Quelques verrous scientifiques et techniques en robotique médicale

Etienne Dombre
LIRMM, Montpellier
dombre@lirmm.fr

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

- University Montpellier II and CNRS*
- Staff (01/01/2007):
  - 133 Faculty members (100 from University, 30 CNRS*, 3 INRIA**)
  - 29 Technical and Administrative staffs (8 from University, 21 CNRS)
  - 151 PhD students

www.lirmm.fr

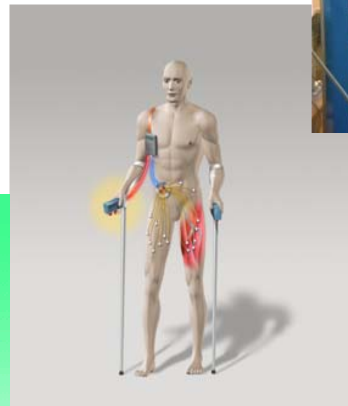
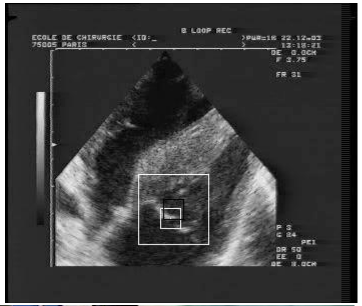
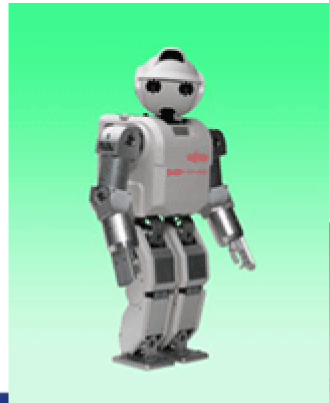
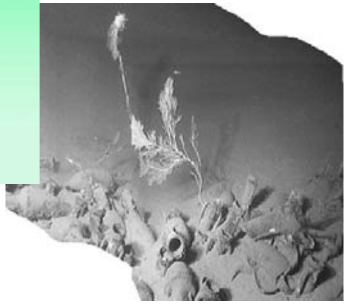
***CNRS: French National Center of Scientific Research**

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

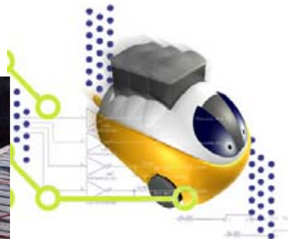
- **24 Faculty members (17 Univ., 5 CNRS, 2 INRIA), 35 PhD students, 6 Post docs**

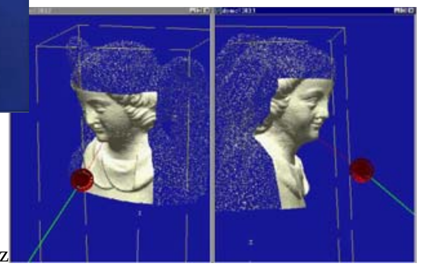
- **Four project teams**
  - DEMAR: deambulation and artificial movement
  - DEXTER: design & control of robot-manipulators
  - ICAR: image, computing and augmented reality
  - NERO: networked robots

- **Several application domains**
  - Parallel robots and high speed machines
  - Medical robotics
  - Artificial walking and FES
  - Mobile robotics
  - Autonomous underwater vehicles
  - Humanoids
  - …





Medical Robotics =

Robotics to assist doctors / surgeons

Assistive technologies

Robots and machines that improve the quality of life of disabled and elderly people, mainly by increasing personal independence

- Prothetic devices /Artificial limbs
- Orthotic devices / Exoskeletons
- FES
- Robotic aids
- Smart living spaces
- Personal assistants

Rehabilitation robotics

Robots and mechatronic tools for clinical therapy in neuro-motor rehabilitation, training…

Therapeutic tools used temporarily

Robotics for surgery, exploration, diagnosis, therapy...

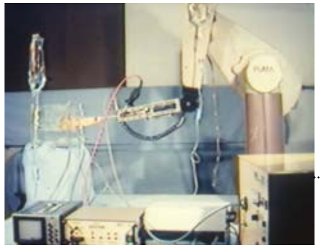
- Neurosurgery
- Orthopedics
- Minimally invasive surgery
- Percutaneous surgery
- Tele-echography
- …

Robotics to assist people

1. State of the art (Robotics for surgery and diagnosis)

2. Future directions of R&D and technical challenges

- Some milestones



1985 — Neurosurgery
Puma 260
Kwoh et al.
22 patients

1989 — Neurosurgery
Speedy (AID robot)
Lavallée, Benhabid et al.
Hundreds of patients

TransUrethral Res. of Prostate
Puma 560
(Imperial College)

1992 — Orthopedic surgery
ROBODOC (ISS)
>70 robots,
over 10000 patients

1994 — MIS
AESOP
(Computer Motion)
> 400

1998 — MIS
Zeus
(Computer Motion)

MIS Da Vinci
(Intuitive Surgical)
Still in use: > 200

2001 — Tele-echography
SYRTECH (LVR)
Bourges-Kathmandu

MIS + Tele-surgery
(IRCAD)
"Operation Lindbergh"
New York-Strasbourg

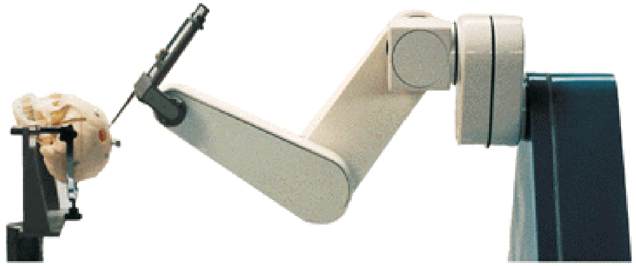
(revisited from J. Troccaz, UEE 2003)

- Today main robotically assisted surgical specialities
  - Neurosurgery
  - Orthopedics
  - Minimally-invasive surgery (MIS)
  - Percutaneous therapy / interventional surgery / Image-guided surg.

- Other non surgical specialities
  - Tele-echography

State of the art: Neurosurgery

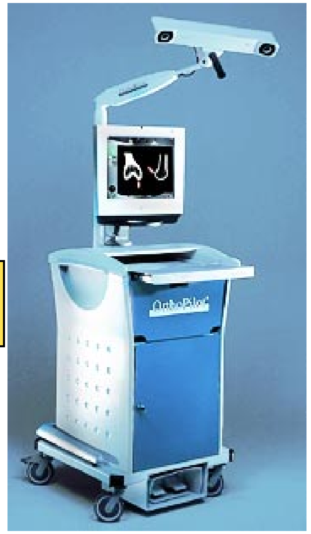
NEUROMATE (IMMI/ISS/Schaerer-Mayfield), 1996



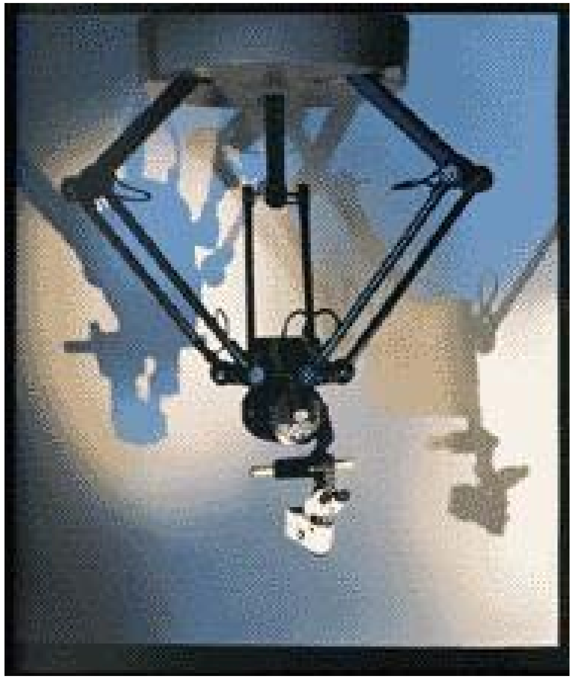
- Robots = tool holders

- Navigation systems

OrthoPilot (Aesculap)




NDI




TIMC

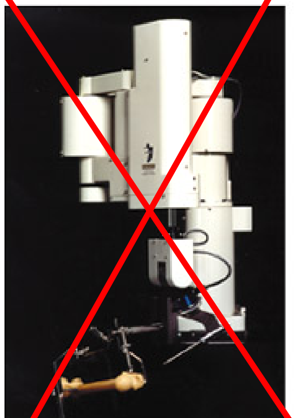
- Microscope holders

Surgiscope (Elekta-IGS, now ISIS), 1997: microscope-holder

State of the art: Orthopedics

- Navigation systems
- Robots : Industrial robots ➔ Dedicated robots ➔ "Portable" robots

CASPAR (OrtoMaquet / URS Ortho), 1997



ROBODOC (ISS), 1992

ACROBOT (Imperial College/Acrobot Ltd), 2001

BRIGIT (MedTech/Zimmer, LIRMM), 2005

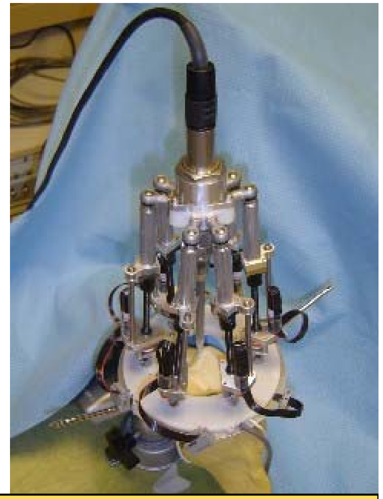
MARS (Technion/Mazor SurgIcal Haifa), 2002

State of the art: Orthopedics

- **Advantages of patient-mounted robots**
  (L. Joskowicz, CARS, Berlin 2005)
  - Small size/footprint –minimal obstruction
  - Close proximity to surgical site
  - No patient/anatomy immobilization
  - No tracking/real-time repositioning
  - Small workspace –fine positioning device
  - Potentially higher accuracy
  - Intrinsic safety due to small size/low power

6 dof

MARS (Technion/Mazor Surg. Haifa), 2002: spine surgery



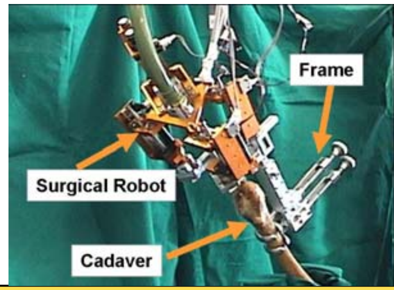
MBARS (CMU, Pittsburg): TKA

5 dof

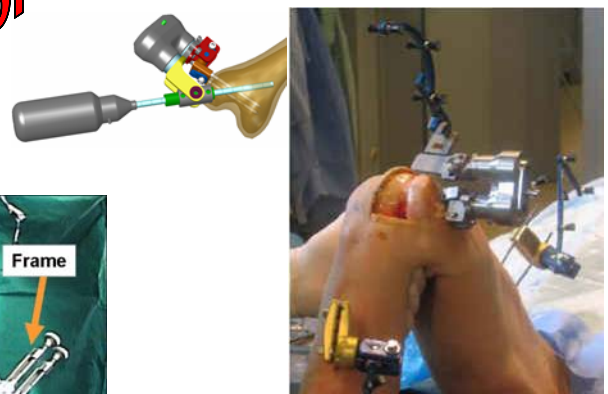
GP system (Medacta, Switzerland): TKA

PIGalileao CAS (PLUS Othopedics AG, Switzerland): TKA

2 dof



ARTHROBOT (KAIST), 2002: TKA

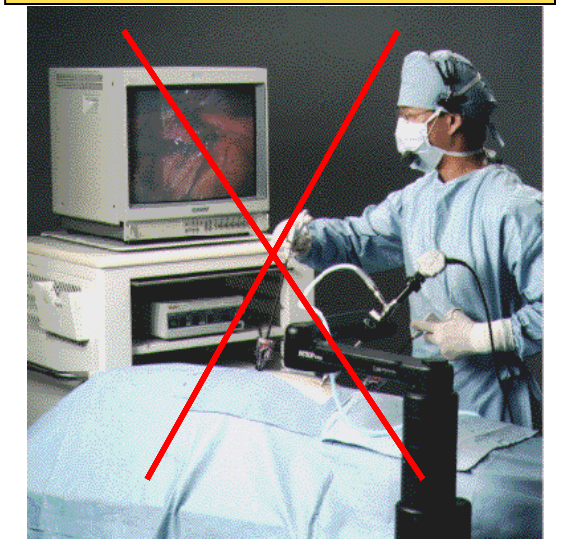


Praxiteles (TIMC): TKA

State of the art: Minimally Invasive Surgery (MIS)

- Endoscope holders

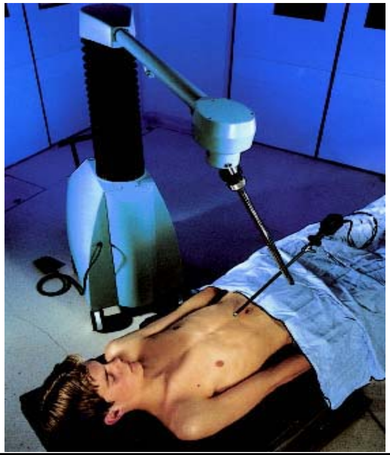
AESOP (Computer Motion), 1992



Voice control,
Foot control

Lapman
(Medsys, Belgique)

Hand control



EndoAssist
(Armstrong Healthcare)

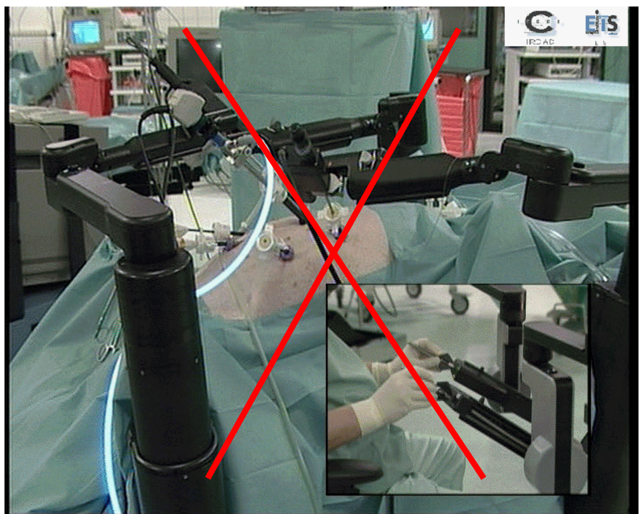
Head control

LIRMM

State of the art: Minimally Invasive Surgery (MIS)

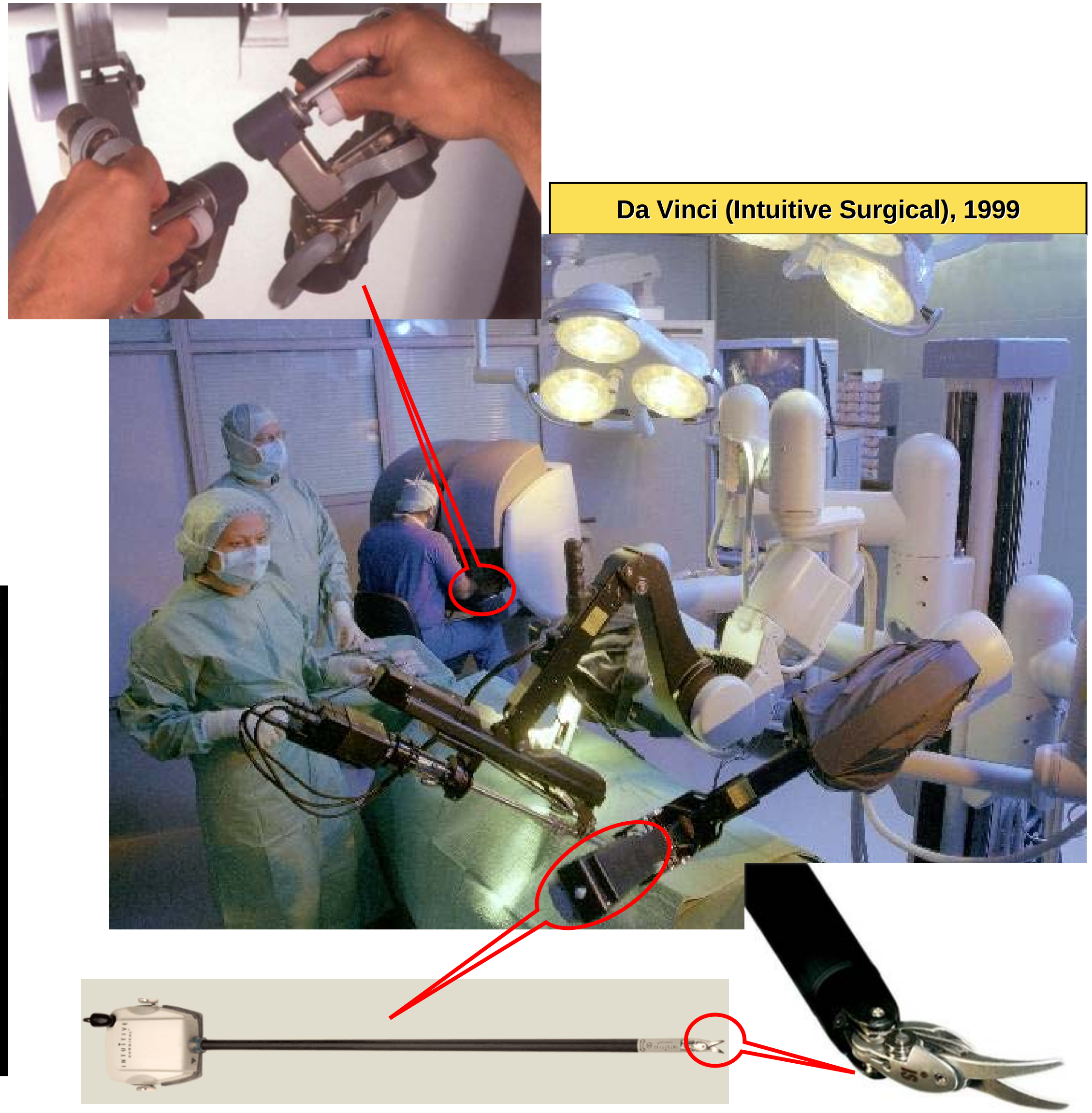
- Master-slave robots

Laprotek (Endovia Medical)



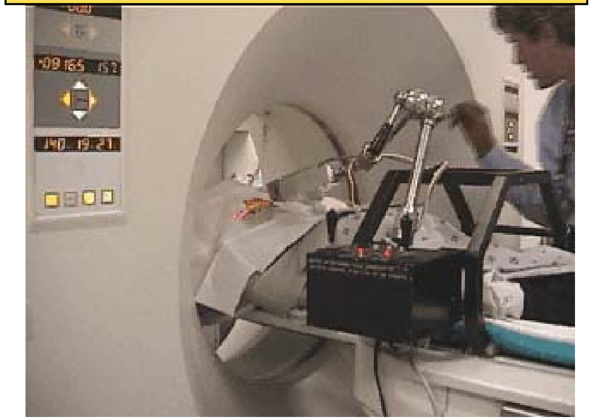
ZEUS (Computer Motion), 1998

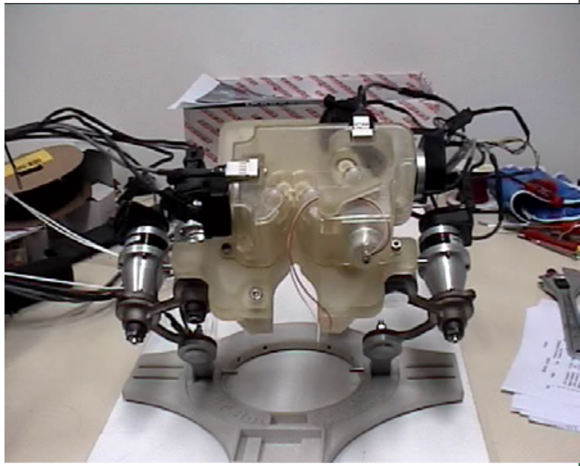
Da Vinci (Intuitive Surgical), 1999

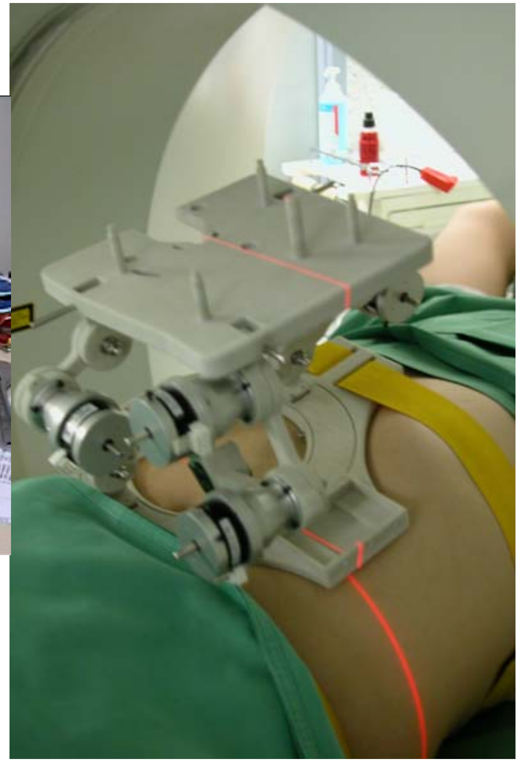


State of the art: Percutaneous therapy

ACUBOT (JHU, Baltimore & Georgetown Univ. Washington)

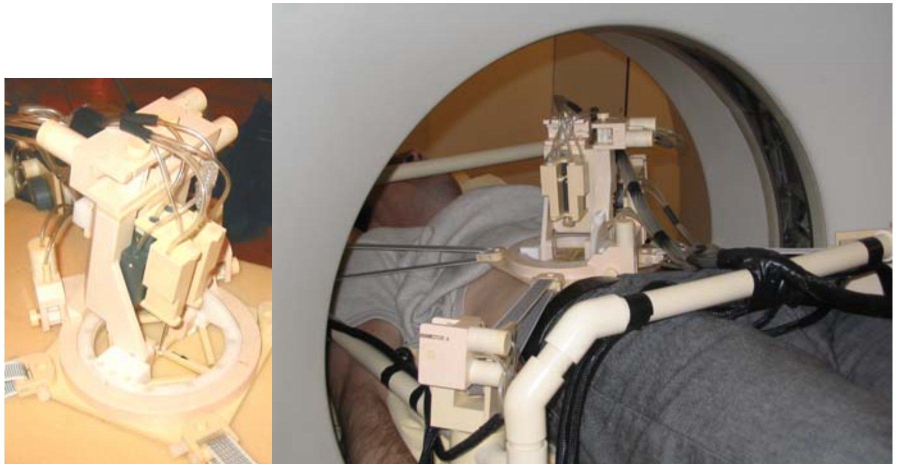






CT-BOT (LSIIT, Strasbourg), 2005

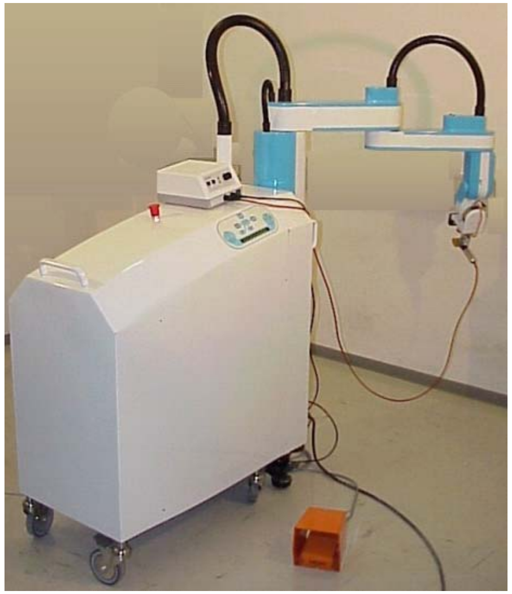
- parallel robot
- CT-image servoing
- 5 dof + 2 dof for needle insertion
- piezoelectric actuators
- force sensor (teleoperation mode)



CT/MRI compatible biopsy robot (TIMC), 2004

State of the art: Other surgical specialities

SCALPP (LIRMM/SINTERS), 2002, Skin harvesting



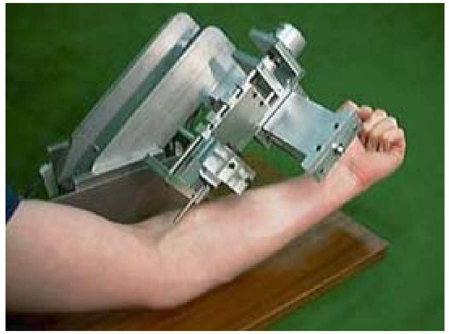
Cyberknife (Accuray, Stanford): radiotherapy

A lightweight linac is mounted on the robot. Tracking of respiratory motion

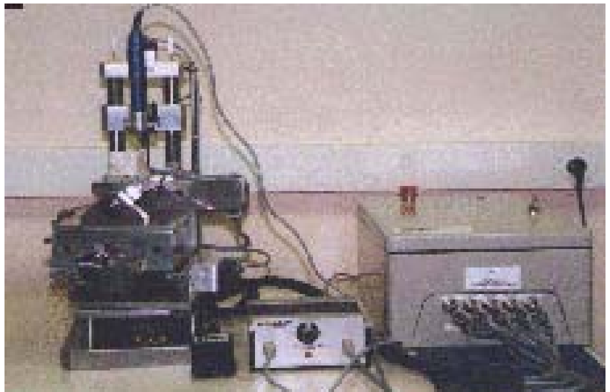
Centre de Protonthérapie (Orsay): radiotherapy

The patient is on a bed mounted on the robot.

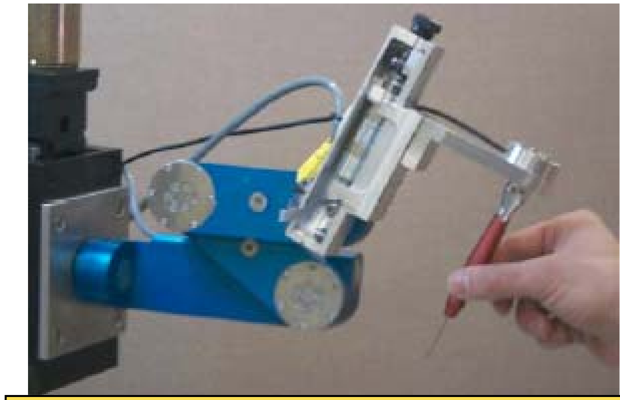
Bloodbot (Imperial College, London



PROBOT (Imperial College, London): prostate resection



VISIMPLANT for dental implantology (EU project, Ecole des Mines, Paris



Sready-hand robot (JHU, Baltimore): microsurgery

SCALPP (LIRMM/SINTERS)

Joint project with the Burnt Dpt, Lapeyronie Hosp., Montpellier (Dr Téot)

Expérimental validation : Labo. de Chirurgie Expérimentale, Fac. de Médecine, Montpellier

State of the art: Skin harvesting with SCALPP

- Learning phase: the dermatome is manually driven on the initial and final points that are recorded
- Execution phase : the motion and force exerted by the dermatome between the initial and final points are controlled by the robot

LIRMM

State of the art: Tele-echography

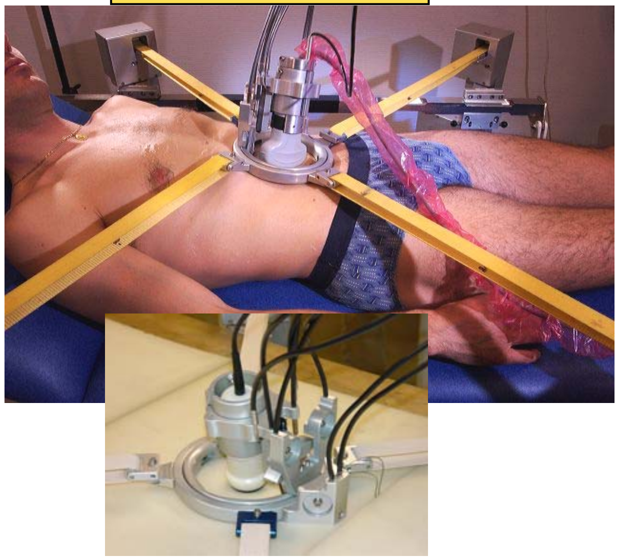
HIPPOCRATE (LIRMM/SINTERS), 1999

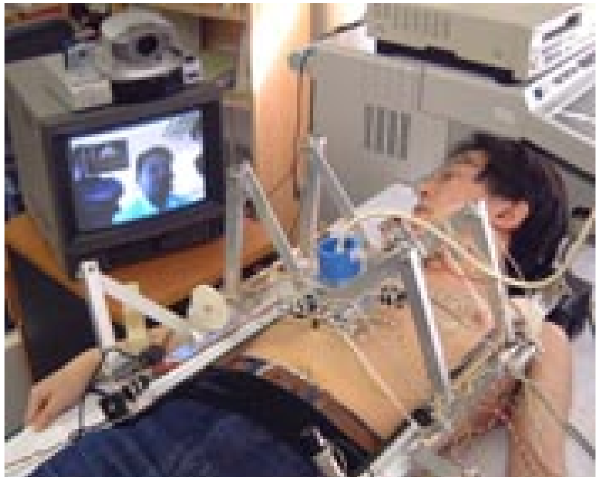
The Ultrasound robot (UBC), 1999

TERESA (LVR-Bourges/ SINTERS), 2003

SYRTECH (LVR-Bourges), 2001

TER (TIMC), 2001





Masuda Lab. Tokyo Univ. A&T, 1999

State-of-the-art: commercial systems

- **Today commercial systems**
  - Navigation systems for neurosurgery, orthopedics & maxillofacial surgery: *StealthStation (Medtronic), VectorVision (BrainLab), Surgetics (Praxim), Navigation System (Stryker), OrthoPilot (Aesculap), Galileo (PI Systems), InstaTrack (GEMS), Acustar (Z-Cat)…*
  - Neurosurgery / Microscope holder: *Surgiscope (ISIS), ~~MKM (Zeiss*)~~*
  - Neurosurgery / Robot: *Neuromate (Schaerer-Mayfield)*
  - Orthopedics: *~~ROBODOC (ISS*)~~, ACROBOT (Acrobot Ltd), MARS/Smart Assist (Mazor Surgical Technologies), BRIGIT (MedTech/Zimmer)*
  - MIS: *Da Vinci (Intuitive Surgical), ~~ZEUS (Computer Motion**)~~, ~~EndoVia Medical~~*
  - Endoscope holders: *~~AESOP (Computer Motion**)~~, EndoAssist (Armstrong Healthcare), Lapman (Medsys)*
  - Radiotherapy: *Cyberknife (Accuray)*
  - Tele-echography: *Othello (LVR / Robosoft)*

* out of business

** merged with Intuitive Surgical since March 2003

State-of-the-art: commercial systems

- **French companies specialized in medical robotics:**
  - ISIS (Microscope holder Surgiscope, Tele-neurosurgical robot)
  - MedTech (BRIGIT for orthopedics)
  - EndoControl (Portable endoscope holders LER et MC^{2}E)
  - Koelis (CAMI in urology)
  - Praxim (Navigateur Surgetics, Robotized spacer for TKA, Praxiteles)
  - CAD Implant (Dental implantology)
  - Robosoft (Othello for tele-echography)
  - …

- **Some expected "added-values" of robots…**
  - *In neurosurgery, percutaneous therapy, radiosurgery*: limits collateral effects due to lesions of instruments or radiations while accessing smaller and smaller targets closer and closer to vital areas; removes the operator from hazardous environment such as X-ray
  - *In orthopedic*: less revision surgeries; longer life expectancy of protheses; less risk (e.g. pedicular screw placement)
  - *In MIS*: control of additional mobilities at the distal part of instrument; haptic feedback; performing surgeries that cannot be executed manually (e.g. beating heart surgery); compensation for physiological motion
  - *Long distance surgery*

➔ **Less invasive, more accurate, improvement of surgeon's capabilities**

- **Some expected "added-values" of robot…**

- **… but also some reserve to the use of a robotic system in the OR:**
  - Cost effectiveness **not yet proved** (source B. Armstrong, CARS Berlin, 2005):
    - increase OR cost
    - technical team in the OR
    - training of the surgical team
    - setup and skin-to-skin times longer than conventional procedure
  - Clinical added value **not yet clear:** *"it is difficult to prove their effectiveness since there are no established methods to relate conventional (non robotic) techniques that would serve as benchmarks* …"
  - Compatibility with the environment of the OR (cluttered, other electrical devices…): **yet too bulky**
  - Safety

➔ **Still a lot of technical and clinical (new procedures) research work**

See also http://www.nsf.gov/eng/roboticsorg/IARPMedicalRoboticsWorkshopReport.htm

1. State of the art

2. Future directions of R&D and technical challenges

Future directions of R&D and technical challenges

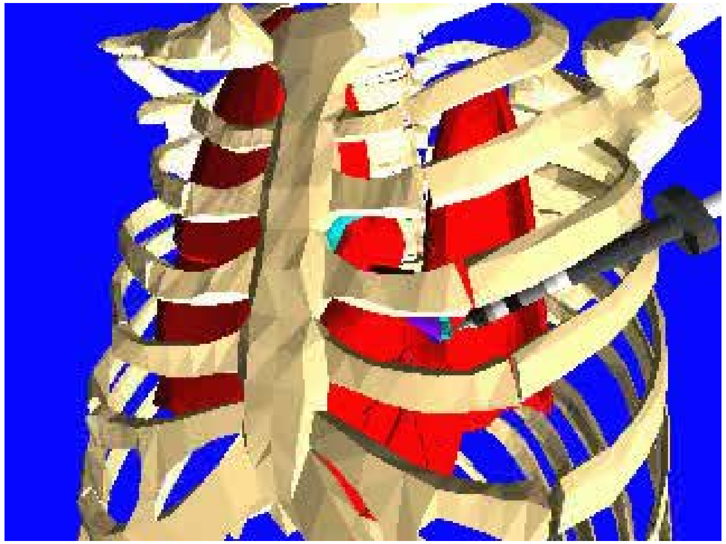
- **Technical challenges**
  - lightweight, smaller, simpler, cheaper,
  - integration in the OR: plug-and-play systems
  - sensors: sterilizable or disposable
  - MMI: real cooperation between Surgeon and Robot ("Hands-on" concept: the surgeon operates the device)…
- **Trends:**
  - Dedicated robotized instruments
  - Autonomy

Future directions of R&D and technical challenges

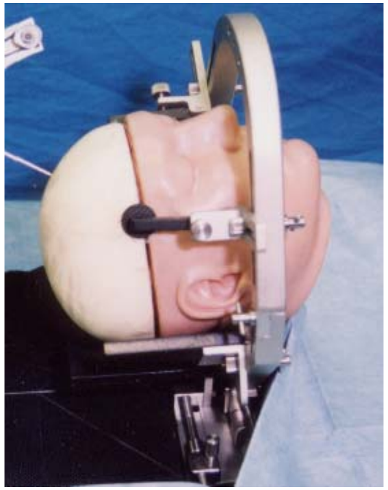
- **Some examples of solutions currently explored:**
  - "Smart" instruments
  - Intra-body robots
  - Beating heart surgery

Future directions of R&D and technical challenges: Smart instruments (1/5)

- **Mini-manipulators "inside the body"**
  - high dexterity
  - size requirements : Ø < 10mm, L = a few cm, small radius of curvature
  - force: a few Newtons (penetration force in a coronary artery = 1N), up to 50 N to grasp a needle
  - main technical issues: miniaturization; force sensor; sterilizability…



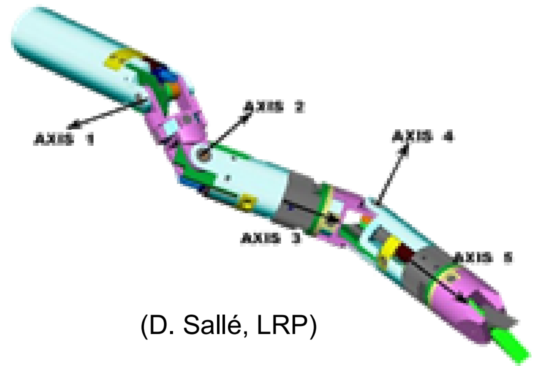
Cardiac surgery (D. Sallé, LRP)



Neurosurgery

Future directions of R&D and technical challenges: Smart instruments (2/5)

- **Mini-manipulators "inside the body"**
  - must provide bending + eventually extension and obstacle avoidance capabilities (high dexterity)



(D. Sallé, LRP)

➔ Two approaches
  - discrete ("classical") mini-serial manipulator made of rigid bodies and joints) with embedded actuators+ gear transmissions:

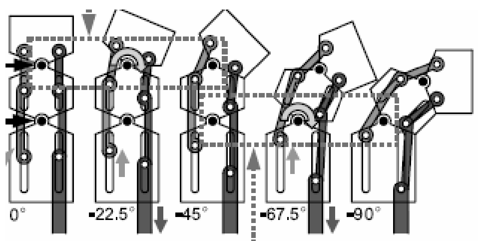
    bulky, power limitation, low reliability

  - or continuous backbone ("snake-like") architecture made of flexible material (cable, elastomer, bellows…) and remotely actuated

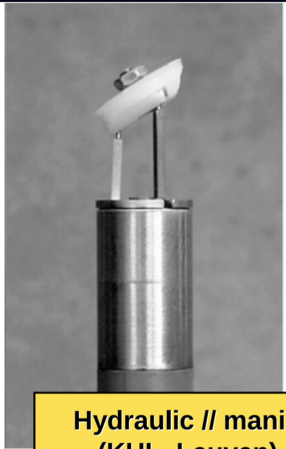
    high dexterity

  - limitations of remote actuation:
    - mechanical linkages: bulky
    - cable-drives: backlash, limited reliability
    - SMA wires (NiTi): large stroke length / weight ratio but limited bandwidth

(Univ. Tokyo)



Future directions of R&D and technical challenges: Smart instruments (3/5)

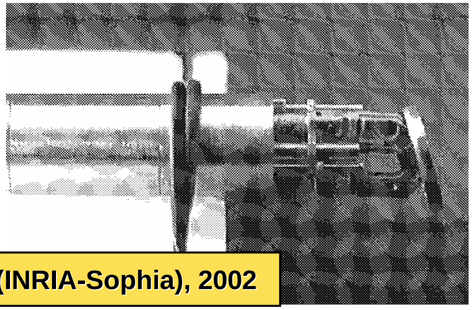


Hydraulic // manipulator (KUL, Leuven), 2000

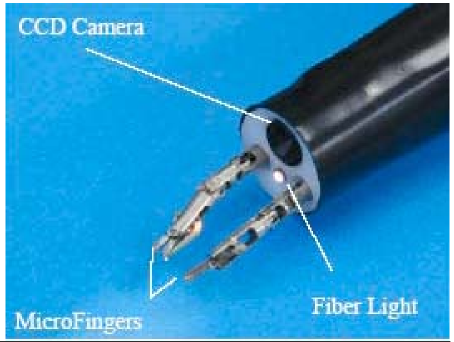
HARP (Robotics Institute, CMU, Pittsburg), 2006

Bending forceps (Hitachi, Japan), 2000

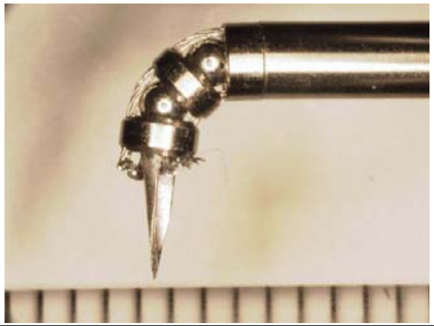
Bending forceps based on rigid linkage mechanism (Univ. Tokyo), 2003



MIPS (INRIA-Sophia), 2002

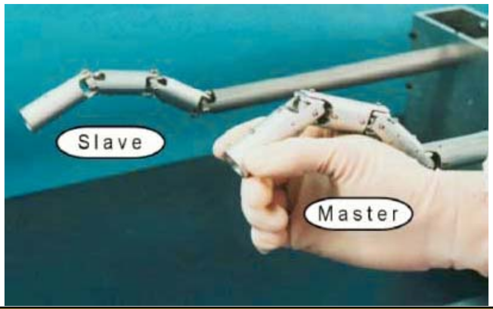


Endoscopy surgery system (Nagoya Univ.), 2004



Micro-manipulator for Intrauterine fetal surgery (Wasesa Univ., Japan), MMF et al. ICRA 2005

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

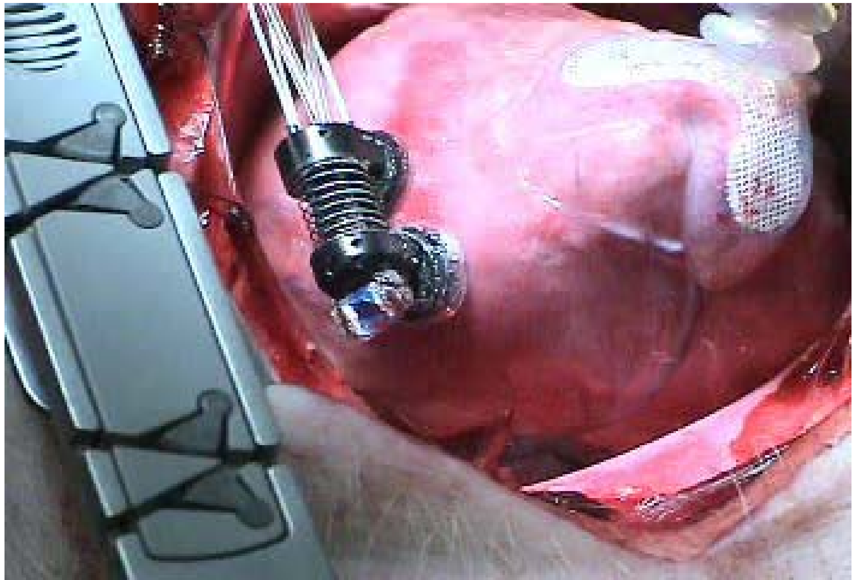


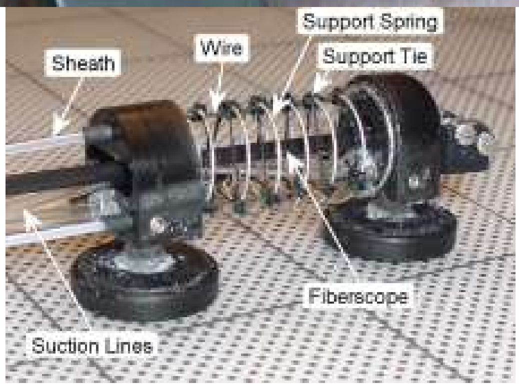
HyperFinger (Nagoya Univ., Japan), 2003

Future directions of R&D and technical challenges: Intra-body robots (4/5)

HeartLander (The Robotics Institute, CMU, Pittsburgh)

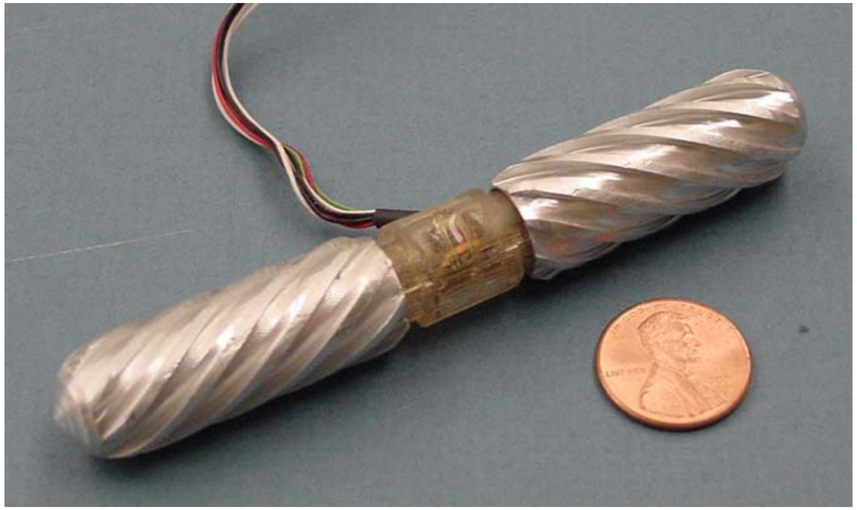
… an inchworm-like mobile robot for minimally invasive beating- heart cardiac surgery

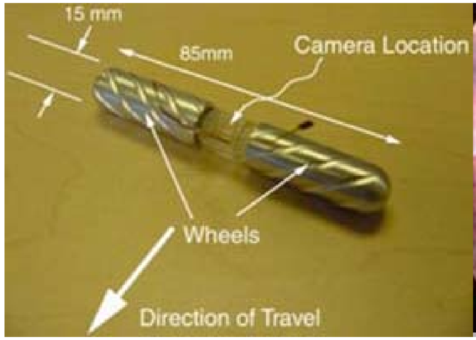




(Robotics & Mechatronics Lab., Univ. Nebraska)

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



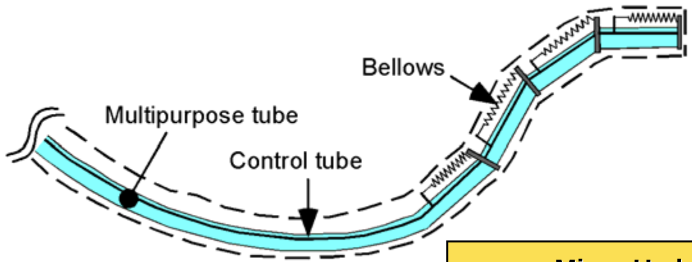


Active catheters

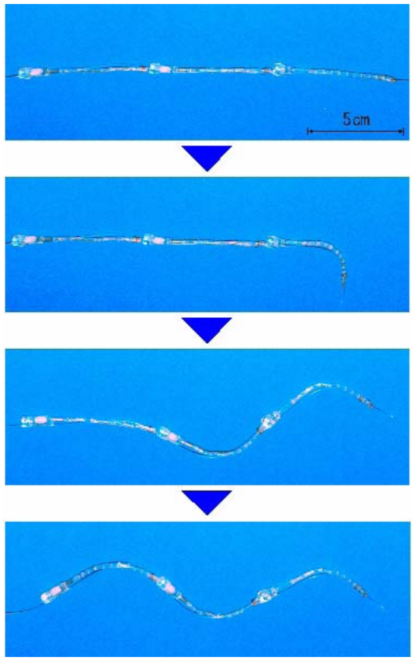
- Catheter: a tube that can be inserted into a body cavity duct or vessel. Catheters thereby allow drainage or injection of fluids or access by surgical instruments (Wikipedia). Also used for angioplasty, blood pressure measurement...
- Typical sizes: Ø <2-3 mm, L > 1m
- Manually introduced by the surgeon, 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, ICPF…



Ø = 1.5 mm, L = 15 cm



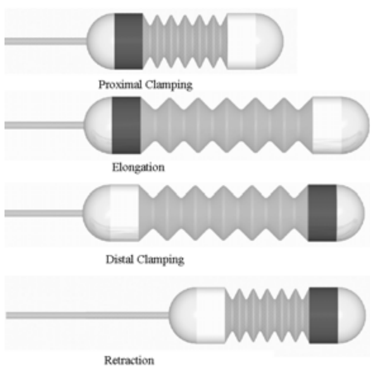
Micro Hydraulic Active Catheter with micro-valves (Nagoya Univ., Japan)

- **Some examples of solutions currently explored:**
  - "Smart" instruments
  - Intra-body robots
  - Beating heart surgery

Future directions of R&D and technical challenges
Intra-body robots (1/5)

- **Intra-body robots**
  - Goal: Inspection of the gastrointestinal tract (small intestine, colon).
  - Colon cancer: one of the main causes of death in the industrialized countries
  - Currently, manual colonoscopy: push-type flexible endoscope (up to Ø 2cm) with CCD camera, optical fiber for illumination, working channel (air, water, wire-actuated instruments for biopsy…).
  - Difficult, painful and hazardous procedure

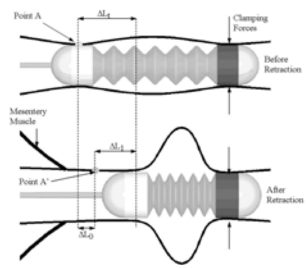
➔ Solution
  - Semi-autonomous colonoscope: self propelling robot with a tether to transport fluids and energy
  - Autonomous untethered pill swallowed by the patient (thus, the whole tract may be inspected)



Ø = 12 mm
Lmin = 115
Lmax = 195

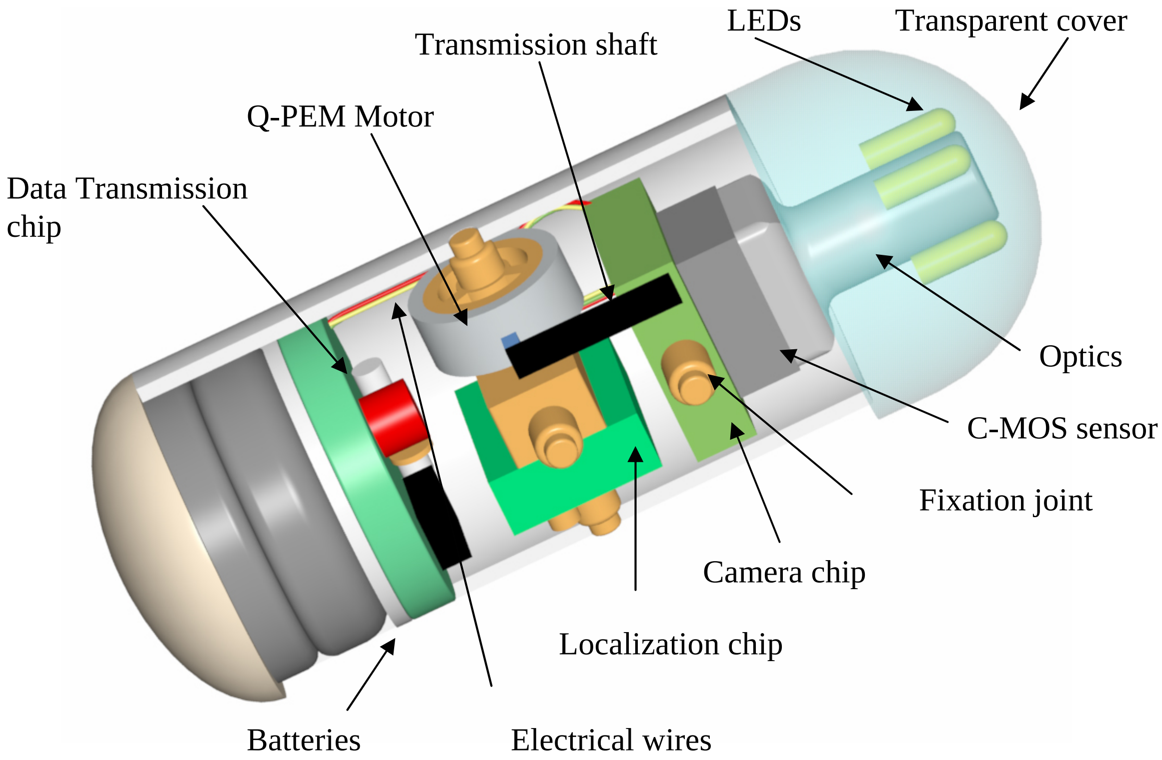
EMIL (SSSA, ARTS Lab., Pise)

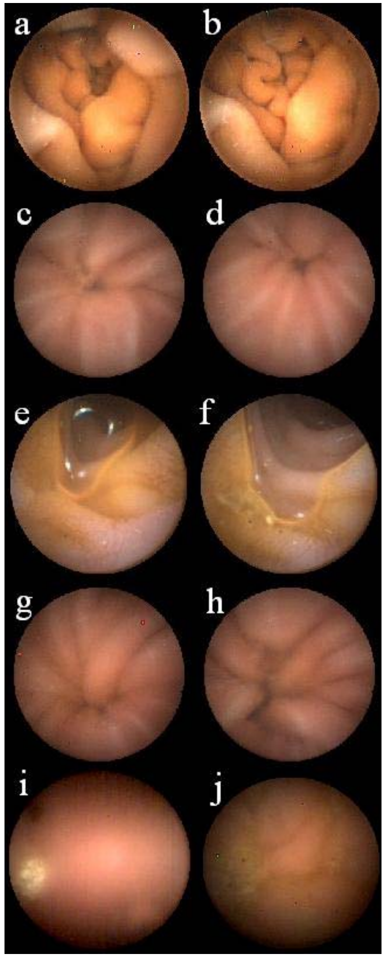
… but colon is collapsible, slippery, has acute bends, which limit traveling capabilities of semi-automatic colonoscopes



Accordeon effect

The Endoscopy « Pill »
Given Imaging – M2A





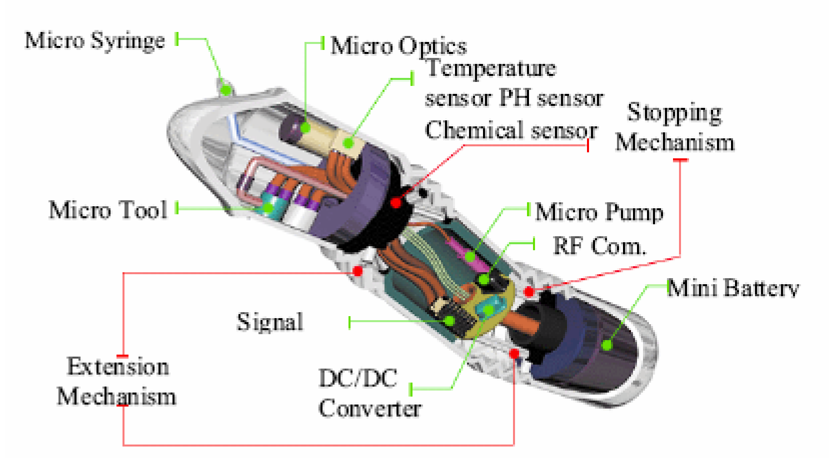
Intracorporeal Video Probe

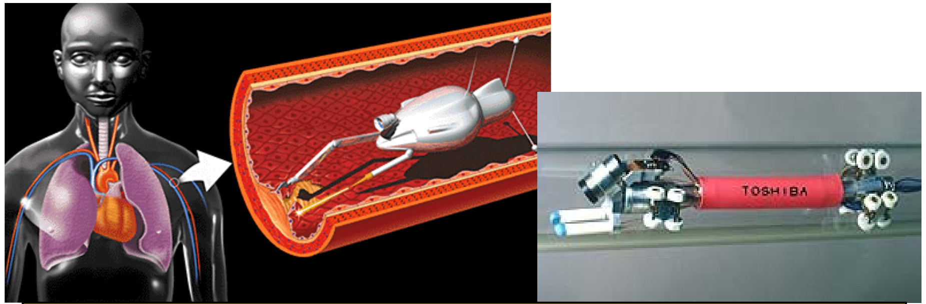
L = 20 mm, Ø = 8 mm
CMOS technology
RF trasmission data
With steerable camera

Future directions of R&D and technical challenges: Intra-body robots (5/5)

LIRMM

Microcapsule for gastrointestinal diagnosis and therapy (IMC, Korea)





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

Sayaka, Japan, 2005

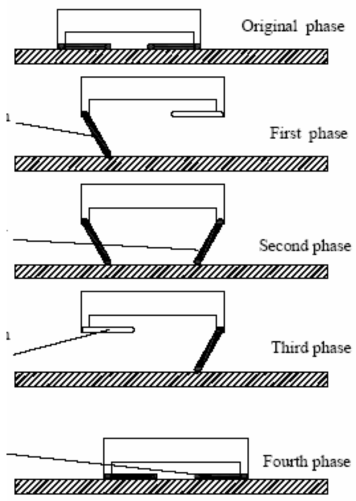
The Endoscopy « Pill » M2A (Given Imaging, Israel), 2001

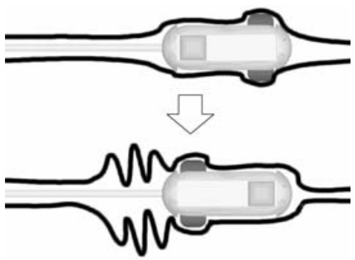
Norika3 et (RFSystem Lab., Japan), 2001

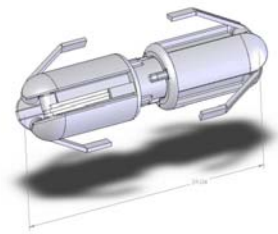
Smart capsule endoscope (Olympus Co., Japan)

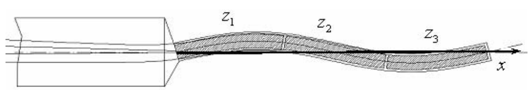
Future directions of R&D and technical challenges
Intra-body robots (3/5)

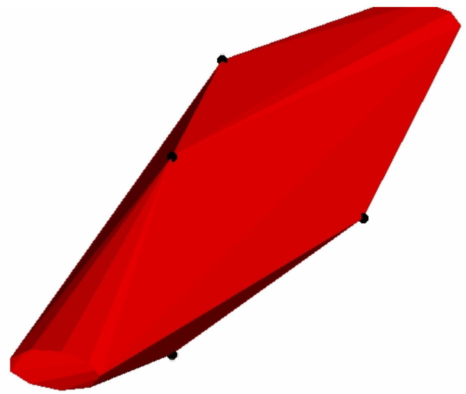
- Technical issues
  - Miniaturization, energy
  - localization of the pill in the tract
  - Active locomotion (wrt natural peristaltic waves of the tract):
    - biomimetic approaches: Inchworm, legs (SSSA), cilia, swimming (fins, tails)
    - sliding clampers
    - paddling
    - inertia impact





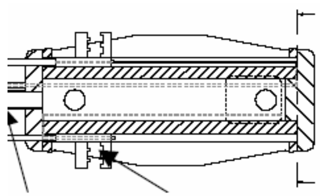


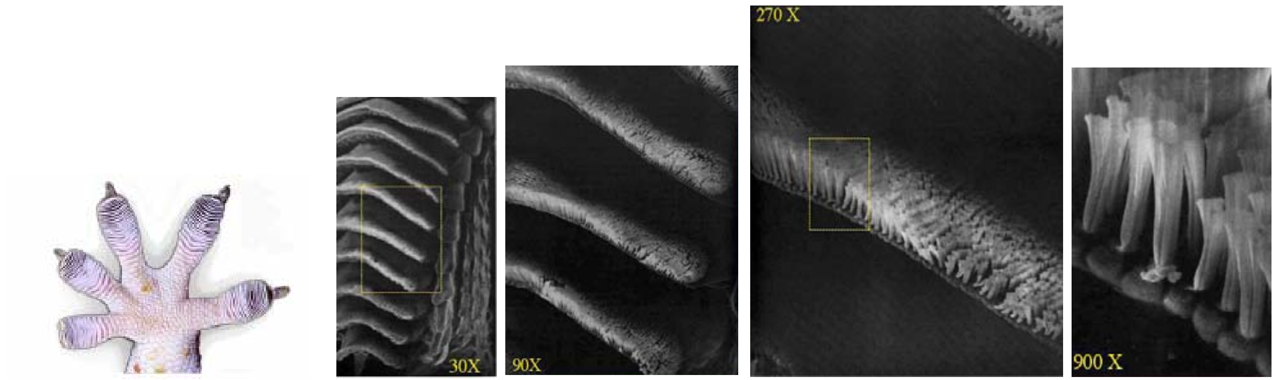




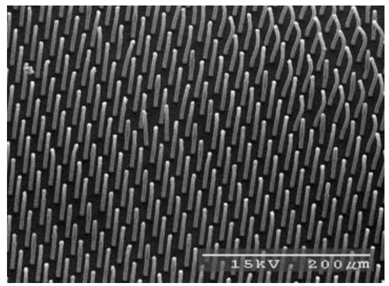
Future directions of R&D and technical challenges
Intra-body robots (4/5)

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





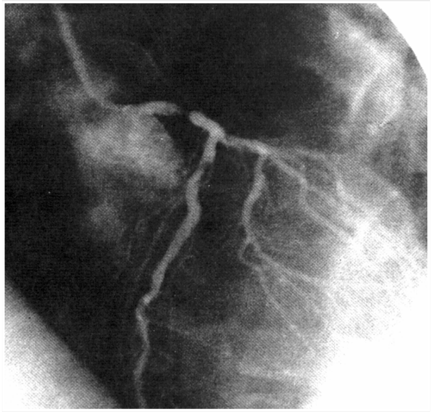
Lamellae → Setae (mm) → Nano-fibers (200 nm)

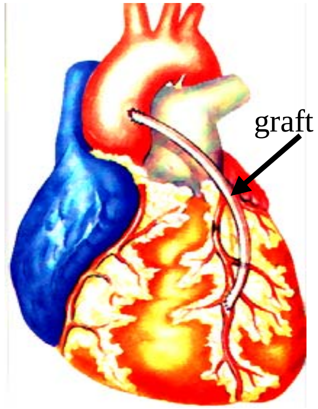


4 μm molded polyurethane fibers

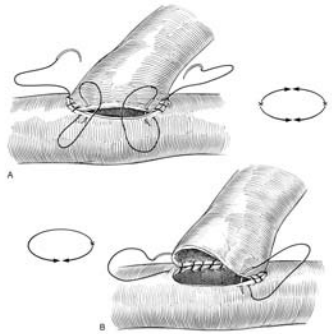
- **Some examples of solutions currently explored:**
  - "Smart" instruments
  - Intra-body robots
  - Beating heart surgery

- **Example:**
  - anastomosis for coronary artery bypass grafting (CABG)
  - Ø 2 mm, 10 to 20 penetrations
  - Ø of the thread: few tens of μm
  - Penetration force: up to 1N
  - Resolution: better than 0.1 mm
  - suturing (stitching + knot tying)

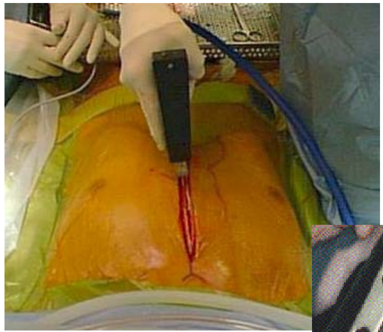


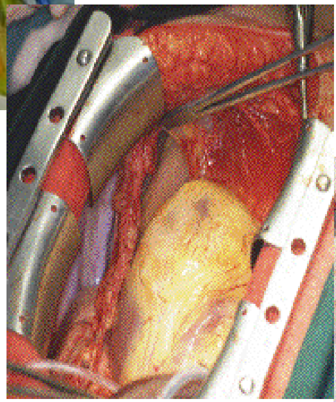


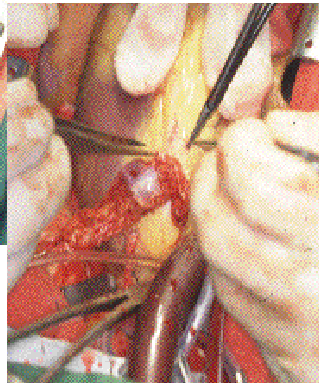
Suturing of the graft to the aorta and the coronary artery

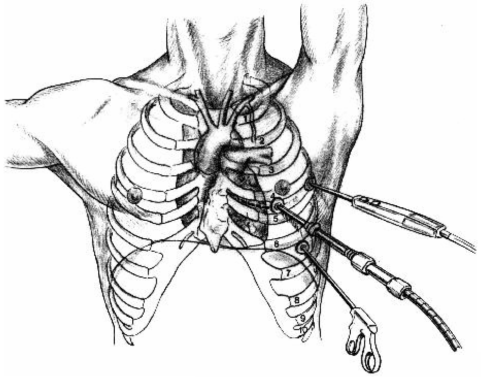


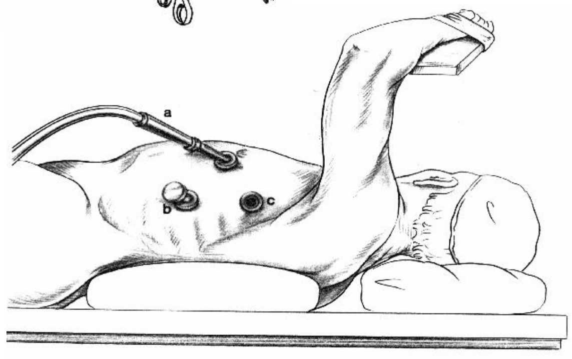
Future directions of R&D and technical challenges: Minimally invasive beating heart surgery (1/7)











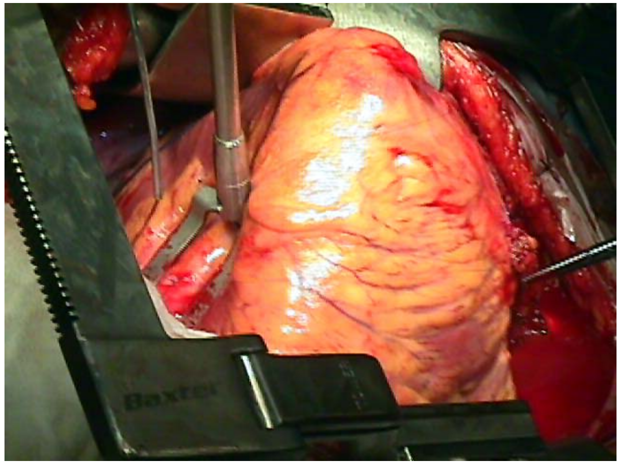
- **Invasive surgery:**
  - open the chest (sternotomy)
  - setup the heart-lung machine
  - stop the heart
  - execute surgical gestures,
  - restart the heart and close the chest
  - many drawbacks: risk, pain…

- **Minimally invasive surgery:**
  - execute surgical gestures through trocars without stopping the heart

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

➔ **Solution:**
  - use of mechanical stabilizers
  - or virtually stabilize the region of interest with a robot

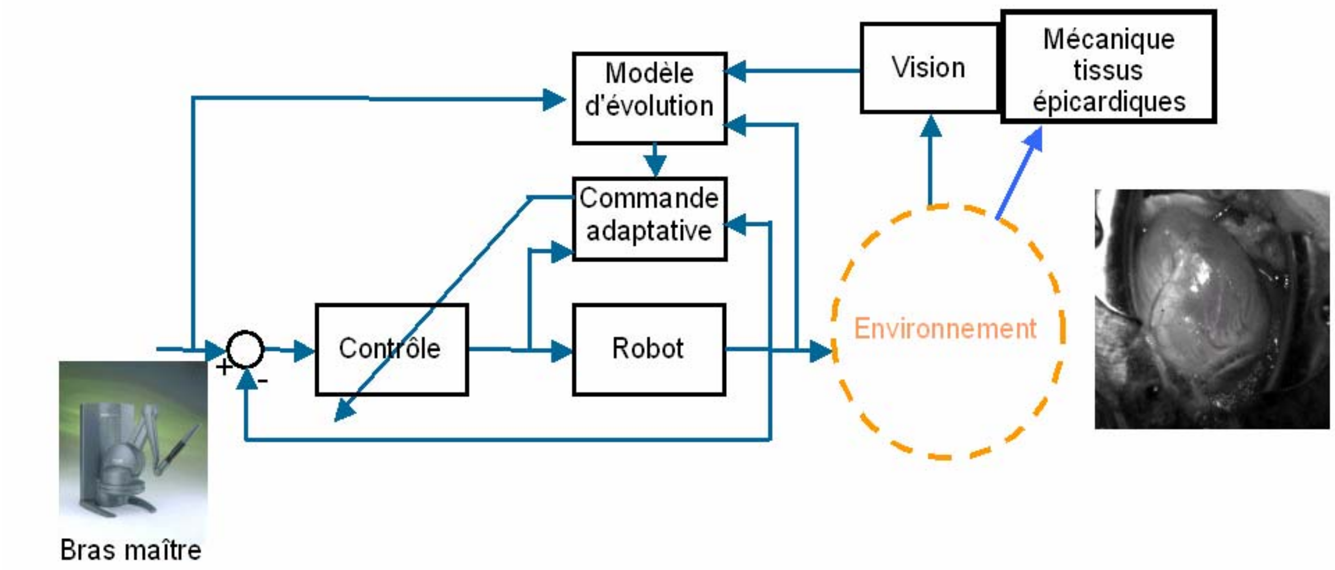
➔ develop appropriate vision-based (endoscopy or echography) and force-based control algorithms



Octopus , Medtronic

Future directions of R&D and technical challenges: Beating heart surgery (4/7)

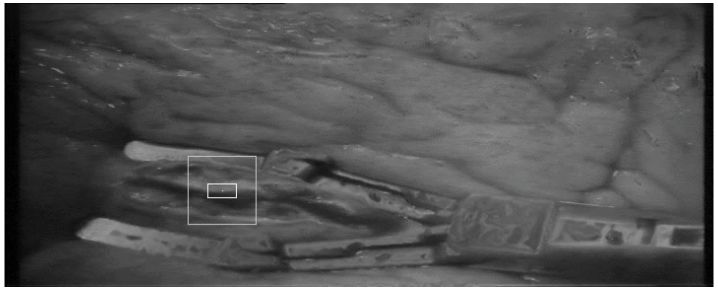
- **Université de Tokyo (2001)**
  - **Stabilisation d'images**
- **DLR Munich (2002)**
  - **Stabilisateur mécanique**
  - **Micro-capteur d'effort mais pas stérilisable**
- **Imperial College London (2004)**
  - **3D measurement with stereo-endoscopes**
- **LSIIT Strasbourg (2002-2003)**
  - **Marqueurs artificiels**
- **LIRMM – LRP – CEA – GHPS – TIMC - CHUG / PIR CNRS ROBEA**
  - **MARGE : Modélisation, Apprentissage et Reproduction du Geste Endochirurgical (2001 / 2003)**
  - **GABIE : Guidage Actif basé sur l'Imagerie Echographique (2003 / 2005)**
- **LRP → Thèse N. Zemiti, *Commande en effort des systèmes robotiques pour la chirurgie mini-invasive*, décembre 2005**
- **LSIIT → Thèse L. Cuvillon, *Compensation du battement cardiaque en chirurgie robotisée : asservissement visuel d'un robot médical avec flexibilités* , décembre 2006**



- Modèle électro-mécanique du cœur [Master 2006]
- Estimation 3D du mouvement [IFAC MCBMS'06, Thèse M. Sauvée 12/06]
- Analyse de la texture [BIOROB'06], [Workshop MICCAI'06]
- Asservissement visuel prédictif [IFAC NMPC-FS'06, CDC'06, Thèse M. Sauvée 12/06]
- Téléopération avec retour haptique [IROS'06]

Future directions of R&D and technical challenges: Beating heart surgery (5/7)

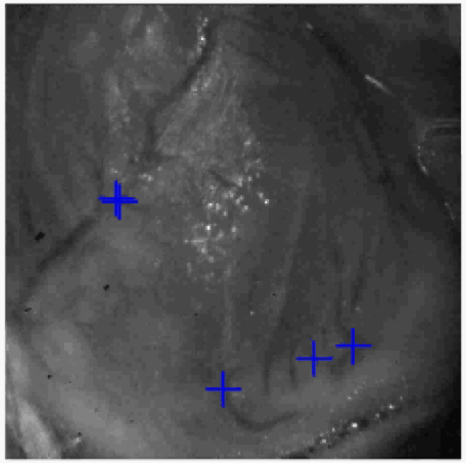
Motion estimation



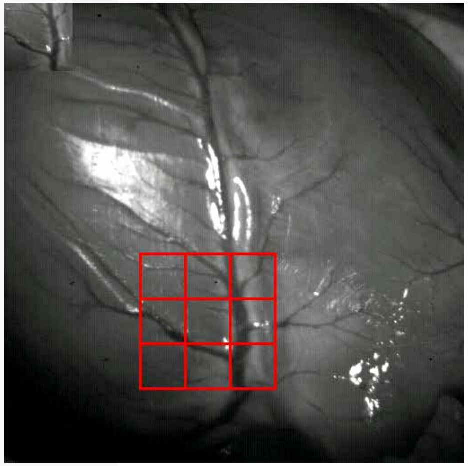
DLR, Munich

LSIIT, Strasbourg

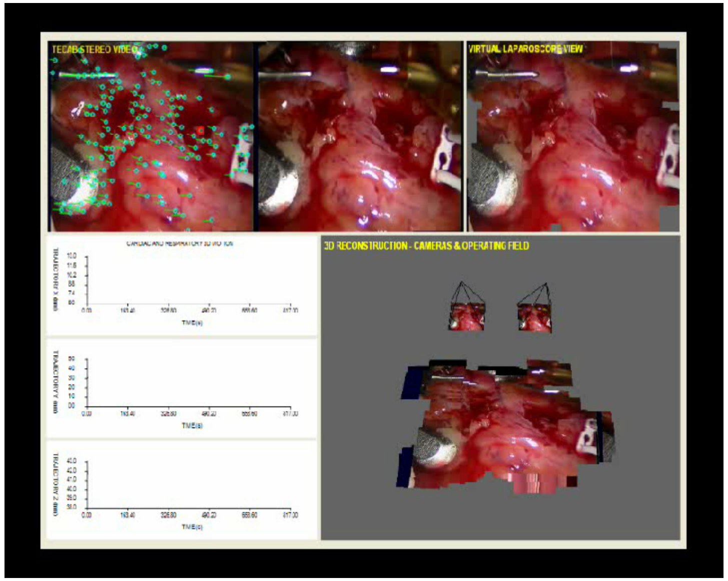
Correlation algorithm (LIRMM)



Texture analysis (LIRMM)



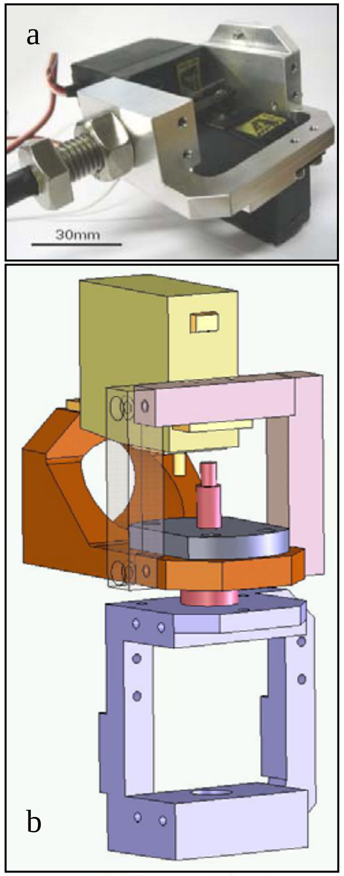
Texture analysis (INRIA Sophia)



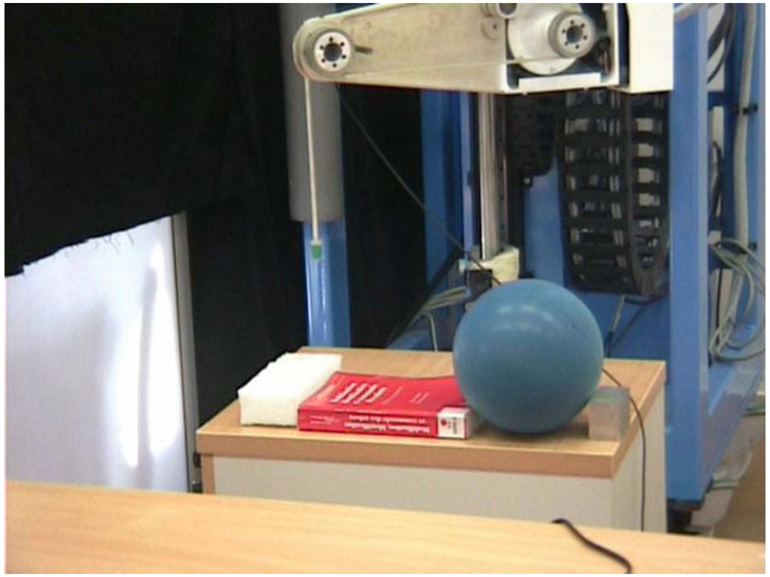
Texture + Stereo vision
(Imperial College London)

Future directions of R&D and technical challenges: Beating heart surgery (6/7)

Experimental setup



Tele-operation with haptic feedback



Virtual stiffness adaptation

Man-machine interaction

Ex vivo experiment on chicken

- **… and tomorrow?**

Film

DARPA Project for Military Surgery

(revisited from J. Rosen, UEE 2005)

- **Suggested readings and websites:**
  - IEEE Trans. on Robotics & Automation, Special issue on Medical Robotics, Vol. 19(5), October 2003
  - IARP Workshop on Medical Robotics, Hidden Valley,May 2004: http://www.nsf.gov/eng/roboticsorg/IARPMedicalRoboticsWorkshopReport.htm
  - CARS Workshop on medical Robotics, Berlin, June 2005: http://www.caimr.georgetown.edu/Medical%20Robotics%20Workshop/main.htm
  - **1st Summer School in Medical Robotics, September 2003, Montpellier:** http://www.lirmm.fr/manifs/UEE/accueil.htm
  - **2nd Summer School in Medical Robotics, September 2005, Montpellier:** http://www.lirmm.fr/UEE2005/
  - EURON Research Roadmap (April 2004): http://www.cas.kth.se/euron/euron-deliverables/ka1-3-Roadmap.pdf
  - MICCAI, Tutorials "From mini-invasive surgery to endocavitary / endoluminal interventions", St Malo 2004: http://miccai.irisa.fr/index2.php?menu=Exhibits_and_Workshops&page=Tutorials
  - Journals: general Robotics and Biomedical J. (IEEE RO, BME, Mechatronics,…) and more "Image processing" oriented (MedIA, JCAS, IEEE PAMI…)
  - Conferences: general Robotics conf. (ICRA, IROS, ISER…) and more dedicated: MICCAI, CARS, CA0S…