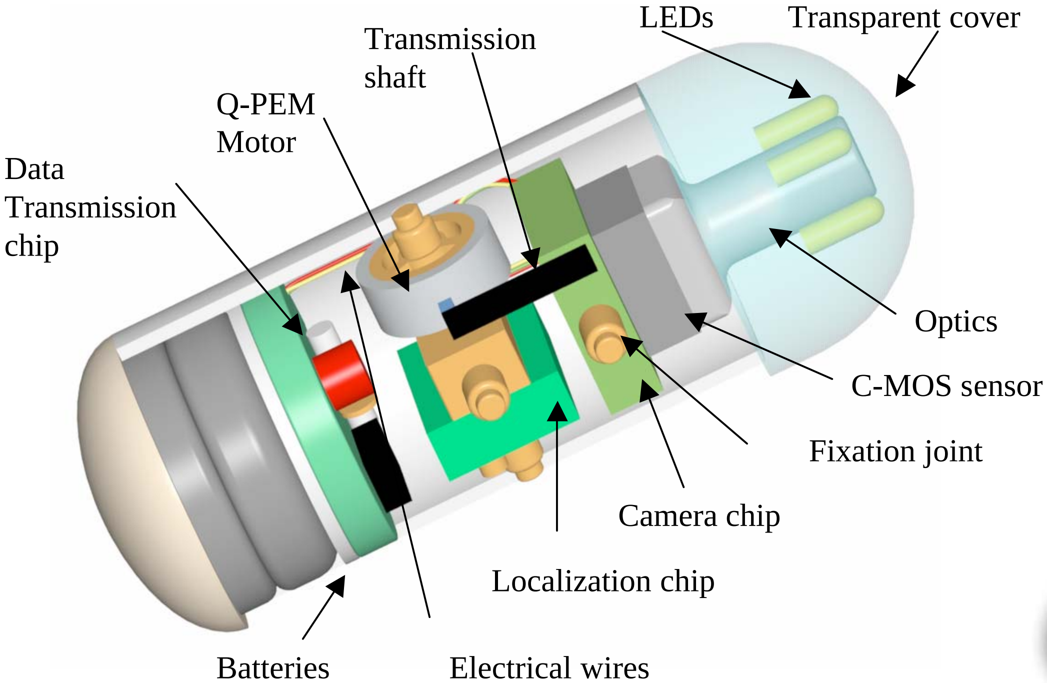
… but colon is collapsible, slippery, has acute bends, which limit traveling capabilities of semi-automatic colonoscopes



Accordeon effect

Autonomous untethered pill swallowed by the patient

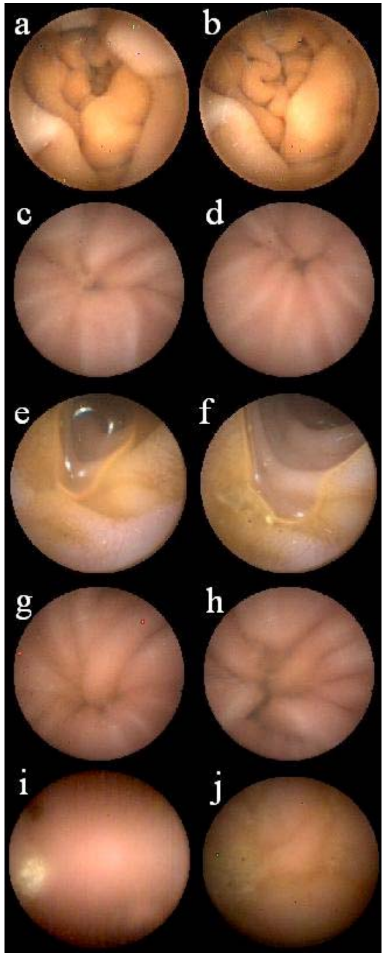
The Endoscopy « Pill », Given Imaging – M2A



Intracorporeal Video Probe

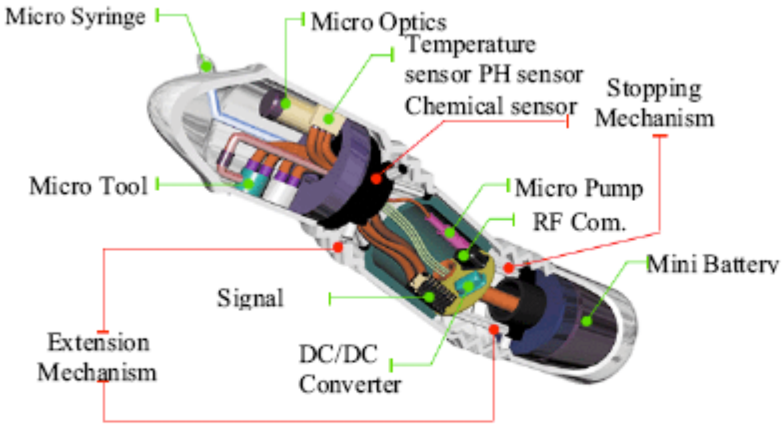
L = 20 mm, Ø = 8 mm
CMOS technology
RF trasmission data
With steerable camera

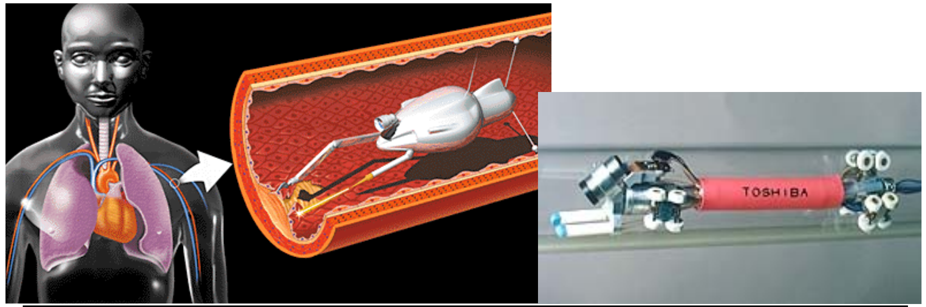
PillCam SB2 :
L = 26 mm, Ø = 11 mm P = 3,7 g
Autonomy : 6h à 8h
2 images / sec. (240x240 pixels)➔> 50000 images to process!



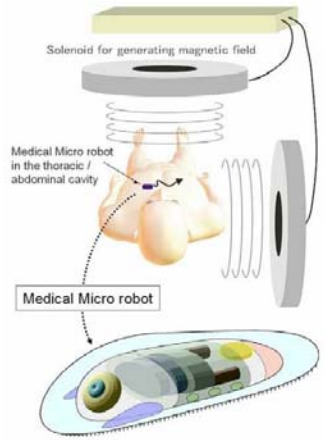
Toward intra-body robotics

Microcapsule for gastrointestinal diagnosis and therapy (IMC, Korea)





"In pipe" inspection microrobot (weight: 16g) (Toshiba, Japan)



Life Support Mechatronics Lab. (Ritsumeikan Univ., Japan)i)

Norika3 et (RFSystem Lab., Japan), 2001

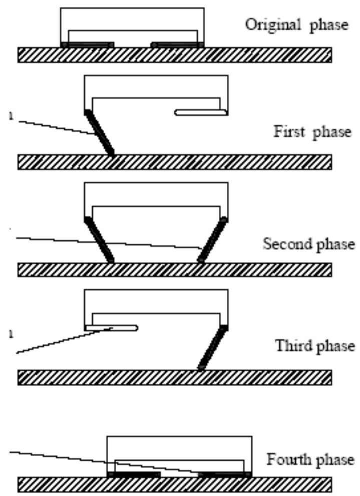
Sayaka, Japan, 2005

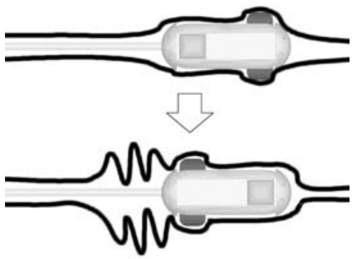
Smart capsule endoscope (Olympus Co., Japan)

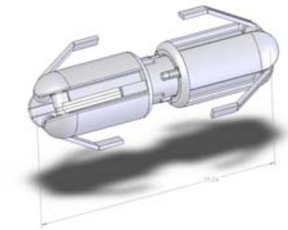
Toward intra-body robotics

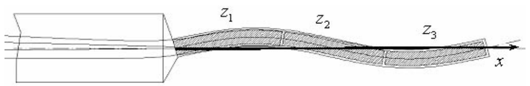
Technical issues

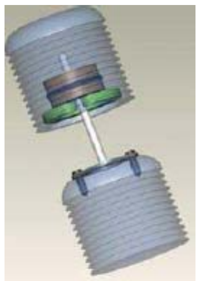
- Energy storage for longer autonomy
- Active locomotion (wrt natural peristaltic waves of the tract):
  - biomimetic approaches: Inchworm, legs (SSSA), cilia, swimming (fins, tails)
  - sliding clampers
  - paddling
  - inertia impact



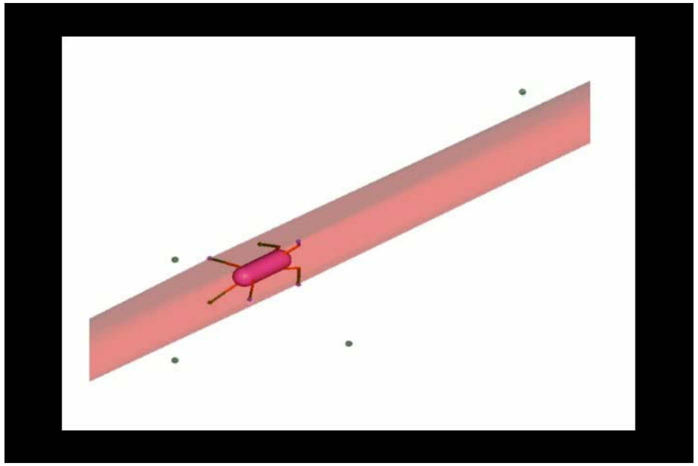








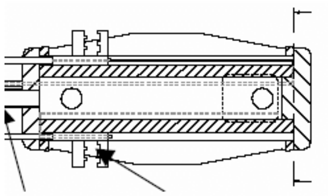
Toward intra-body robotics

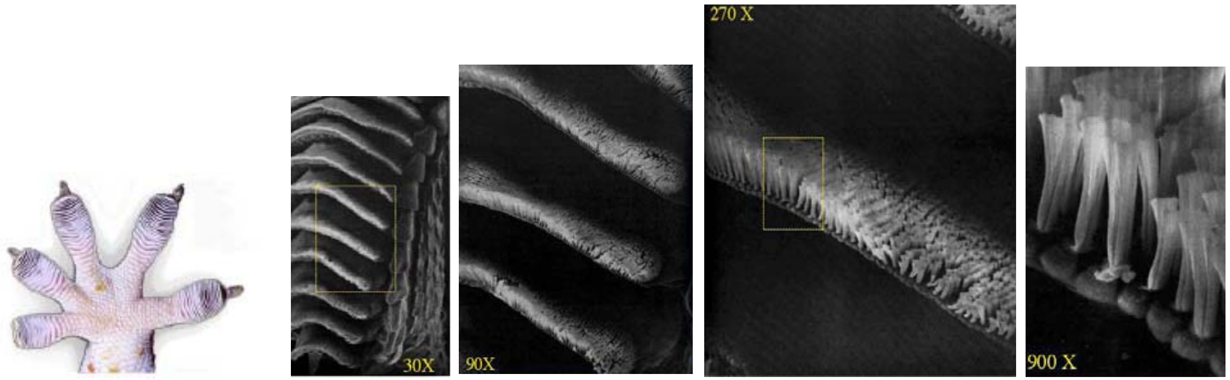


SSSA, ARTS Lab., Pise

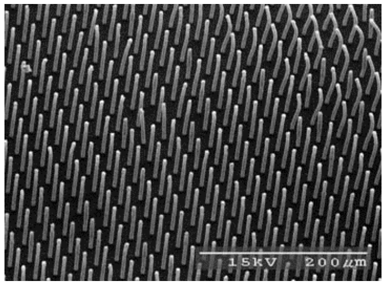
➔ **Technical issues**

- Miniaturization, energy
- Active locomotion (wrt natural peristaltic waves of the tract):
  - biomimetic approaches: Inchworm, legs (SSSA), cilia, swimming (fins, tails)
  - sliding clampers
  - paddling
  - inertia impact
- Clamping capabilities
  - mechanical grippers
  - suction
  - biomimetic approaches: gecko, beetle, fly, cockroach pads…





Lamellae → Setae (mm) ➝ Nano-fibers (200 nm)



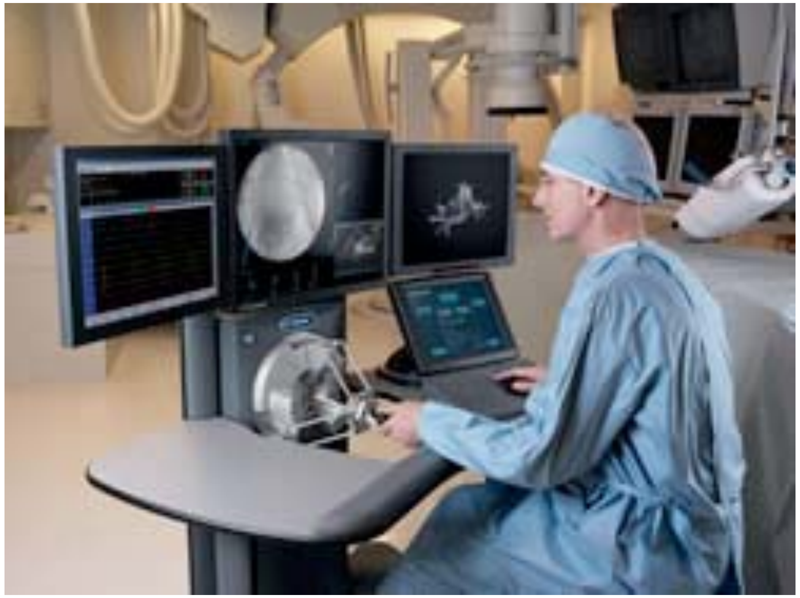
4 μm molded polyurethane fibers

- **Active catheters**
  - Catheter: a tube that can be inserted into a body cavity duct or vessel. Catheters thereby allow drainage or injection of fluids or access by surgical instruments (Wikipedia). Also used for angioplasty, blood pressure measurement...
  - Typical sizes: Ø <2-3 mm, L > 1m
  - Manually introduced by the surgeon, often at the level of the groin in the femoral artery, by pushing and rotating actions under X-ray control
  - Difficulty: transmit force and motion to the catheter tip with no or poor tactile feedback while minimizing X-ray irradiation. Risks of perforation of the artery or vein

➔ Solution
  - Active bending of the tip
  - Actuation: Hydraulic, SMA, conductive polymers…

Toward intra-body robotics

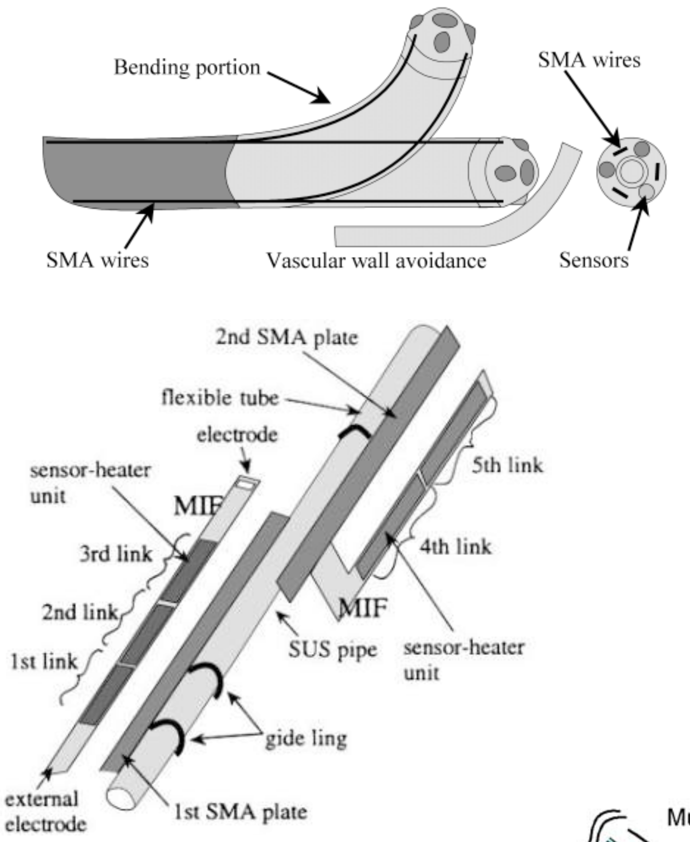
Sensei Robotic Catheter System (Hansen Medical, Mountain View, CA), 2002



- **Steerable catheter for percutaneous procedures:**
  - Remote accurate positioning, manipulation and stable control in 3D
  - The doctor is then shielded from radiation exposure
  - « Instinctive » control: the catheter immediately replicates the hand movement of the motion controller

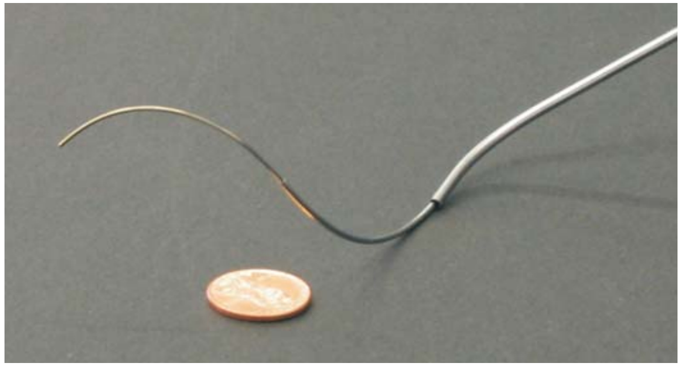
Toward intra-body robotics

- **Active catheters**

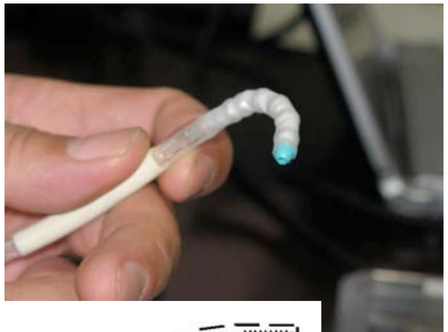


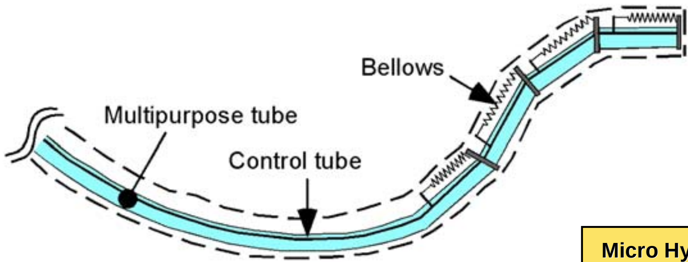
Olympus catheter, Japan, 1999

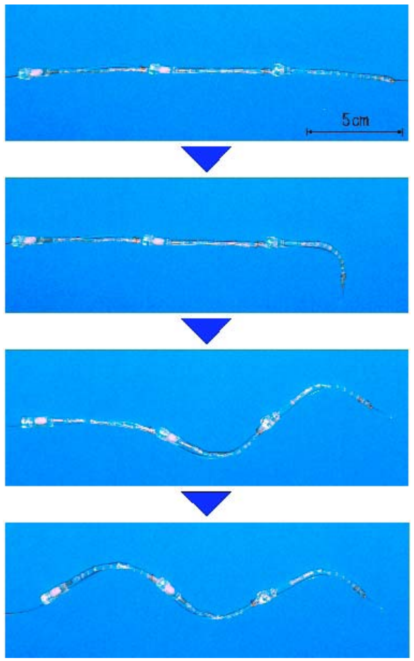
Ø = 1.5 mm, L = 15 cm



Active canula made of superelasctic nitinol tube (JHU, Baltimore, 2006)





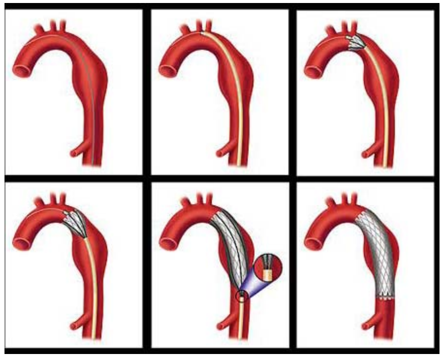


Micro Hydraulic Active Catheter with micro-valves, (Ikuta Lab., Nagoya Univ., Japan)

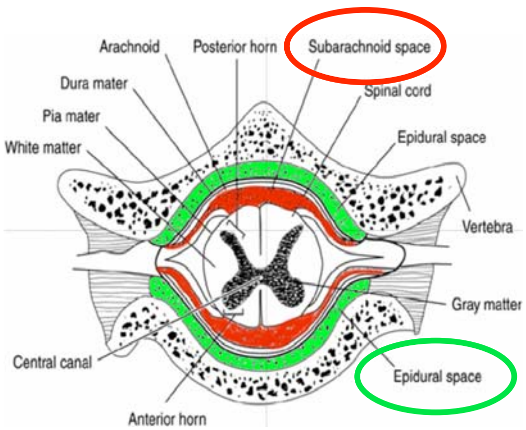
Film..\Conf. Rob Méd\MALICA.avi

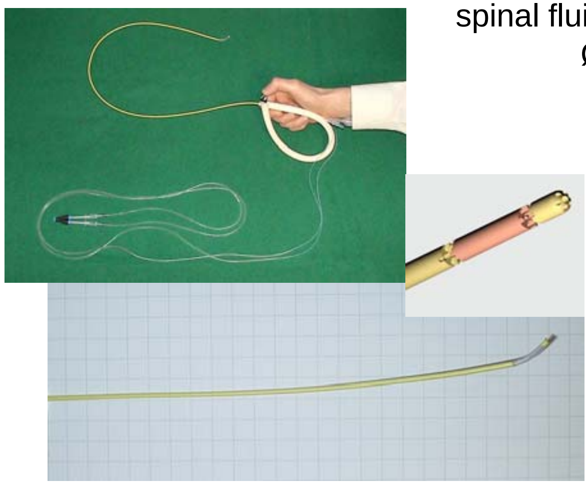
MALICA (LIIA, Paris XII): aneurysm repair

- Guidance of catheter to fix endoprothesis inside the artery (aortic aneurysm repair)
- Hydraulic « Snake like » robot: 2 ddl, Ø 5mm x 20mm



MINOSC (5th FP EU project coordinated by SSSA, Pisa): precise and early diagnosis of spinal cord lesions





Endoscopy of the spinal cord: navigation in the cerebro-spinal fluid with micro-jets to avoid touching tissues
Ø 2.7 mm

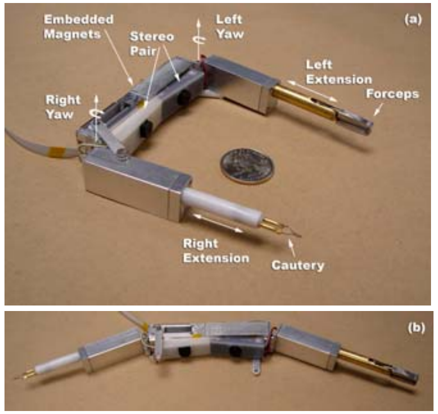
Toward intra-body robotics

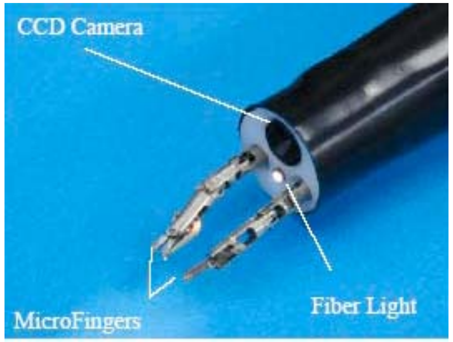
Transluminal endoscopic surgery

- NOTES : Natural Orifice Transluminal Endoscopic Surgery
- Incisionless surgery
- Through transgastric and transvaginal route
- Justification:
  - reduction or absence of postoperative pain
  - ease of access to some organs
  - absence of trauma to the abdominal wall
  - ideal cosmetic results

Bending forceps (Hitachi, Japan), 2000

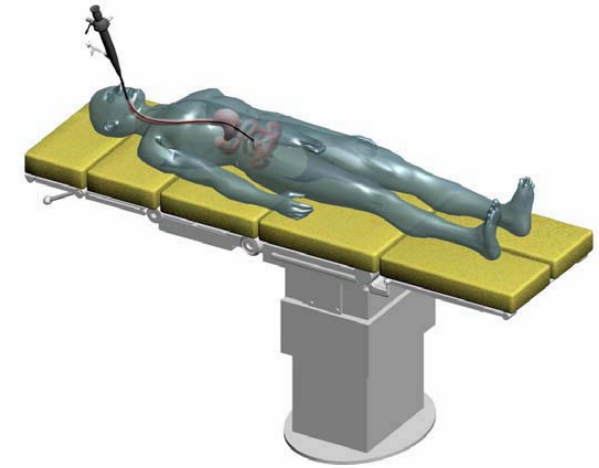
Notes robot (Robotics & Mechatronics Lab., Univ. Nebraska)

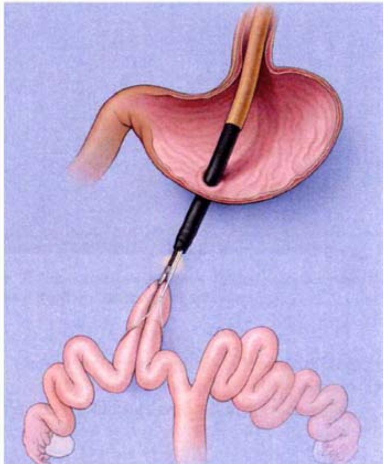


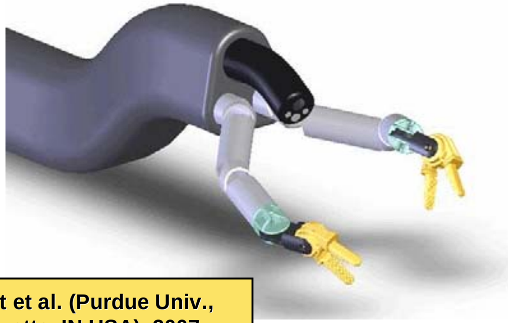


Endoscopy surgery system (Nagoya Univ.), 2004

"Anubis operation" (transvaginal cholecystectomy using a flexible endoscope), Storz, IRCAD, LSIIT Strasbourg, April 2007



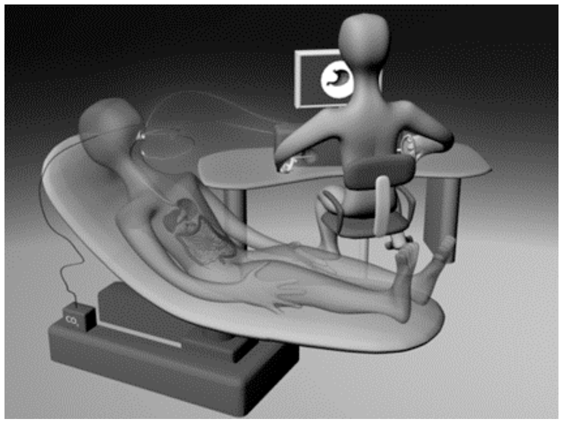


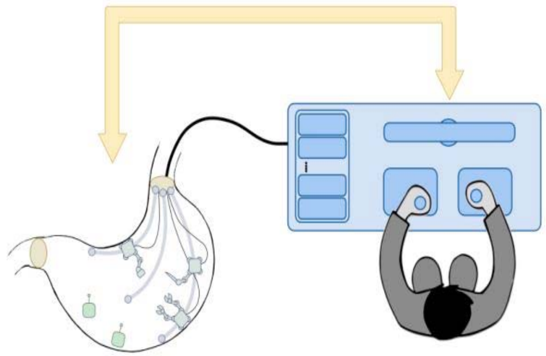


D.J. Abbott et al. (Purdue Univ., West lafayette, IN,USA), 2007

Toward intra-body robotics

- **Projet ARAKNES :** Array of Robots Augmenting the KiNematics of Endoluminal Surgery (2008-2011)
- SSSA (Pise), Univ. Pise, Imperial College (Londres), EPFL (Lausanne), LIRMM, Univ. Barcelone, Karl Storz, ST Microelectronics…
- Pathology: morbid obesity and gastro-oesophageal reflux
- Design of mini-robots with anchoring and locomotion capabilities; mounted on a deployable and collapsible platform; equipped with appropriate sensors; introduced in the stomach through oesophagus; all components will be tele-operated (thetered in a first step, then wireless)





Future directions of R&D and technical challenges

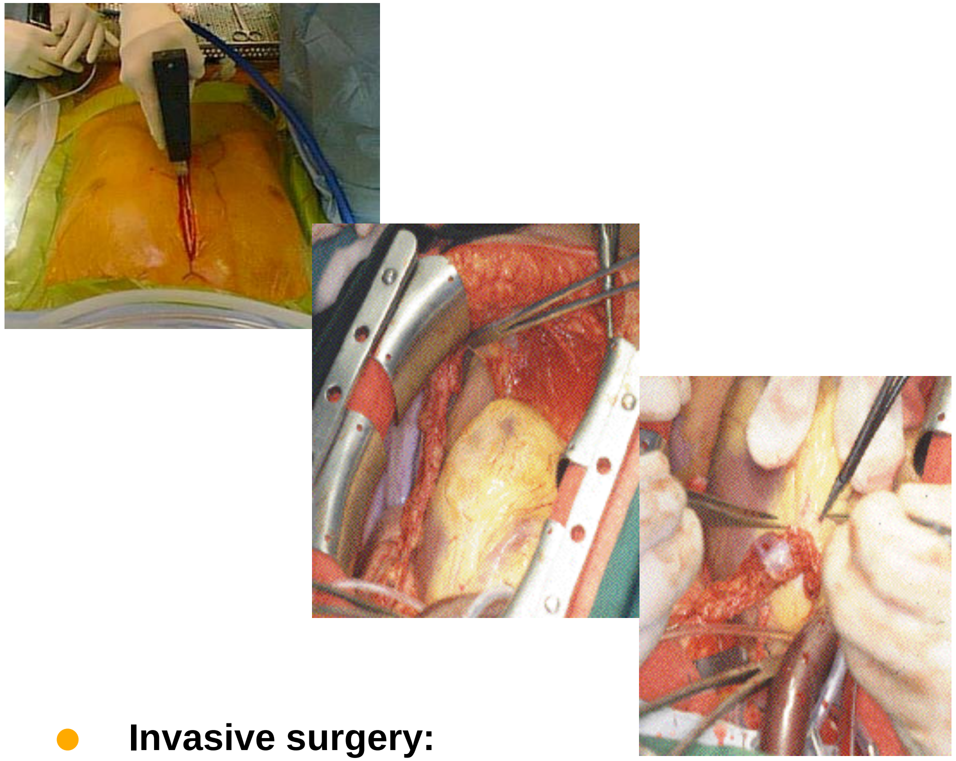
- **Technical challenges**
  - lightweight, smaller, simpler, cheaper,
  - integration in the OR: plug-and-play systems
  - setup and skin-to-skin times as in conventional procedure
  - sensors: sterilizable or disposable
  - MMI: real cooperation between Surgeon and Robot ("Hands-on" / Comanipulation concept: the surgeon operates the device)…

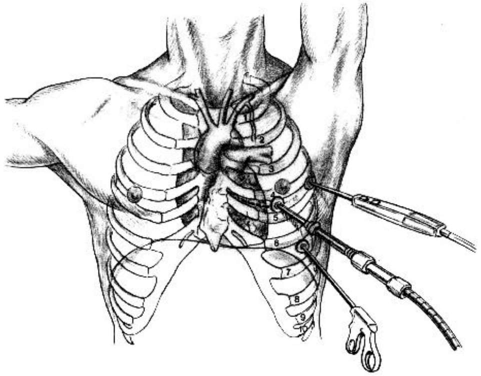
- **Trends:**
  - Dedicated robotized / "smart" instruments
  - Autonomy

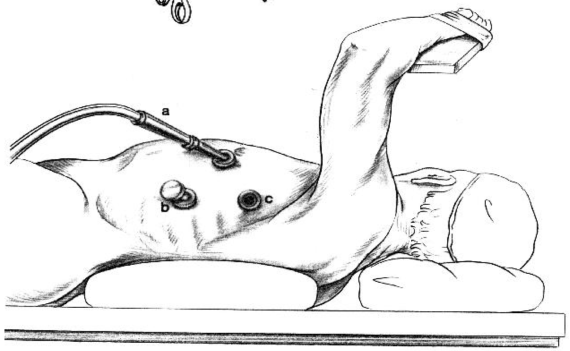
➔ Towards intra-body robotics
  - Tele-operated mini-manipulators / instrument holders
  - Robotized colonoscopes and autonomous pills
  - Active catheters

➔ Towards beating heart surgery

Minimally-invasive beating heart surgery





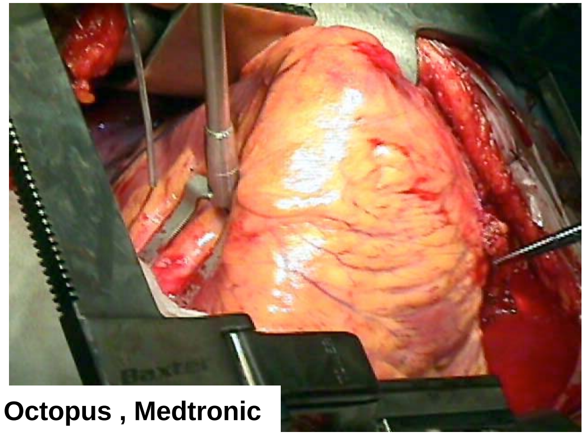


- **Invasive surgery:**
  - open the chest (sternotomy)
  - setup the heart-lung machine
  - stop the heart
  - execute the surgical gestures,
  - restart the heart and close the chest
  - many drawbacks: risk, pain…
- **Minimally invasive surgery:**
  - Off-pump surgery without stopping the heart
  - execute the surgical gestures through trocars

- **Requirements:** compensate for physiological motions (heart beats and respiratory motions)

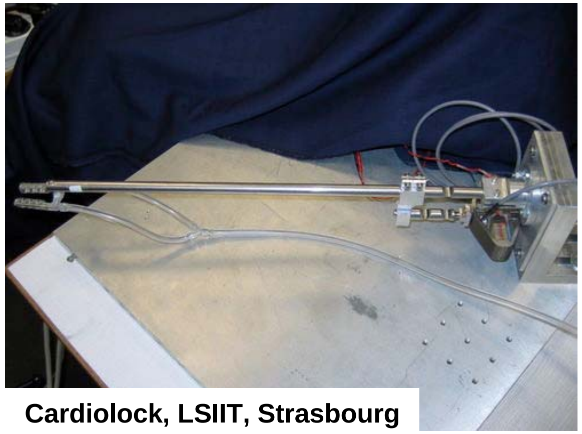
➔ **Solutions:**

- make use of a **mechanical stabilizer**



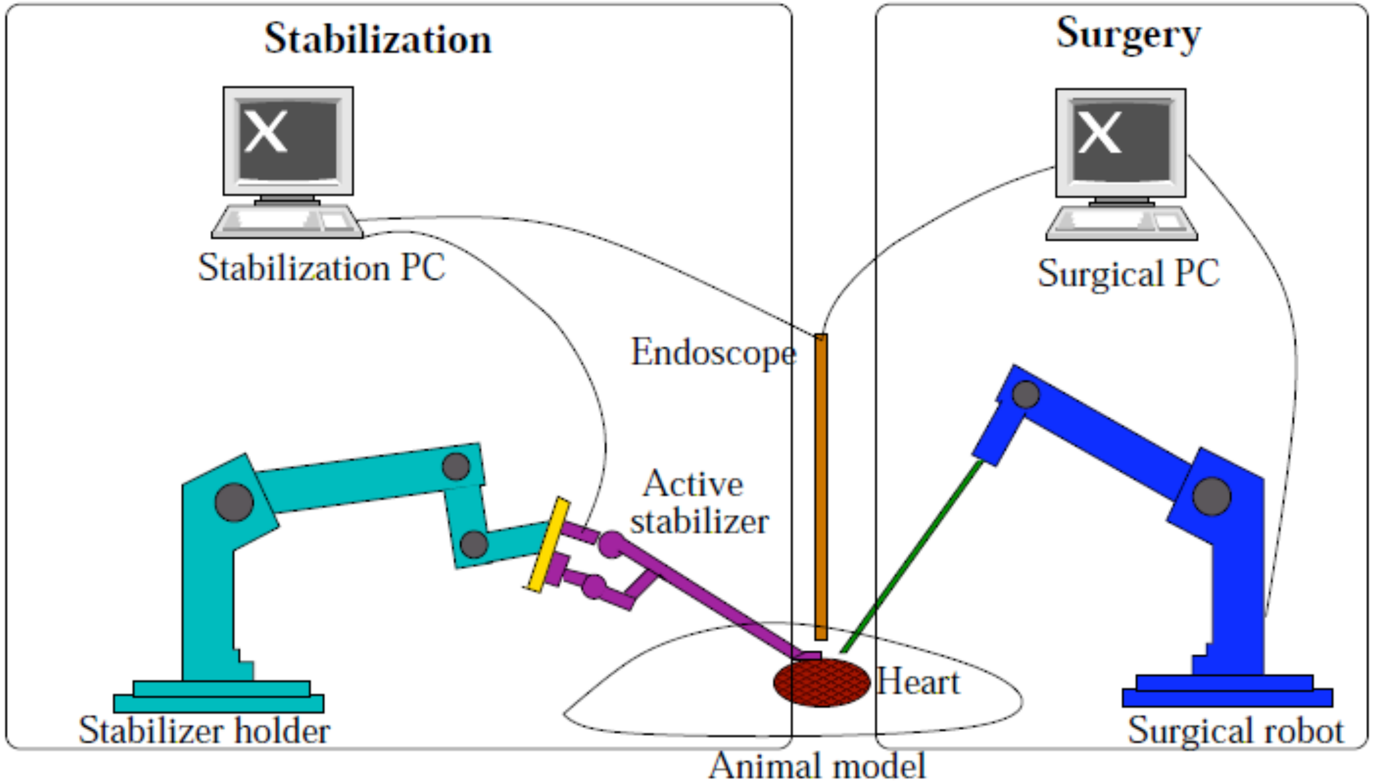
Octopus , Medtronic

- make use of an **active stabilizer**



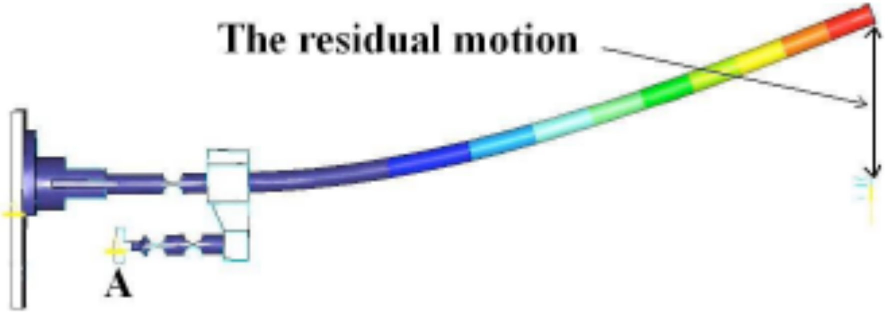
Cardiolock, LSIIT, Strasbourg

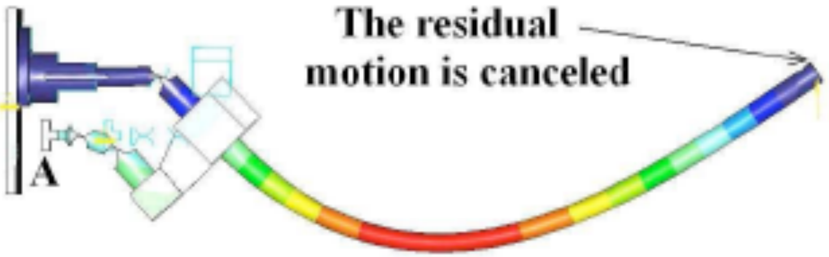
- Active stabilizer



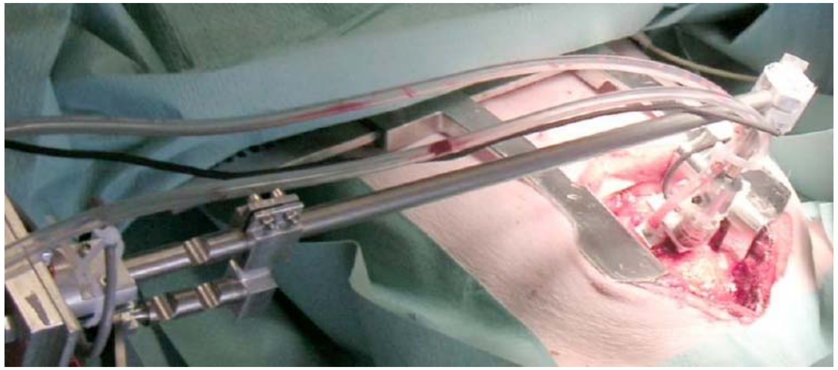
J. Gangloff, LSIIT, Strasbourg

Minimally-invasive beating heart surgery



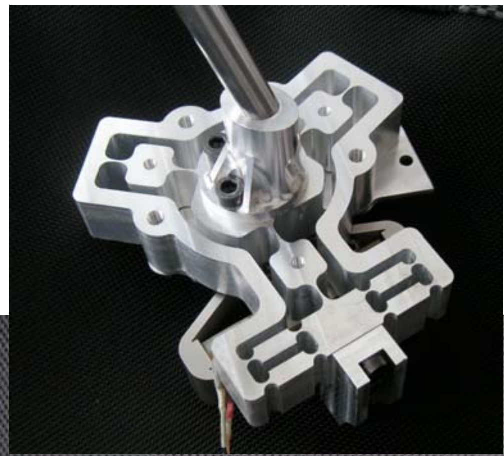


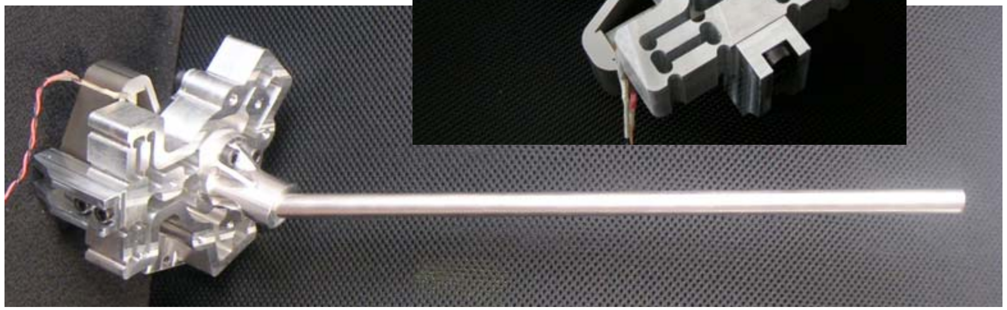
Cardiolock (LSIIT, Strasbourg), 2007



Cardilock 1-dof version

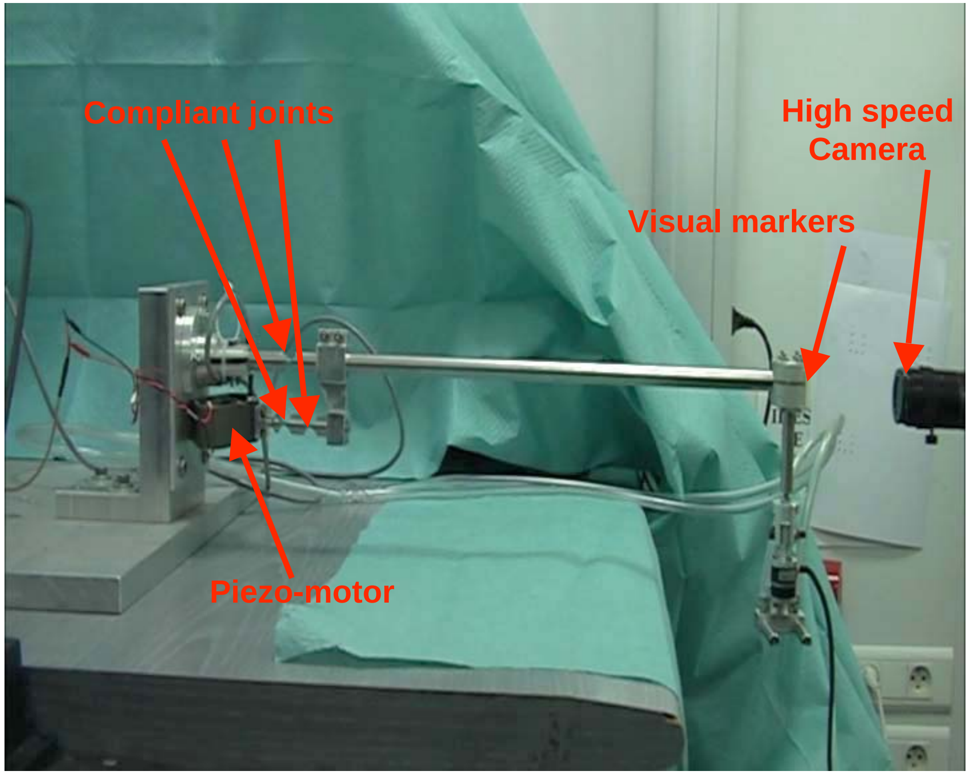
Cardilock 2-dof version



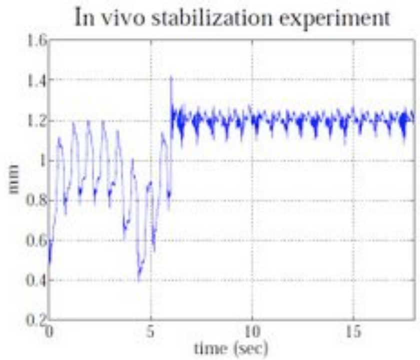


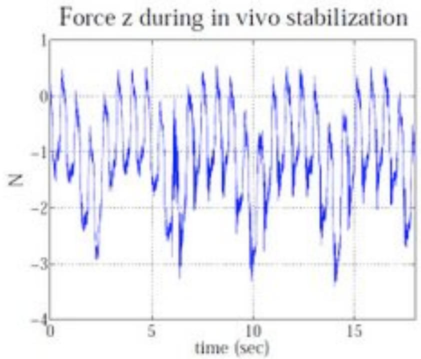
J. Gangloff, LSIIT, Strasbourg

Minimally-invasive beating heart surgery



Cardiolock (LSIIT, Strasbourg), 2007





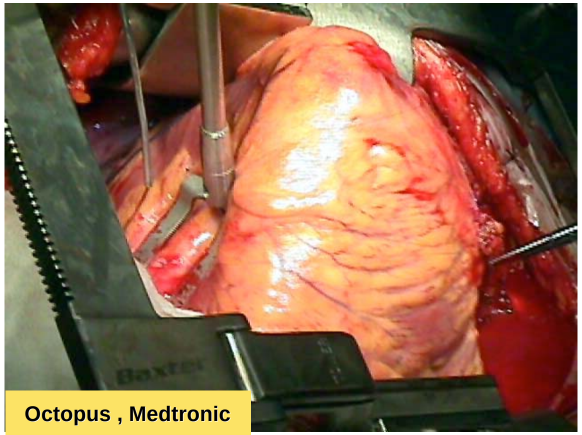
J. Gangloff, LSIIT, Strasbourg

Minimally-invasive beating heart surgery

- **Requirements:** compensate for physiological motions (heart beats and respiratory motions)

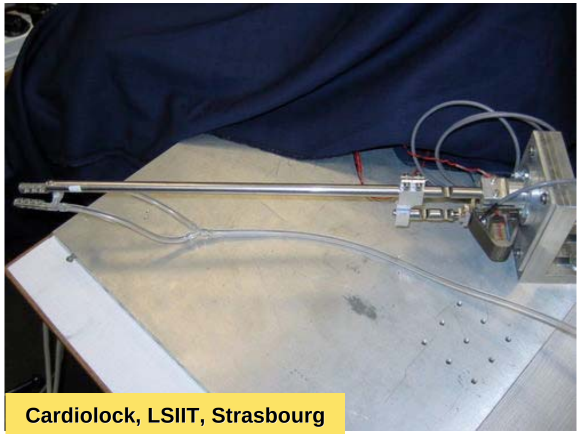
➔ **Solutions:**

- make use of a **mechanical stabilizer**



Octopus , Medtronic

- make use of an **active stabilizer**



Cardiolock, LSIIT, Strasbourg

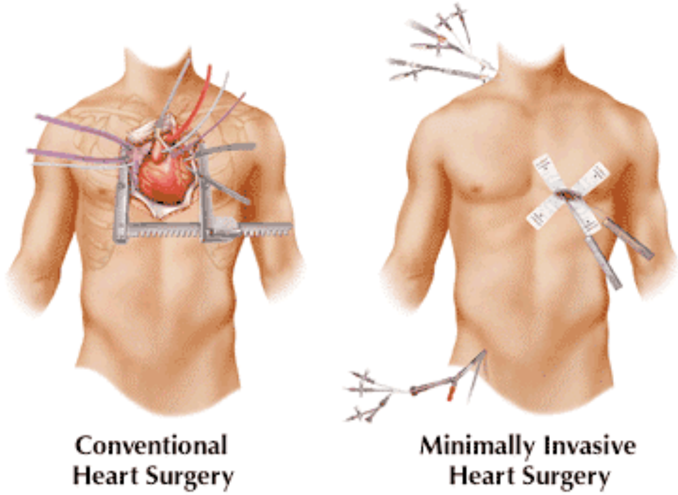
- or **virtually stabilize the region of interest with a robot**

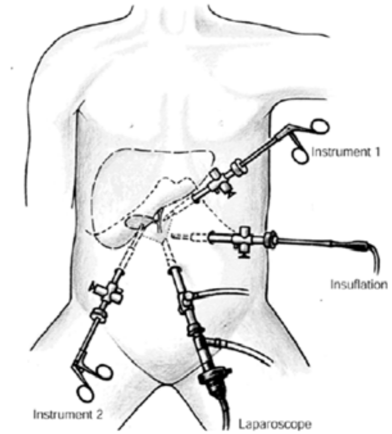
➔ ***develop appropriate vision-based (endoscopy or echography), force-based and model-based control algorithms***

Outline

- Future directions and technical challenges
  - Intra-body robotics
  - Beating heart surgery
- Some control issues in assisted MIS and cardiac surgery

- From open to minimally invasive surgery …
- … to improve surgical operation conditions for the patient
  - With less risk and trauma
  - Quick return to daily life





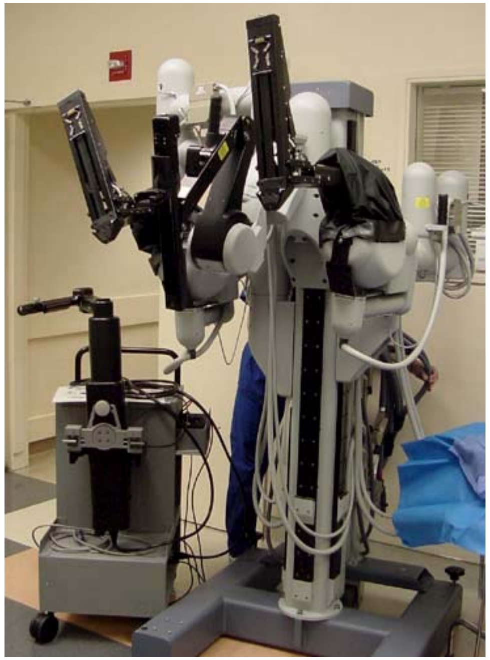
Some control issues in assisted MIS and cardiac surgery

(source : www.gynlaparoscopy.com)

MIS limitations

- Monocular vision - depth information lost
- Decreased mobility
- Hand-eye coordination
- Three hands required
- No tactile feedback
- Surgeon position
- …

DaVinci (Intuitive Surgical)



Zeus (Computer Motion)

Robotized MIS

Advantages of robotized MIS

- Increase dexterity of surgeon gestures
- Movement coordination
- Possibility of enhancing the visualization of the operating field through e.g. stereo view of the operating site

Main limitations

- Price
- Size

But also

- No actual solution to feedback interactions between organs and instrument to the surgeon
- No actual solution for compensating physiological motions or stabilizing the environment

Three challenges …

- Increasing the perceptual capabilities in MIS through force feedback teleoperation
- 3D reconstruction of the beating heart surface for assisted cardiac surgery
- Automatic guidance under ultrasound images

Increasing the perceptual capabilities in MIS through force feedback teleoperation

[CDC'07] Zarrad W., Poignet P., Cortesão R., Company O., Stability and Transparency Analysis of a Haptic Feedback Controller for Medical Applications, CDC'07: International Conference on Decision and Control (2007)

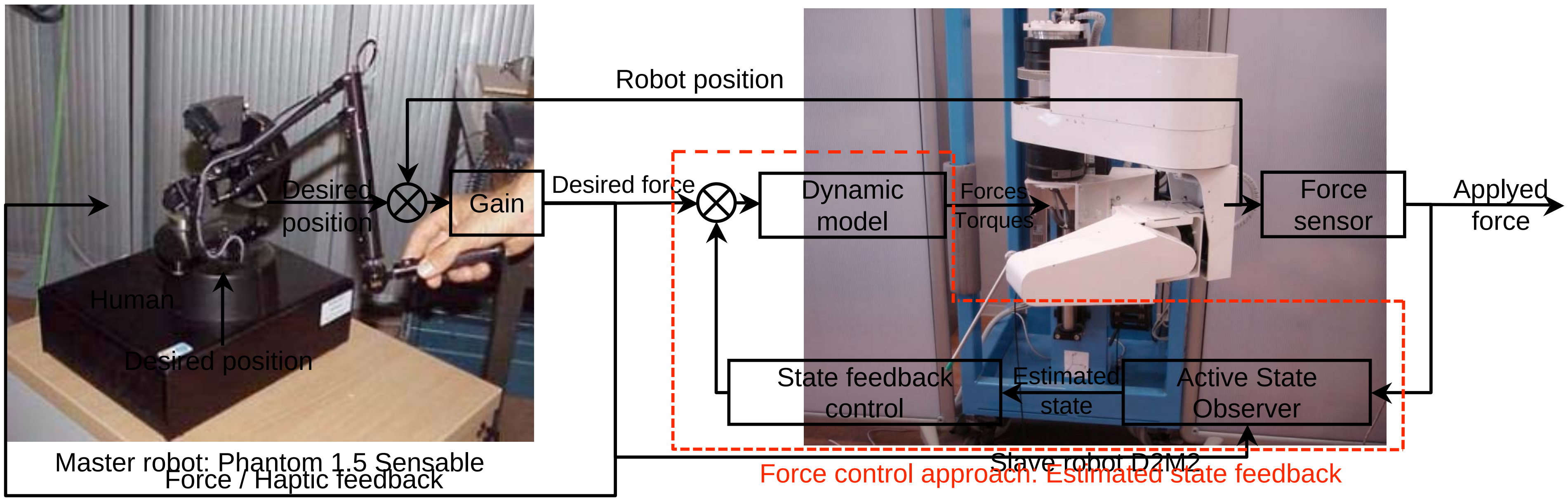
[IROS'07] Zarrad W., Poignet P., Cortesão R., Company O., Towards Teleoperated Needle Insertion with Haptic Feedback Controller, IROS'07: International Conference on Intelligent Robots and Systems (2007)

Force feedback teleoperation control

- Objectives
  - Remotely manipulate the robot
  - Free space motion / Contact with different stiffness objects
  - Force feedback
  - Trade-off between stability and transparency

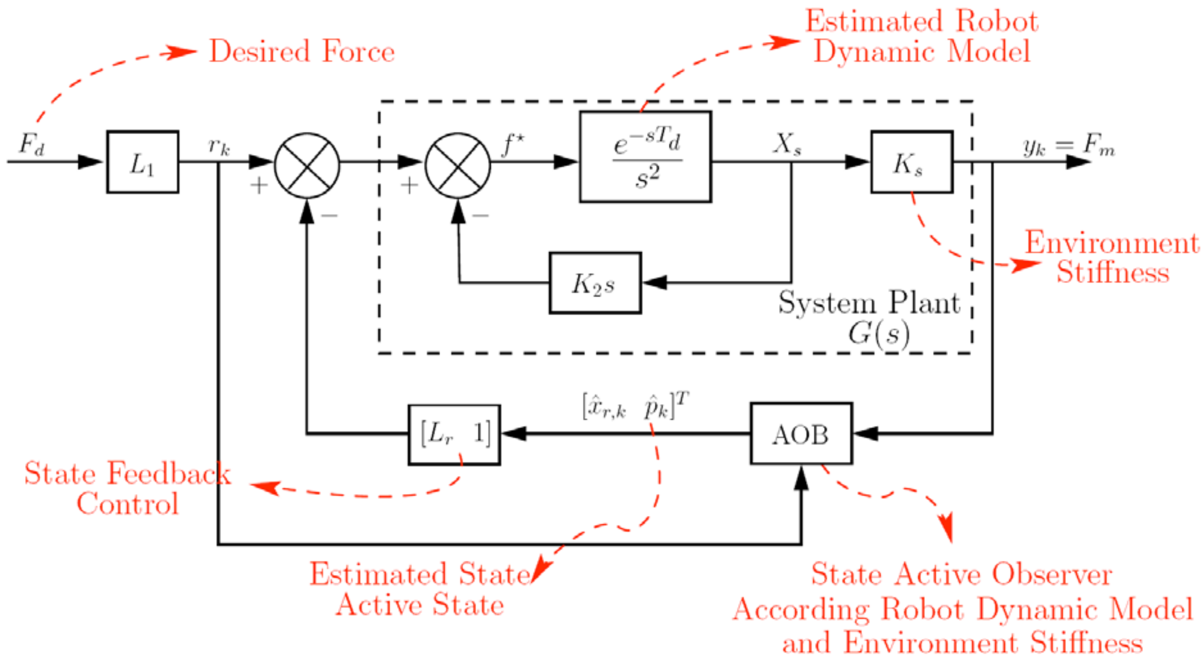
[Delft Univ. Tech. 2007]

- Control approach



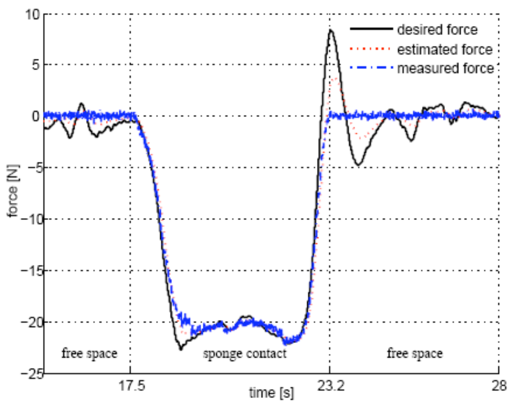
Force active observer

- Compliant motion with force controlled robot and force active observer



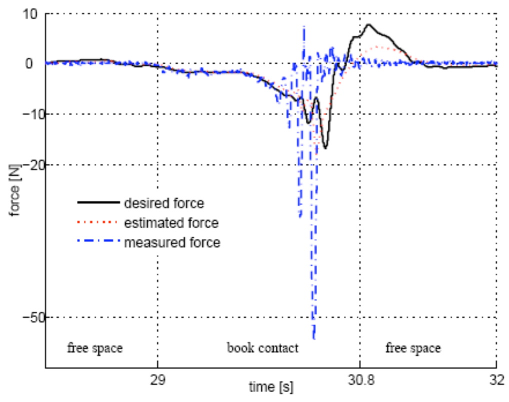
- Principles
  - State estimation using Active Kalman Filtrering
  - Additional active state
  - Feedback gain tuned to limit under/overshoot

$K_{real} < K_s$



(a) Soft sponge contact "Stable"

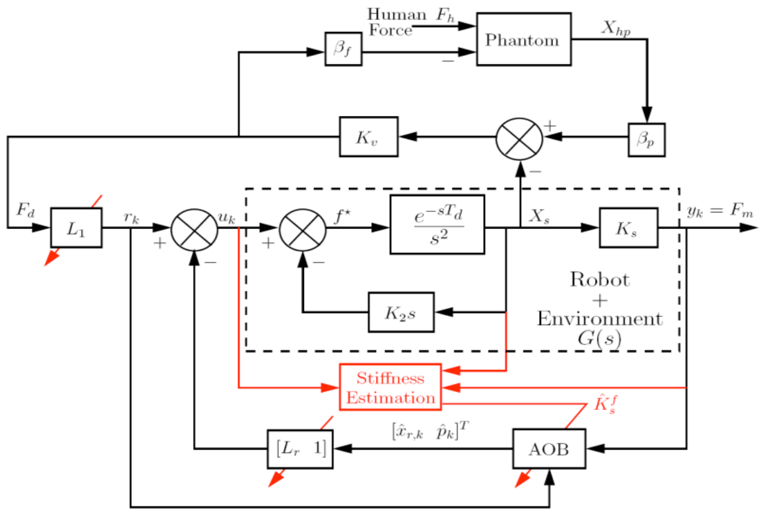
$K_{real} > K_s$



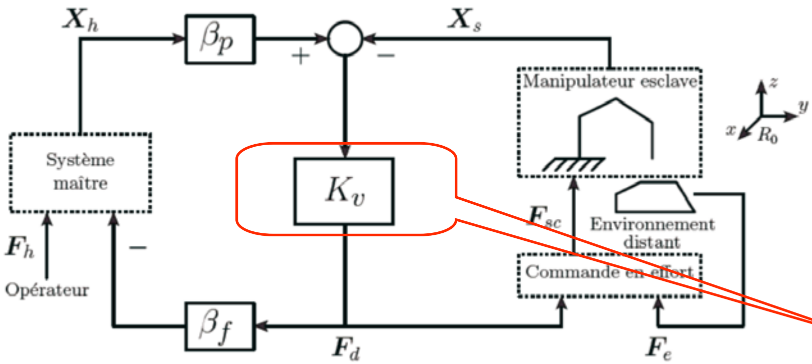
(b) Stiff book contact "Unstable"

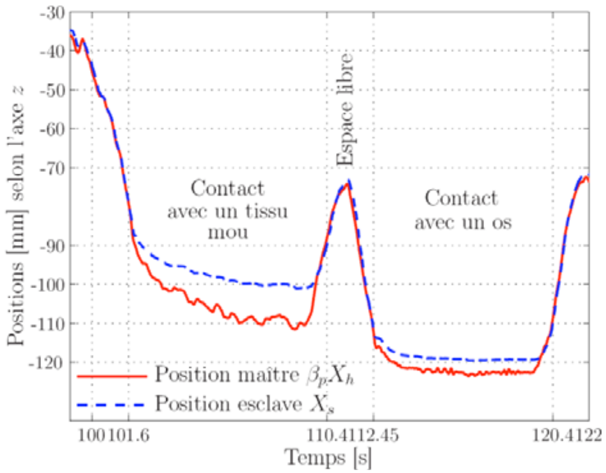
Adaptive force control

- Environment stiffness estimation



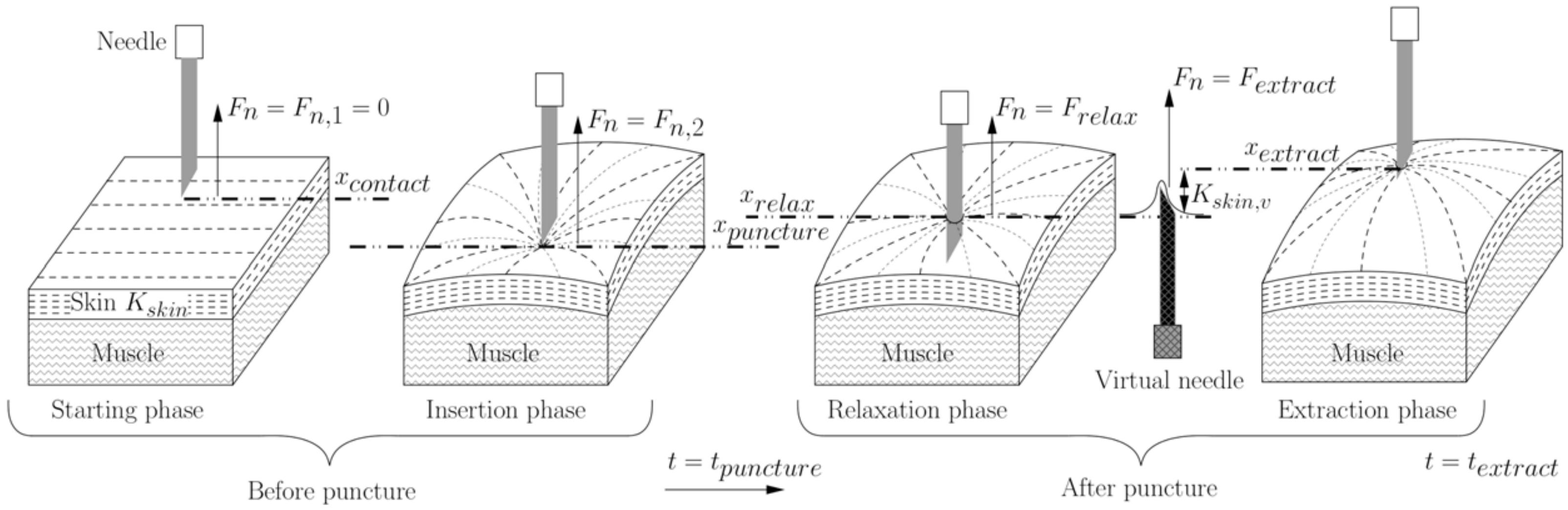
Teleoperation scheme with environment stiffness estimation strategy

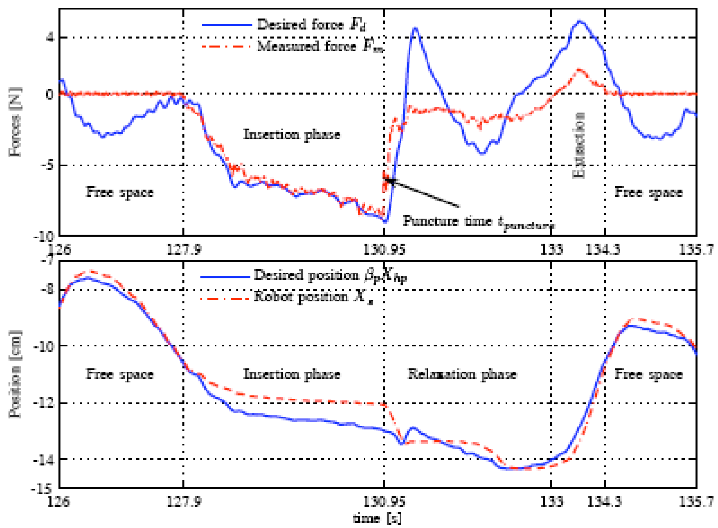


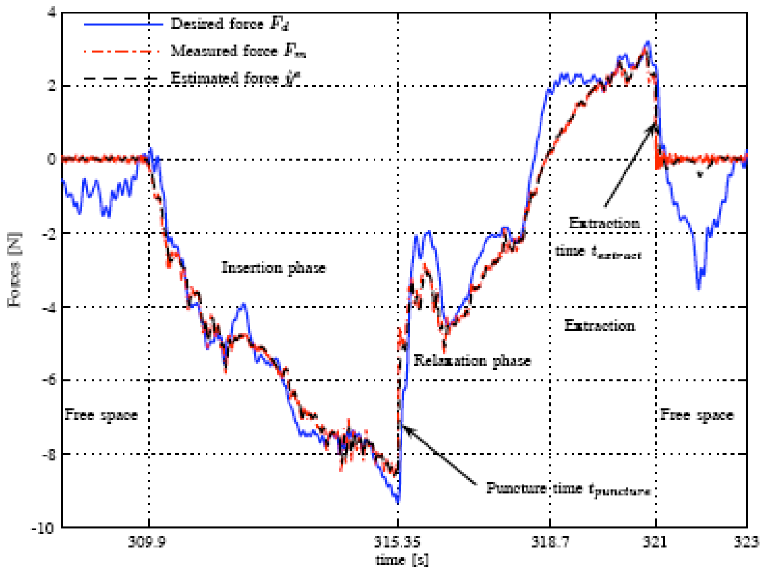


Transparency adaptation

Needle insertion







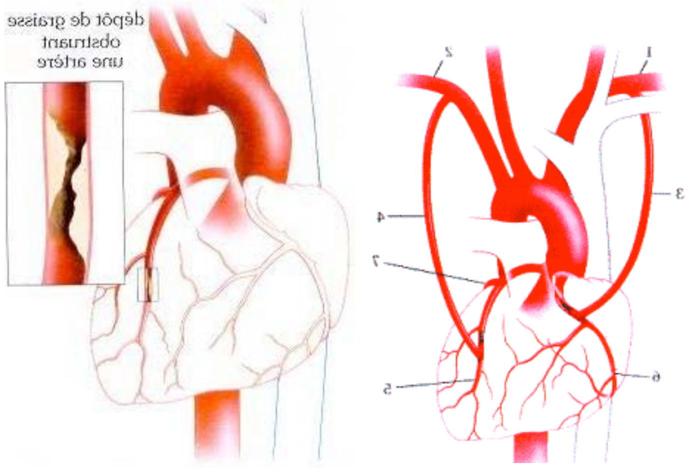
3D reconstruction of the beating heart for assisted cardiac surgery

[MICCAI'08] Richa R., Poignet P., Liu C., Efficient 3D tracking for motion compensation in beating heart surgery 11th International Conference on Medical Image Computing and Computer Assisted Intervention, (2008)

[IROS'08] Richa R., Poignet C., Liu C., Deformable motion tracking of the heart surface, IROS'08 : IEEE/RSJ 2008 International Conference on Intelligent ROobots and Systems (2008)

AccuRobAs (Accurate Robot Assistant) European Project funded from the European Community Sixth Framework Program (FP6 / 2006-2009) under grant agreement num. 045201.

Cardiac MIS



Coronary Artery Bypass Grafting

- The goal of cardiac MIS is to avoid stopping the heart and using the cardiopulmonary bypass
- Manual tracking is painfull, tiring and compromises the precision required for an anastomosis
- Use of mechanical stabilizers (e.g. Medtronic Octopus, …) [Lemma 05]
- Residual motion of the heart is still high
- Toward assisted beating heart surgery

One challenge

- Automatically compensate for physiological motion (beating heart and/or breathing)
  - Virtually stabilize the heart motion thanks to the use of external sensors (force, vision, …)
  - In the following, we focus on vision sensor
- Challenge : accurate motion estimation of the heart deformable surface without the use of artificial landmarks i.e. tracking natural features
- Difficulties
  - High dynamics and non rigid object with complex motion
  - Illumination changes and specular reflection
  - Occlusions due to surgical instruments, blood, etc.

Physiological motion compensation

- Y. Nakamura *et al*., Heartbeat synchronization for robotic cardiac surgery, ICRA 2001
  - First (impressive) high speed visual servoing experiment which uses a serial 4 dof robotic finger to track a marker attached to the heart
- R. Ginhoux *et al*. Active filtering of physiological motion in robotized surgery using predictive control, IEEE TRO 2005
  - Also high speed vision system and optical markers
  - Advanced control
- O. Bebek and M. C. Çavusoglu. Intelligent control algorithms for robotic assisted beating heart surgery, IEEE TRO 2007
  - Multi-sensors fusion including biological signals considering that some of them precedes heart motion

Tracking heart surface motion using vision

Two classes of methods for motion estimation are used:

- Feature based tracking [Stoyanov 05a, Noce 06]

  Detection and tracking of given structures on the heart surface (e.g. blood vessels)

- Region based tracking [Ortmaier 02, Lau 04, Stoyanov 05b, Richa 08]

  Deformation of a whole region of interest is estimated based on a parametric model (e.g. FFD, Spline, TPS)

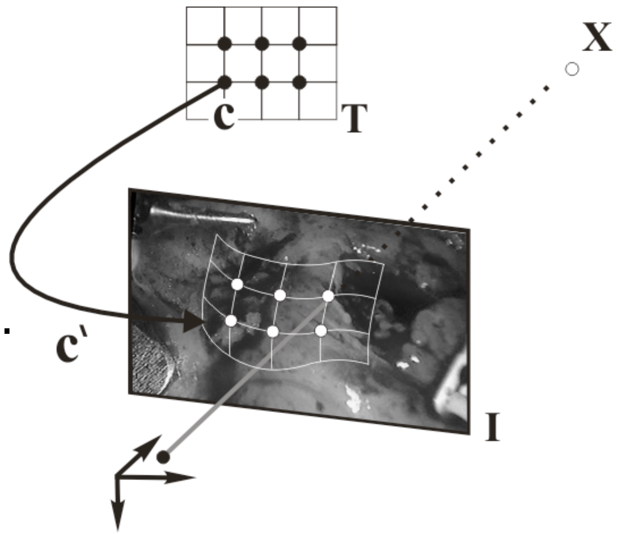
- Region based tracking is rather well adapted to heart surface deformations
- Thin-Plate Splines transformations have been successfully applied to model non-rigid deformations for numerous applications (augmented reality, registration, etc.) [Malis 2007]
- Extension of the TPS transformations for 3D tracking in a stereo framework.
- Difference with the other region based approaches -> exact tracking of the surface

Thin-Plate Spline mapping

- The TPS is a radial basis function that specifies an approximation function f which minimizes the bending energy

$$m(\mathbf{x}) = \begin{bmatrix} f^x \\ f^y \end{bmatrix} = \begin{bmatrix} r_2^x & r_3^x & r_1^x \\ r_2^y & r_3^y & r_1^y \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} + \sum_{i=1}^{n} \begin{bmatrix} w_i^x \\ w_i^y \end{bmatrix} U(||\mathbf{c}_j - \mathbf{x}||)$$

where $U(s) = s^2 log(s^2)$ and $\{r,w\}$ are the TPS coefficients.

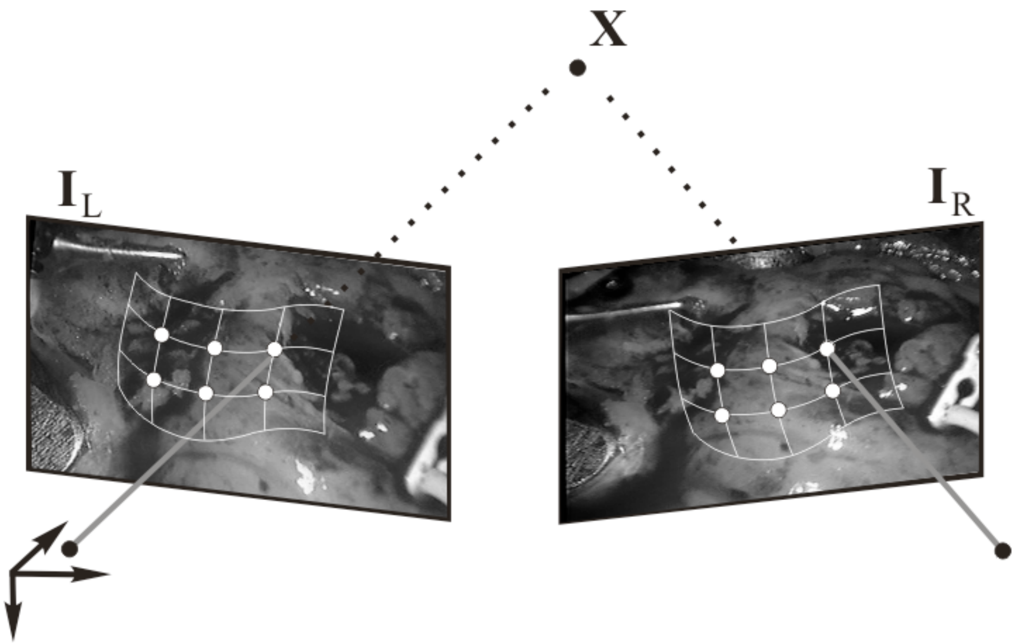


- 2D warping: $w(\mathbf{x}_i, \mathbf{h}) = [\mathbf{x}'_i \;\; \mathbf{y}'_i] = [\, \mathbf{M}_i \, \mathbf{K}_* \mathbf{h}^x \mid \mathbf{M}_i \, \mathbf{K}_* \mathbf{h}^y \,]$

- Tracking: $\min_{\mathbf{h}} \; \epsilon = \sum_{\mathbf{x} \in \mathbf{A}} \left[\mathbf{I}(w(\mathbf{x}, \mathbf{h})) - \mathbf{T}(\mathbf{x}) \right]^2$

Stereo tracking problem

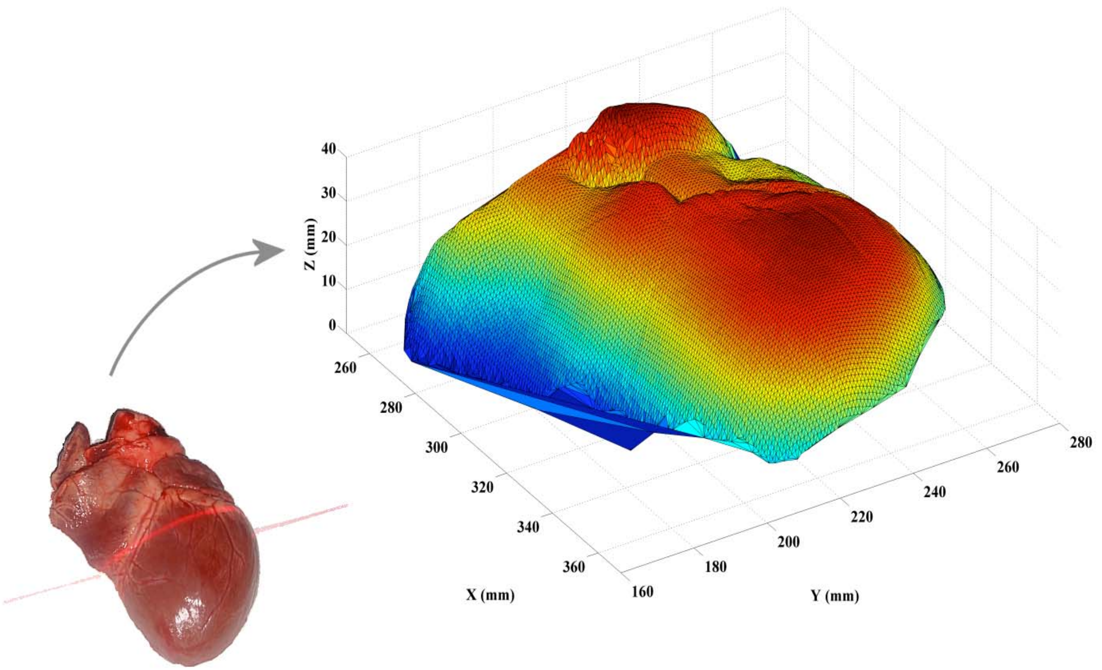
Estimation of an optimal warping parameter vector **h** that minimizes the alignment error between the reference image **T** and both left and right images of the stereo pair $\mathbf{I}_l$ and $\mathbf{I}_r$ simultaneously.



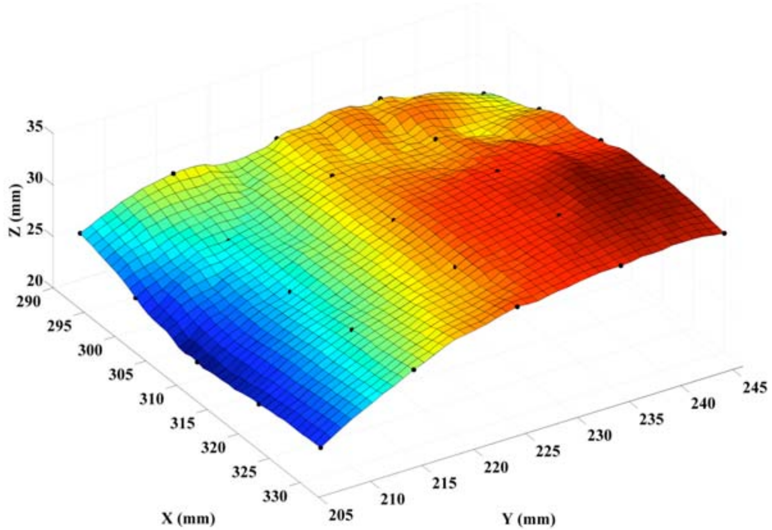
The control points are seen as the projections of 3D points onto the image plane

Assessment of the model

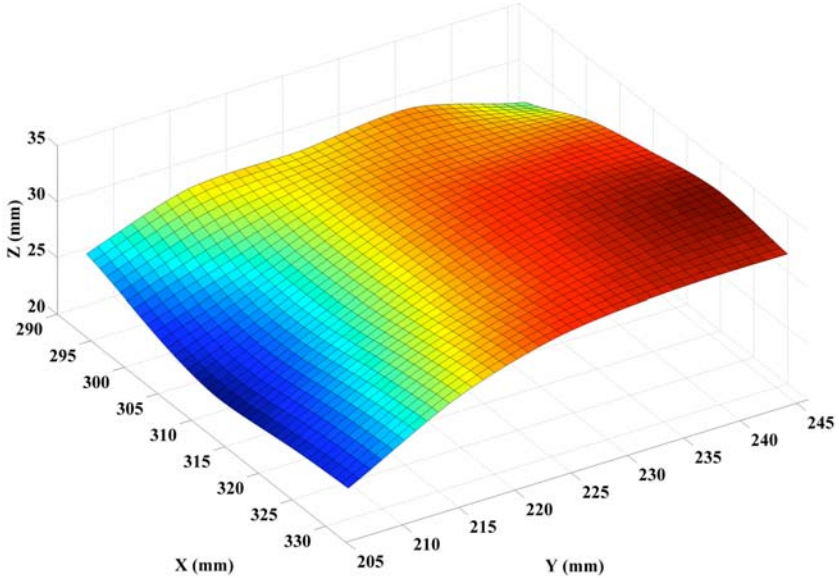
Comparison of the 3D surface shape of an *ex-vivo* heart from a pig approximated by a TPS surface and the ground truth provided by a laser profilometer (0.2mm depth precision)



Ex-vivo experiment



Detail of heart surface shape retrieved by the laser-profilometer



Surface approximation by the TPS model

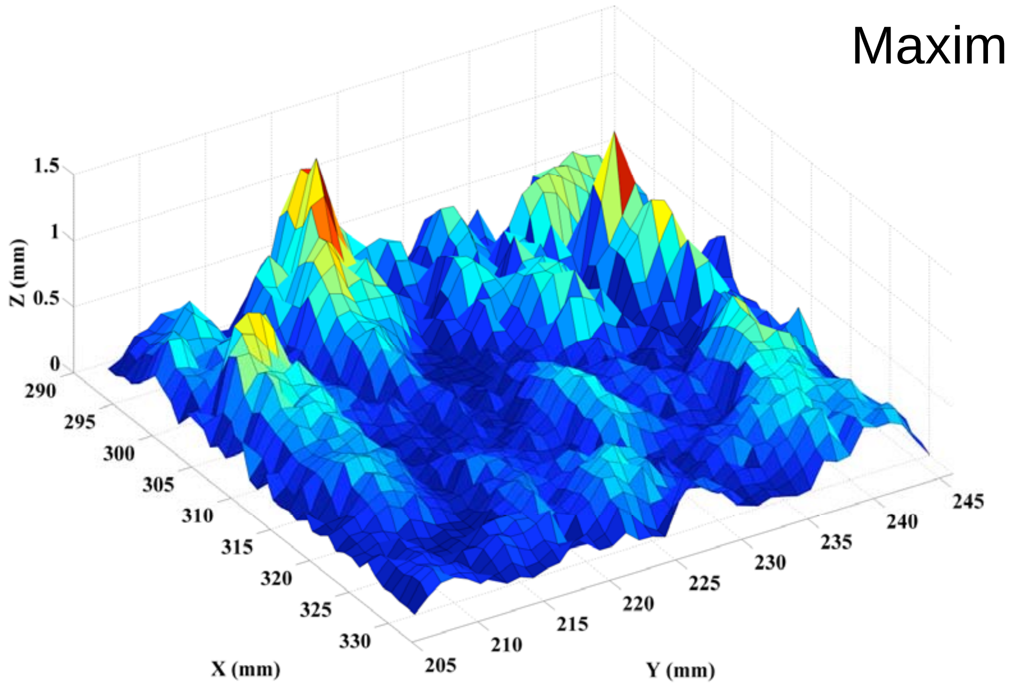
4cm*4cm region

25 control points

Average approximation error: 0.24 mm

Standard Deviation: 0.19 mm

Maximum Error Value: 1.1 mm



Approximation error

Experimental setup

- Stereo endoscope of the DaVinci system
- Image sequence 50 Hz
- 320*288 color images
- Calibration using a planar object [Zhang 00]
- Tracking : 80*80 pixels region using 6 control points

Courtesy of Intuitive Surgical, Inc., 2008

Acknowledgement : Image sequences from the DaVinci system are provided by D. Stoyanov and Y. Guang-Zhong, Imperial College London, England

3D Motion Tracking for Beating Heart Surgery using a Thin-Plate Spline Deformable Model

R. Richa, P. Poignet, C. Liu

LIRMM
UMR 5506 CNRS UM2
University of Montpellier, France

Some other results on:

- Illumination modeling and specular detection
- Model prediction to improve the optimization convergence and the robustness

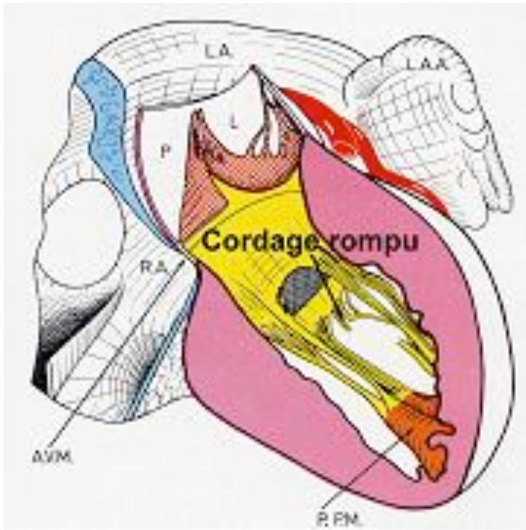
On going research:

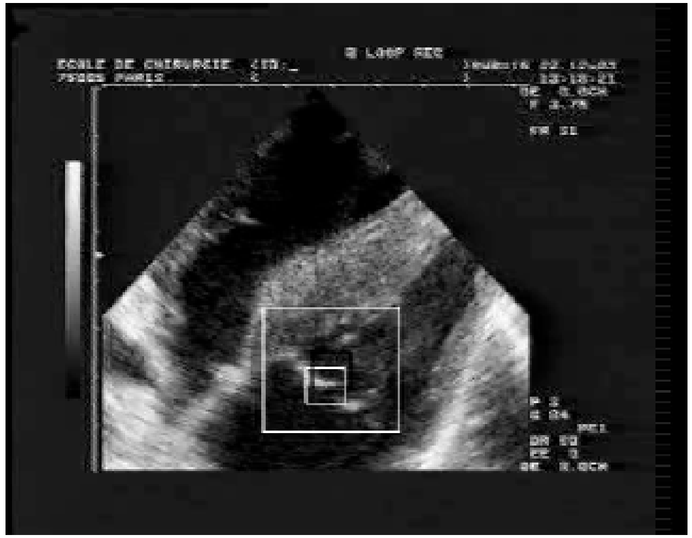
- Real-time implementation (GPU NVIDIA GeForce GTX 280)
- Robustness improvement - Not yet robust enough w.r.t. shadows, appearance changes, instrument occlusions -> motion prediction to tackle the occlusions
- In-vivo evaluation with high speed camera

Automatic guidance under ultrasound images

[IJRR'08] Sauvée M., Poignet P., Dombre E., Ultrasound image-based visual servoing of a surgical instrument through nonlinear model predictive control, International Journal of Robotics Research 27, 1 (2008) 25-40

- Objective : to assist the surgeon to repair mitral valve broken cordages during beating heart surgery under US images





- Difficulties :
  - Valve motion observed with US probe
  - High dynamics
  - Large motion of leaflets
  - Possible motion of the heart

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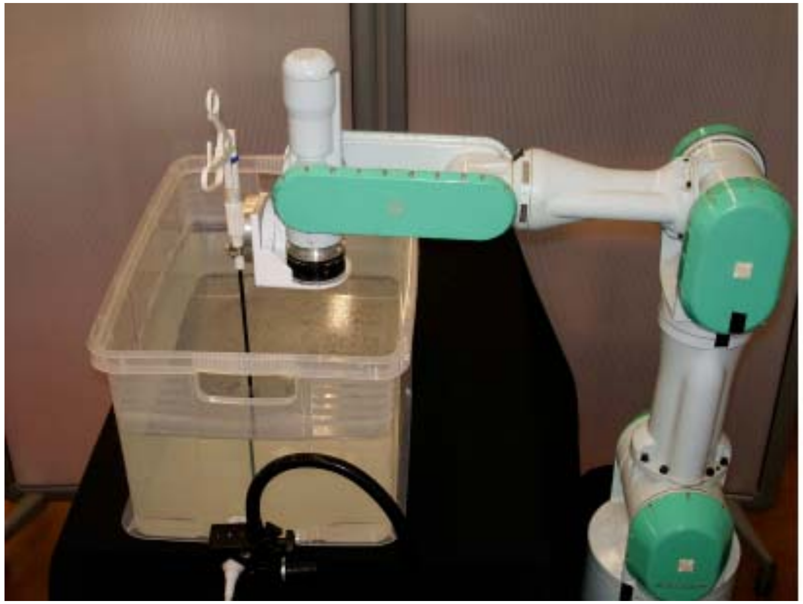
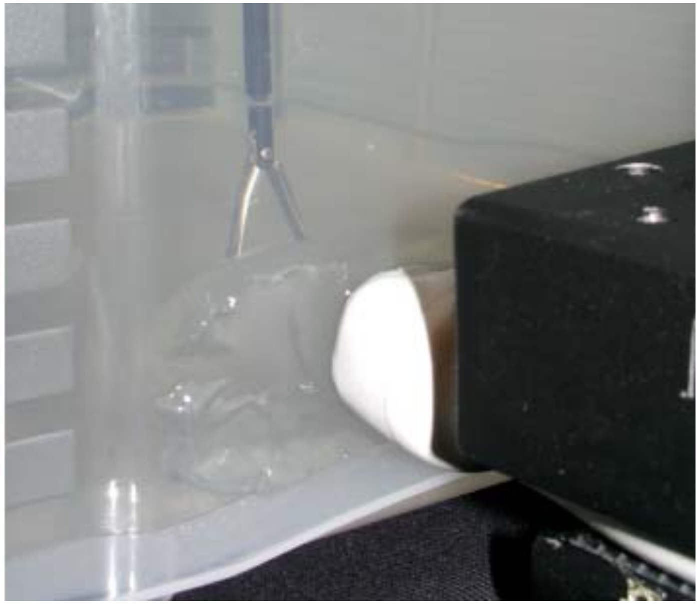
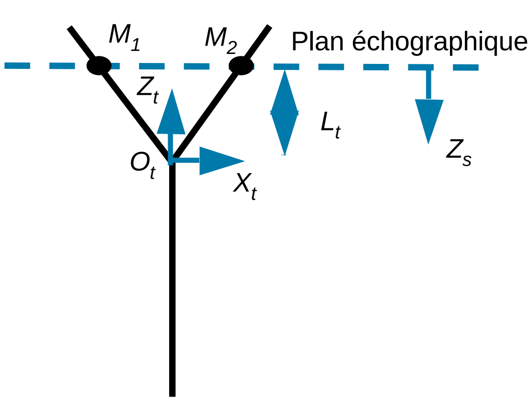
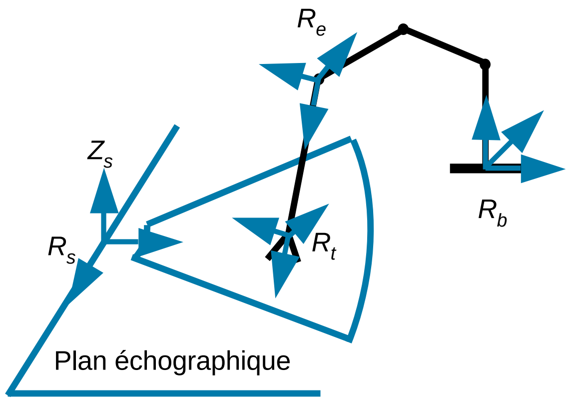
Ultrasound images visual servoing



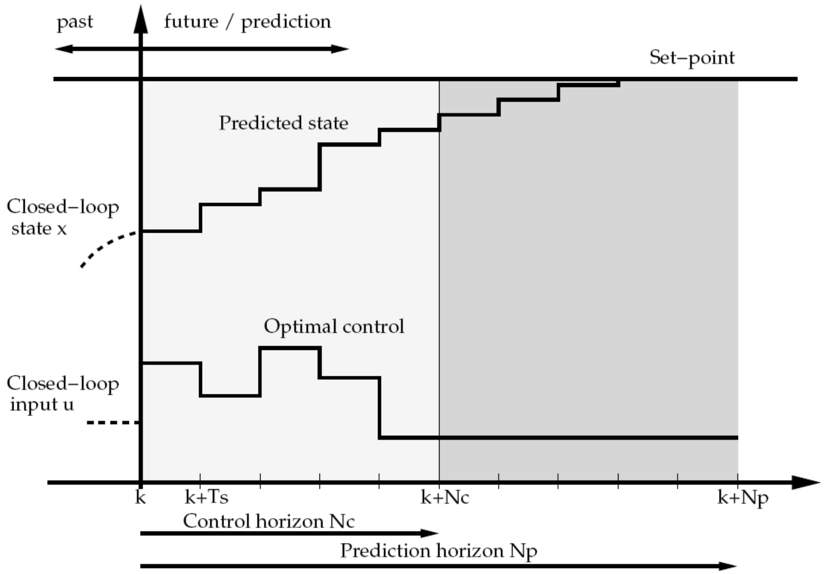


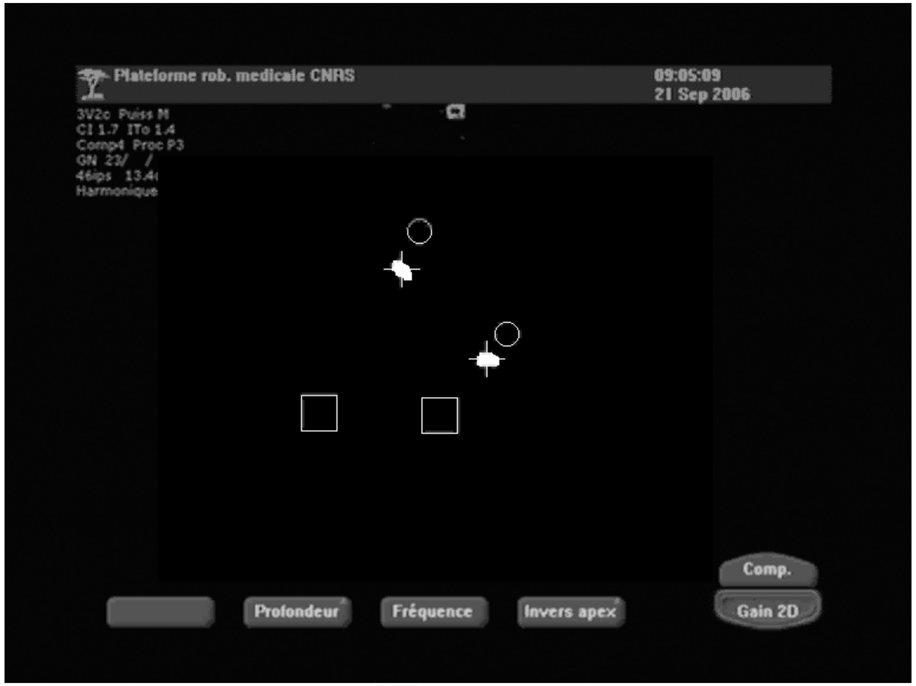


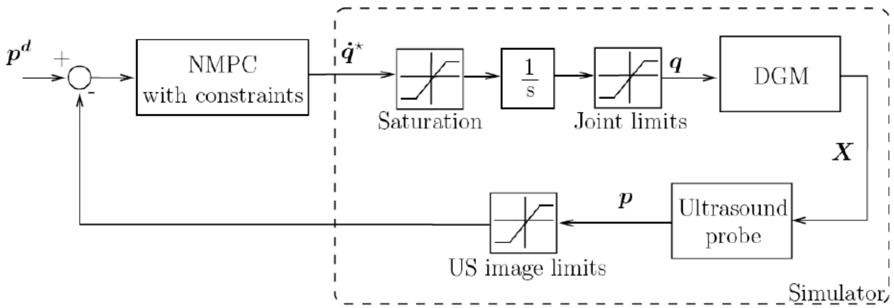


Ultrasound images visual servoing

- Predictive technique







- Future directions and technical challenges
  - Intra-body robotics
  - Beating heart surgery
- Some control issues in assisted MIS and cardiac surgery