LIRMM

Introduction to Surgical Robotics

4th Summer School in Surgical Robotics

September 9-16, 2009

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September 9, 2009

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Medical Robotics

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

Robotics for surgery, exploration, therapy…

Rehabilitation robotics

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

Robotics to assist people

Outline

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E. Dombre, Introduction to Medical Robotics (3)

- Robotics to assist surgeon and to assist people share common basic tools: control, sensing, design, safety, interfaces…
- A short overview on assistive technologies & rehabilitation robotics
- Robotic for surgery

Assistive technologies

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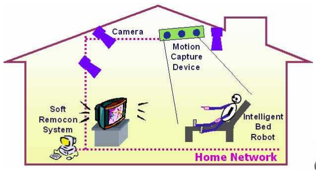
E. Dombre, Introduction to Medical Robotics (4)

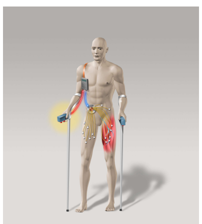
Prothetic devices / Artificial limbs

Smart living spaces



Assistive technologies

Orthotic devices / Exoskeletons



FES

Personal assistants

Robotic aids

Assistive technologies: prosthetic devices

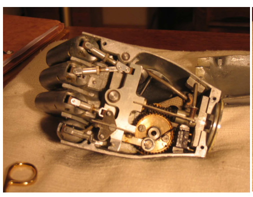
… to replace a lost limb after an amputation

*Cosmetic **or** functional* → *Cosmetic **and** functional*

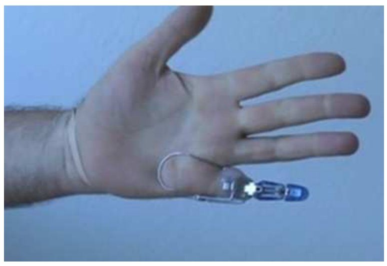
Evolution of the active hand prostheses (revisited from EURON Roadmap, 2004)

Assistive technologies: prosthetic devices

Belgrad's Hand (Mihailo Pupin Institute), early 1970



X-Finger (Didrick Medical Inc, Naples, Fl), 2007



http://www.didrickmedical.com/didrick/index.php?option=com_frontpage&Itemid=1

Assistive technologies: prosthetic devices

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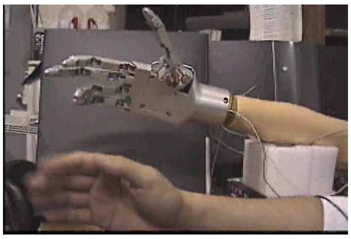
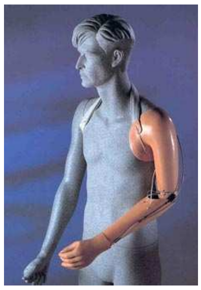
EMG Prosthetic Hand (Autonomous System Engineering Lab., Japon)





Utah Arm 2, Utah Hand (Motion Control, Inc., USA)

The flexion controlled by an electric motor in combination with a continuous adjustment of the damping of the joint → Close to natural movement: natural swinging, fast moves, high torques...

Bionic Arm (Otto Bock HealthCare, Inc., USA)

Assistive technologies: prosthetic devices

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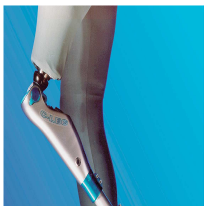
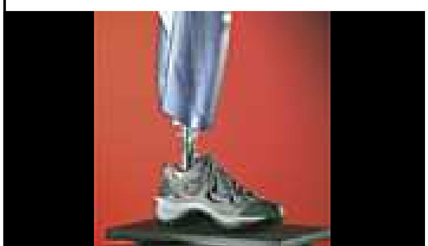
Speed & Patient Adaptive MagnetoRheological Knee Prosthesis (MIT, USA)

- the knee damping is adapted to the gait of the amputee using only local sensing of knee force, torque, and position.
- Natural gait:
  - changing speed
  - slopes
  - uneven terrain
  - stairs





Bionic Leg / Power knee (Victhom Human Bionics, Québec)

C-Leg (Otto Bock HealthCare, Inc., USA)

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Assistive technologies: prosthetic devices

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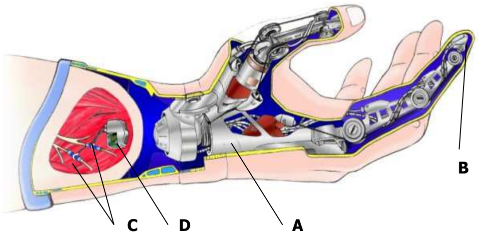
Cyberhand Advanced Prosthetic Hand (EU Project coordinated by SSSA, Pisa)



(A) advanced underactuated multi-degree of freedom hand
(B) finger tip pressure built-in sensors
(C) neuroprosthetic electrodes implanted in or around the nerve stump to detect the user's volitional commands and to feedback sensations from the pressure sensors (and others)
(D) implanted custom stimulator/amplifier

- Neurobotics / Robionics / Biomecatronics prostheses: design interfaces between assistive devices and the human nervous system such that the user's brain functions become part of the system control loop
- R&D issues
  - biocompatible implantable micro-sensors and electrodes
  - Neurophysiology: which neurons to interface?
  - Data processing (volitional command and artificial sensory feedback)…

Courtesy of Ken Yoshida, ROBEA, March 30,2005

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Assistive technologies: orthotic / wearable devices

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… exoskelton worn by a person who cannot control volontary motion of a limb anymore

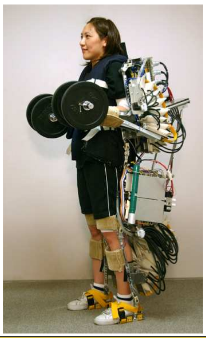
Rancho golden arm (Rancho Los Amigos Hosp., Downey), 1970

... a light, wearable brace support suit which comprises DC motors at the joints, rechargeable batteries, an array of sensors and a computer-based control system. It is fitted on the body and worn underneath the clothing

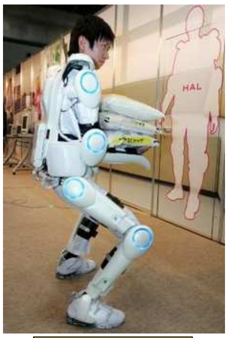
ReWalk (Argo Medical Technologies Ltd./ Technion, Israel), 2007

Assistive technologies: orthotic / wearable devices

**Orthoses to compensate for disability...
but also to extend the human strength**



Power suit: allows a nurse to carry a 85-kg patient (Kanagawa Institute of Tech., Atsugi, Japan)



HAL carrying a 30kg load (Tsukuba Univ., Japan)

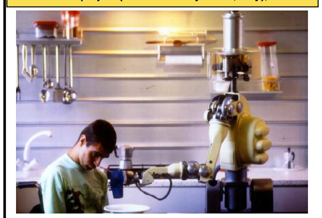
The Berkeley Lower Extremity Exoskeleton (BLEEX) (Univ.of Berkeley, USA), 2004

- R&D issues
  - Miniaturization of actuators and batteries
  - Force control & haptics
  - Safety…

Assistive technologies: Robotic mobility / manipulation aids

Robot MANUS (Exact Dynamics BV, The Netherlands), 1980's

MOVAID EU project (Coordinated by SSSA, Italy), 1990's



VA-PAMAID (VA Pittsburgh Healthcare System)

Smart walker GUIDO (Haptica, Dublin, + Univ. Polytech. Madrid)

Smart / "Intelligent" walker:
- obstacle avoidance capabilities
- navigational assistance
- mobility but also transfer aid

MONIMAD (Robosoft, LRP, France)

Assistive technologies: Personal assistants

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- Robots-pets and humanoids
- Robots-pets are supposed to be helpful for healthcare:
  - Interact with human beings to make them feel emotional attachment
  - Useful to relax, relieve mental stress, and exercise for physical rehabilitation
  - ➔ Robot therapy for elderly, chronically ill children, persons with cognitive impairments…

Seal robot Paro (AIST – Intelligent System Co., Japan)

NeCoRo Cat (Omron, Japan / Institute of Robotic Psychology and Robotherapy, Cyber-Anthropology Research Inc., Chevy Chase , USA)

Aibo (Sony, Japan)

KASPAR (Adaptive Systems Research Group, U. Hertfordshire, Hatfield, UK)

Assistive technologies: Personal assistants

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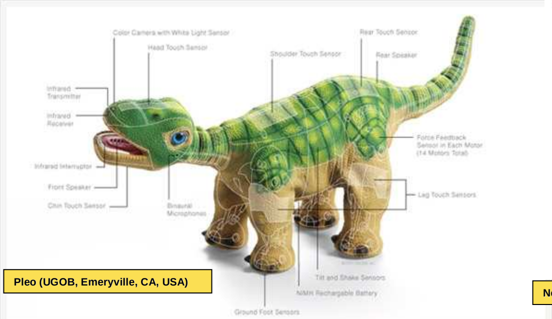
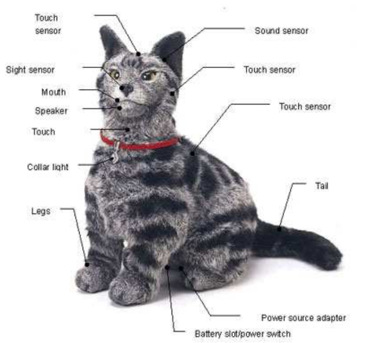
- Pleo, a one week-old baby Camarasaurus dinosaur,
- moves, expresses emotion, autonomously explores and responds to the world around him.
- a color camera, sound sensors, two infrared sensors, 14 motors, over 100 gears, eight touch sensors, and an orientation sensor.
- 349 $

- NeCoRo
- Reacts to human movement and expresses its own emotion
- tactile sensors, 15 motors (2 for each leg, tail and neck, 1 for eyelids, ears and mouth)
- ~ 2000 $



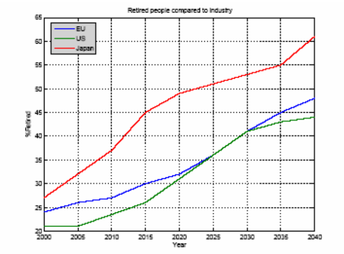
Pleo (UGOB, Emeryville, CA, USA)



NeCoRo (Omron, Kyoto, Japan)

Assistive technologies: Personal assistants

- Humanoids are supposed to help people in the daily life:
  - assistance in housework
  - entertainment
  - healthcare delivery…



[World Bank, 2004]

Asimo, Honda

Care-O-bot II (Fraunhofer, IPA, Stuttgart, DE)

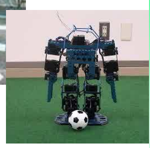
Ri-Man, Riken, Bio-mimetic Control Research Center, Nagoya, Japan

- R&D issues: all the research topics of Robotics + Cognitive sciences

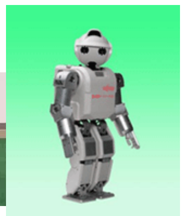
Assistive technologies: Personal assistants

Toyota

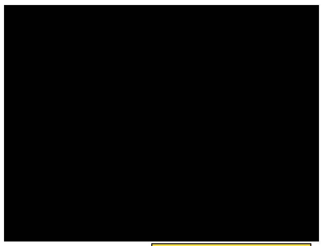
Asimo, Honda



VStone



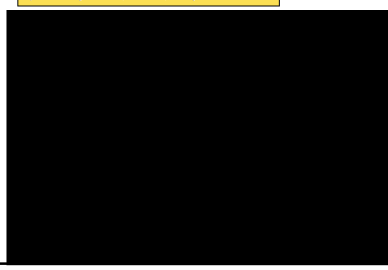
HOAP3, Fujitsu



www.robots-dreams.com)

HRP2, Kawada Industries, Inc. & AIST, Japan

Big Dog, the soldier of the future's best friend (Boston Dynamics, Boston, USA)



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

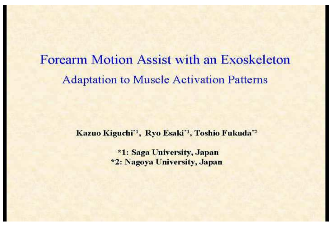
Robotics for surgery, exploration, therapy…

Robotics to assist people

Robotic therapy (Neurobotics Lab, Rob. Institute, Carnegie Mellon, USA)

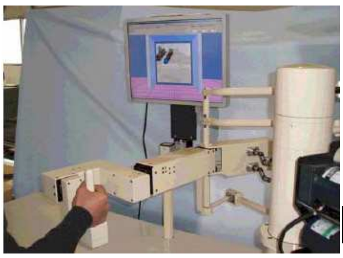
Virtual environment with a robotic device to extend the strength and mobility of people recovering from strokes

Saga Univ. & Nagoya Univ., Japan


Forearm Motion Assist with an Exoskeleton
Adaptation to Muscle Activation Patterns

Kazuo Kiguchi[*1], Ryo Esaki[*1], Toshio Fukuda[*2]
*1: Saga University, Japan
*2: Nagoya University, Japan

Robotic exerciser: the robot guides the patient through a pre-programmed path. The movement may be performed against a resistance provided by the robot



6-dof Rehabilitation Robot Osaka Univ., Japan), 2005

•**Rehabilitation robotics:** robots and mechatronic tools for clinical therapy in neuro-motor rehabilitation

Rehabilitation robotics

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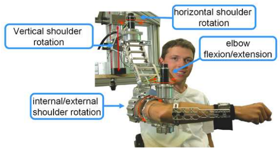
Lokomat for gait restauration (Hocoma & ETHZ Zurich, Suisse)

- R&D issues
  - Better human-robot interfaces
  - FET



Patient-Cooperative Robot-Aided Rehabilitation for the Upper Extremities Therapy

ARMin (Hocoma & ETHZ Zurich, Suisse)

Assistive technologies & Rehabilitation robotics

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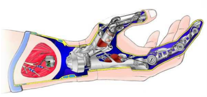
- **Some milestones**



1970 1980 2000

Medical Robotics

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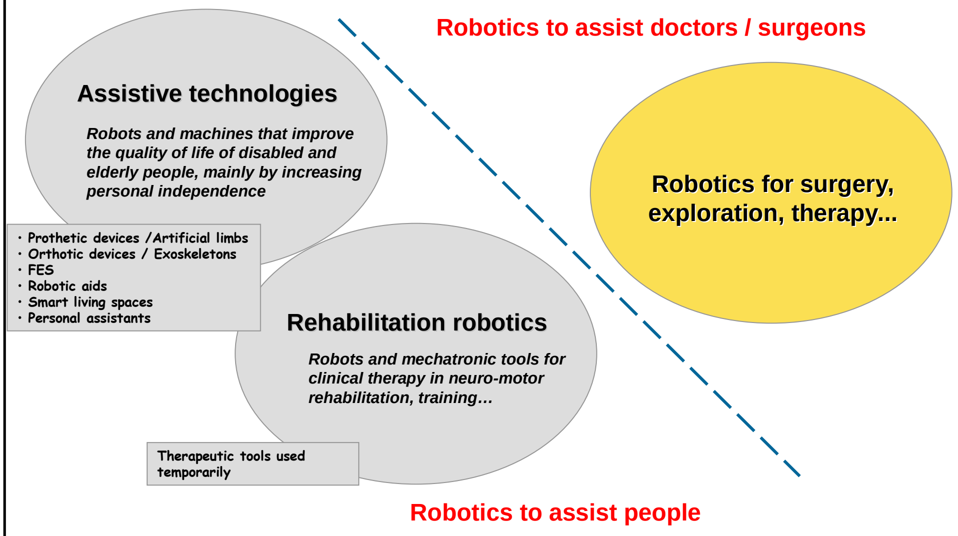
E. Dombre, Introduction to Medical Robotics (21)



Outline

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E. Dombre, Introduction to Medical Robotics (22)

- A short overview on assistive technologies & rehabilitation robotics
- Robotic for surgery
  - **A robot… for what?**
    Analysis of some surgical functions (and a few non surgical functions), and the current robotic solutions
  - **Do we need surgeon anymore?**
    Added value and limitations of robots
  - **… and tomorrow?**
    Future directions and technical challenges
- Conclusion

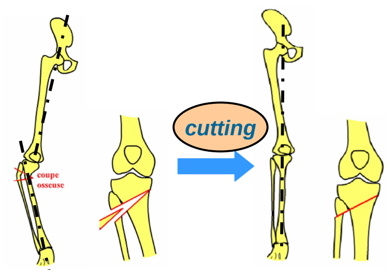
A robot… for what?

Analysis of some surgical functions

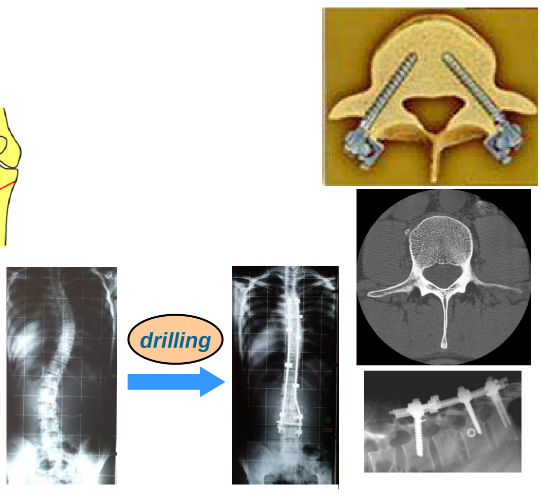
Orthopedics	**"Machining"** **(rigid surfaces as bones)**
MIS	**Constrained manipulation** **(through a trocar)**
Neurosurgery **Interventional radiology** *Radiotherapy*	**Constrained targeting** **(reach a target through an entry port)**
Skin harvesting *TMS*	**Surface tracking**
Microsurgery	**Micro-manipulation**

Function: "Machining" rigid surfaces

High tibial osteotomy for genu varus (bow-leggedness)



http://www.genou.com/arthrose/osteotomies.htm



Pedicular screw placement to affix rods and plates to the spine

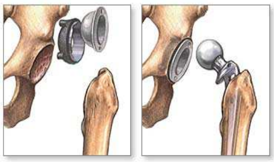
10% to 40% ill-placed screws

(Source J. Troccaz, 1st Summer School in Surgical Robotics 2003)

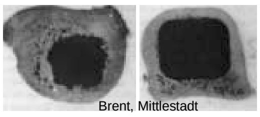
Function: "Machining" rigid surfaces

Total Hip Arthroplasty (THA)

A metal ball and stem are inserted in the femur and a plastic socket is placed in the enlarged pelvis cup

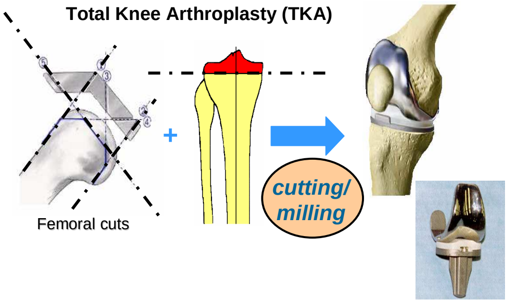


adam.com



milling

Total Knee Arthroplasty (TKA)



- **Main difficulty: precision**
- **Advantages of a robot:**
  - Precision: right angle, right direction, right orientation of plane…
- **Outcomes:**
  - less corrective surgeries,
  - better life expectancy of prostheses.

Machining rigid surfaces: Orthopedics

- Navigation systems / localizers

Y. Patoux, ISIS, 2nd Summer School on Surgical Robotics, Montpellier, Sept. 2005

Machining rigid surfaces: Orthopedics

LIRMM — E. Dombre, Introduction to Medical Robotics (27)

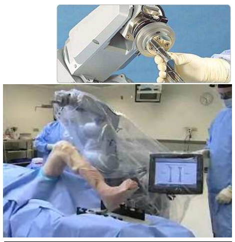
- Navigation systems: limited accuracy. They are not robots…
- Robots: Industrial robots ➔ Dedicated systems ➔ "Portable" robots


ROBODOC (ISS, then Robodoc), 1992

CASPAR (OrtoMaquet / URS Ortho), 1997



ACROBOT (Imperial College/Acrobot Ltd), 2001


BRIGIT (MedTech/Zimmer, LIRMM), 2005

MARS / SpineAssist (Technion/Mazor Surgical, Haifa), 2002

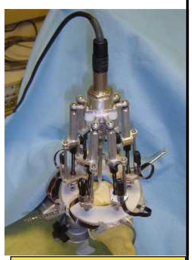

Machining rigid surfaces: Orthopedics

LIRMM — E. Dombre, Introduction to Medical Robotics (28)

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

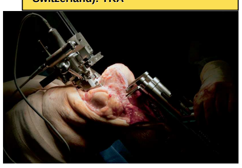

MARS / Spine Assist (Technion/Mazor Surg., Haifa), 2002: spine surgery

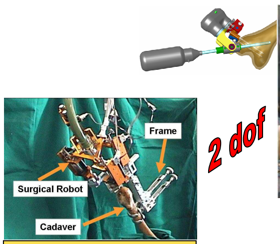
6 dof


MBARS (CMU, Pittsburg): TKA


5 dof

GP system (Medacta, Switzerland): TKA

PiGalileo CAS (PLUS Orthopedics AG, Switzerland): TKA




ARTHROBOT (KAIST), 2002: TKA

2 dof


Praxiteles (TIMC / Praxim): TKA

Function: Constrained manipulation

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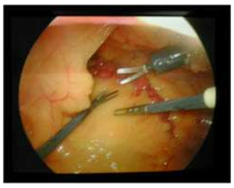
Trocars

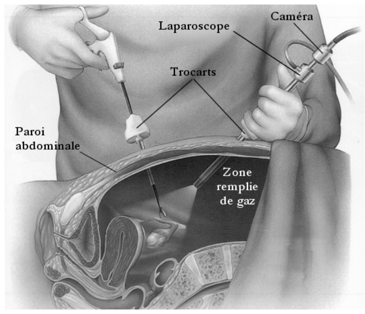
Endoscope + cold light fountain



Control LCD

Instruments

Minimally-invasive surgery (MIS)



The tool axis passes through a "fixed" point
➔Two constraints: the translation is constrained in two directions

Function: Constrained manipulation

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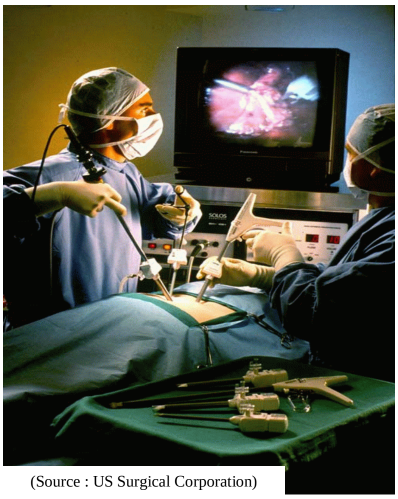
E. Dombre, Introduction to Medical Robotics (30)



(Source : US Surgical Corporation)

- Widely used in abdominal surgery, more and more in cardiac surgery

- **Some difficulties:**
  - 3 hands are mandatory
  - monocular vision (usually)
  - comfort of the surgeon
  - eye-hand coordination (fulcrum effect)
  - loss of internal mobility due to kinematics constraints induced by the trocar
  - restricted workspace
  - no force feedback (friction in the trocar)
  - …

- **Advantages of a robot:** may solve (more or less) most of these difficulties

Constrained manipulation: MIS

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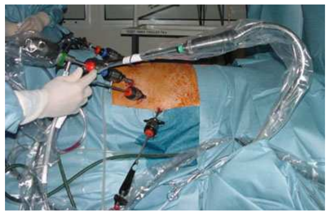
- **2 generations of devices: Endoscope holders and Master-slave systems**
- **Mechanical (passive) endoscope holders**
  - **Several bars connected with (more or less) fast lockable joints:**
    - Unitrak and Endofreeze (Aesculap, Tuttlingen, Germany),
    - Endoboy (Geyser-Endobloc, Coudes, France),
    - Martin (Gebrüder Martin GmbH & Co., Tuttlingen, Germany),
    - PASSIST (Academic Medical Center, Amsterdam, The Netherlands)…
  - **Do not allow frequent camera motions as it requires (at least one) surgeon’s hand**

Endofreeze (Aesculap, Germany): pneumatic locking



Endoboy (Geyser-Endobloc, France): pneumatic locking

Constrained manipulation: MIS

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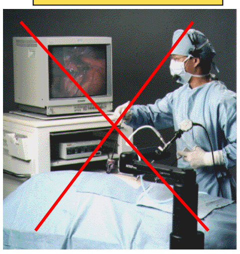
- Active endoscope holders:
  - the robot must provide a built-in remote center of motion to comply with the kinematic constraint imposed by the trocar
  - It must be easily controlled

Lapman (Medsys, Belgium), 2004

Hand control

SoloAssist (AKTORmed, Barbing, Germany), 2008

AESOP (Computer Motion), 1994



Voice control, Foot control

ViKY (Endocontrol, France), 2007

EndoAssist (Armstrong Healthcare / Prosurgics, Bracknell, UK), 1996

FreeHand (Prosurgics, Bracknell, UK), 2008

Head control

Constrained manipulation: MIS

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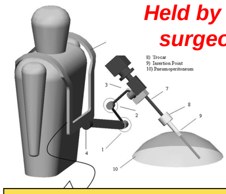
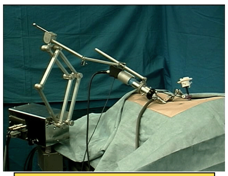
- Active endoscope holders:

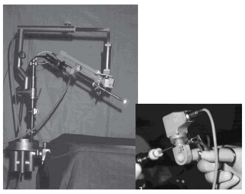
Held by the surgeon



Hand Free Navigation System (Instituto Politécnico Nacional, Mexico), 2009



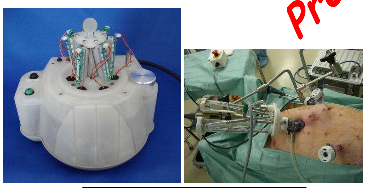
Naviot (BMPE Lab, Tokyo Univ. / Hitachi, Japan), 1999



FIPS Endoarm (Karlsruhe Research Institute & Univ. Tübingen, Germany), 2000

Prototypes

KaLAR (KAIST, Korea), 2003



P-arm (Dpt Mechanical Science & Bioengng, Osaka Univ., Japan), 2007

EVOLAP (CEREM, Univ. Catholique, Louvain la Neuve, Belgium), 2008

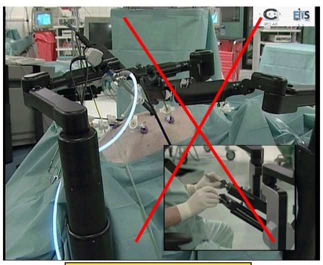
SoloAssist (Micro-Epsilon, Ortenburg, Germany)

Constrained manipulation: MIS

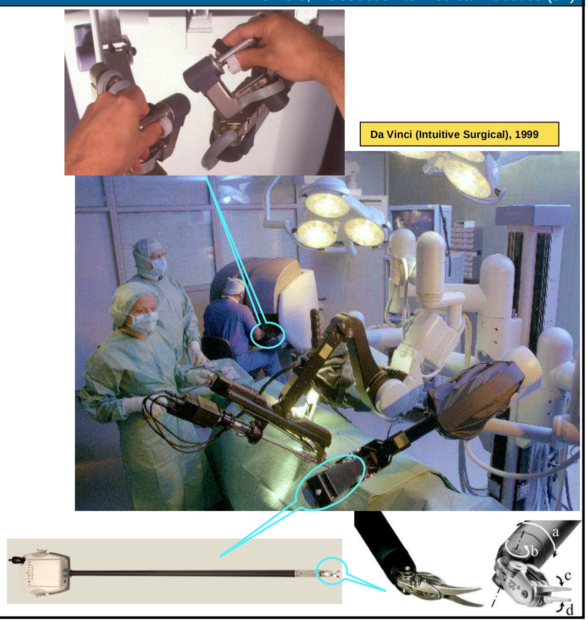
LIRMM — E. Dombre, Introduction to Medical Robotics (34)

- Master-slave robots

Laprotek (Endovia Medical)



ZEUS (Computer Motion), 1998



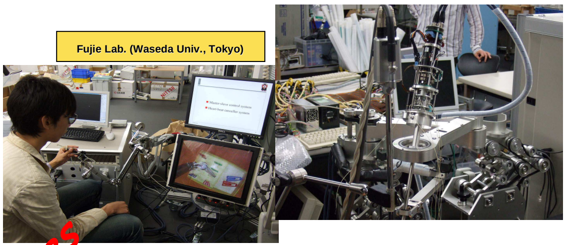
Da Vinci (Intuitive Surgical), 1999

Constrained manipulation: MIS

- Master-slave robots

Artemis (FZK, Karlsruhe)

Fujie Lab. (Waseda Univ., Tokyo)



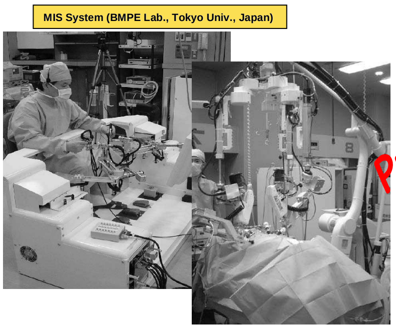
Prototypes

RTW (UC Berkeley), 1999

Mitsuishi Lab., (Tokyo Univ.)

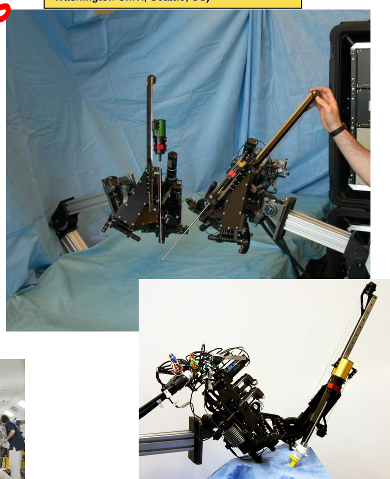
Constrained manipulation: MIS

MIS System (BMPE Lab., Tokyo Univ., Japan)

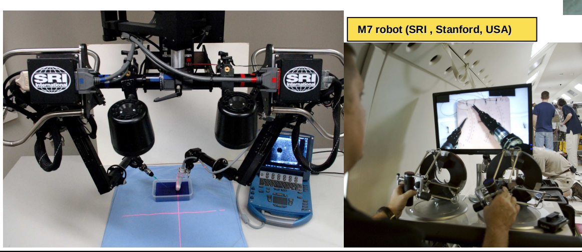


Prototypes

Raven Surgical robot (BioRobotics Lab., Washington Univ., Seattle, US)



M7 robot (SRI , Stanford, USA)



Function: Constrained targeting

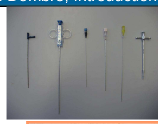
LIRMM

E. Dombre, Introduction to Medical Robotics (37)

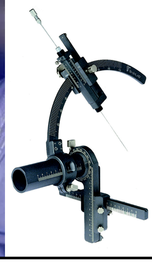
- Insertion of an instrument / needle in soft tissue to reach a target
- The insertion is image-guided (CT-scan, MRI, US)
- Wide use in interventional surgery for biopsy, energetic tumor destruction, drainage, drug delivery…
- …and also in neurosurgery

- **Some difficulties:**
  - the instrument / needle passes through a “semi-fixed” point ➔ the translation is constrained in two directions
  - soft tissues + needle may be deformable…
  - reach smaller and smaller targets

- **Advantages of a robot:**
  - the surgeon is not anymore exposed to radiation
  - accuracy in targeting
  - possible compensation for physiological motions
  - …







Constrained targeting: Neurosurgery

LIRMM

E. Dombre, Introduction to Medical Robotics (38)

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

- Navigation systems (not robots)
  - cranial
  - spine
  - ENT

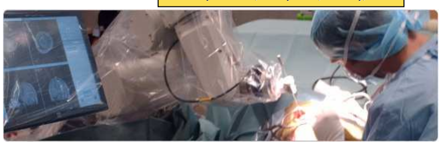
➔ Y. Patoux, ISIS, 2nd Summer School on Surgical Robotics, Montpellier, Sept. 2005

- Robots = tool holders

The guide constrains the direction of the instrument

PathFinder (Prosurgics, UK), 2003

ROSA (MedTech, Montpellier, France), 2009



- Microscope holders

Surgiscope (Elekta-IGS, then ISIS, France), 1997

MKM (Zeiss)

Constrained targeting: Interventional radiology

LIRMM

E. Dombre, Introduction to Medical Robotics (39)

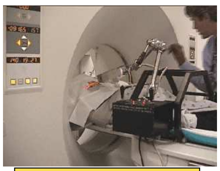
Sensei Robotic Catheter System (Hansen Medical, Mountain View, CA), 2002

- Designed to allow the physician to remotely control the catheter while being shielded from unnecessary radiation exposure
- Steerable catheter for percutaneous procedures
- Remote accurate positioning, manipulation and stable control in 3D
- « Instinctive » control: the catheter immediately replicates the hand movement of the motion controller

Constrained targeting: Interventional radiology

LIRMM

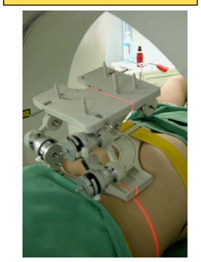
E. Dombre, Introduction to Medical Robotics (40)

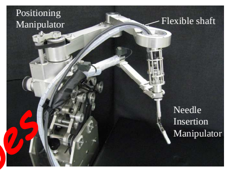


ACUBOT (JHU, Baltimore & Georgetown Univ. Washington)

- To reach a target under image guiding
- The robots have to be compatible with X-ray or magnetic environment

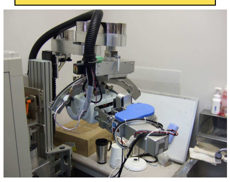
CT-Bot (LSIIT, Strasbourg), 2005



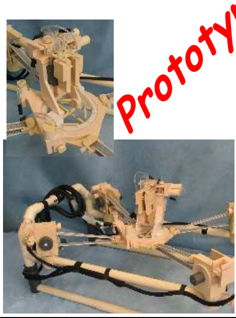


MR- guided-needle insertion robot, (Fujie Lab., Waseda Univ., Tokyo)

Needle insertion robot (BMPE Lab., Tokyo Univ.): vertebroplasty

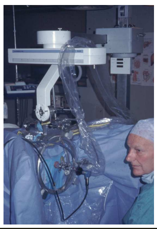


Prototypes

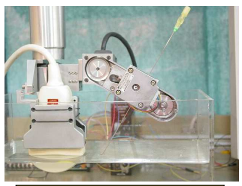


CT/MRI compatible biopsy robot (TIMC), 2004

Bloodbot (Imperial College, London)



PROBOT (Imperial College, London): prostate resection



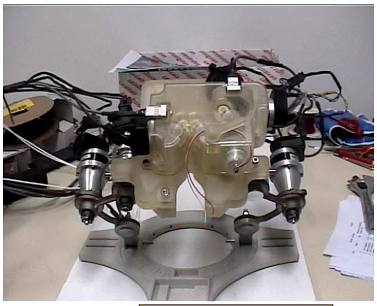
UMI (Tokyo Univ.): Ultrasound-guided Motion-adaptive Instrument

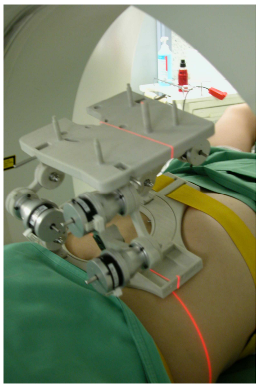
Interventional radiology: example of the CT-Bot

LIRMM

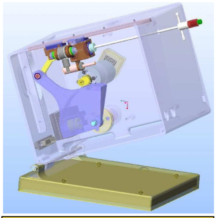
E. Dombre, Introduction to Medical Robotics (41)

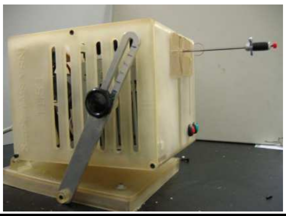
- **CT-Bot:**
  - CT compatible
  - 5 dof parallel robot
  - + 2 dof for needle insertion
  - piezoelectric actuators
  - CT-image servoing (target + compensation of physiological motions)
  - force sensor (teleoperation mode)
- **CT-Master:** HMI to control the insertion force and to return haptic feedback to the doctor





CT-Bot (LSIIT, Strasbourg), 2005





CT-Master (LSIIT, Strasbourg), 2007

Constrained targeting: Radiotherapy

LIRMM

E. Dombre, Introduction to Medical Robotics (42)

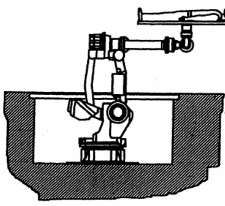
- **A last non-surgical example of constrained targeting**
- **Radiotherapy: the tumor is targeted from multiple radiation ports to minimize radiations on critical areas**
  - Safety
  - Registration

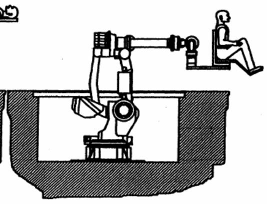
Cyberknife (Accuray, Stanford)

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

Centre de Protonthérapie (Orsay) and ARIPA (Paris)

The patient is on a bed mounted on the robot and his moved in front of the cyclotron





A robot… for what?

LIRMM

Analysis of some surgical functions

Orthopedics	"Machining" (rigid surfaces as bones)
MIS	Constrained manipulation (through a trocar)
Neurosurgery Interventional radiology *Radiotherapy*	Constrained targeting (reach a target through an entry port)
Skin harvesting *TMS*	**Surface tracking**
Microsurgery	**Micro-manipulation**

Function: Surface tracking

LIRMM

Manipulation of various probes

- **on rigid surfaces**
  - for instance, manipulation of probe on skull for transcranial magnetic stimulation (TMS)
  - constraints: accurate positionning along cortical sulci, orientation of the probe, reproducibility

Photo BioMag

- **or on soft surfaces:**
  - for instance, skin harvesting
  - constraints: control of 1 to 6 components of the interaction forces

Photo LIRMM

- **Advantages of robots:**
  - accurate tracking of complex surfaces
  - compensation of patient's motions
  - possible control of the interaction forces

Surface tracking: TMS

LIRMM

E. Dombre, Introduction to Medical Robotics (45)

Bryan Christie Design

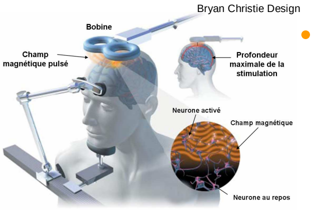
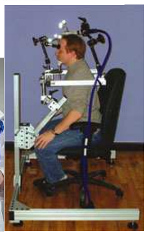
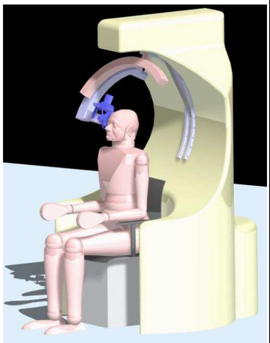


Photo Magstim



Manual solution & passive fixture

- **Transcranial magnetic stimulation**
  - Depression, OCD…
  - Stimulation of precise cortical area determined by MRI with ~2T magnetic field (also Repetitive TMS 1-50Hz)
    ➔ registration issue
  - Quasi-static
  - several sessions
    ➔ reproducibility issue
  - ~ 30' duration each
    ➔ tracking head motion necessary
  - Coil weight: 1-2 kg
  - Force applied on the skull < 2.5N
    ➔ control issue

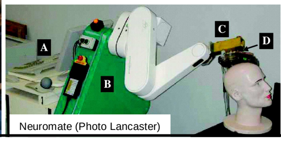


TMS robot (LSIIT, Strasbourg, 2008)

Robotized TMS solutions

Photo Biomag

Photo Matthäus



Neuromate (Photo Lancaster)

Prototypes

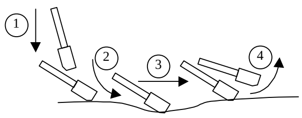
Surface tracking: Skin harvesting with SCALPP

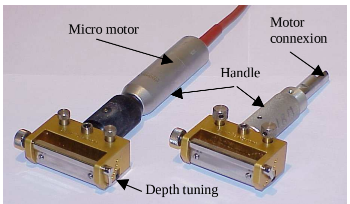
LIRMM

E. Dombre, Introduction to Medical Robotics (46)

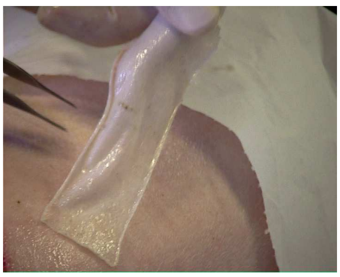
SCALPP (LIRMM/SINTERS)

Robotized skin harvesting for reconstructive surgery (burnt patients, orthopedics...)





Dermatomes

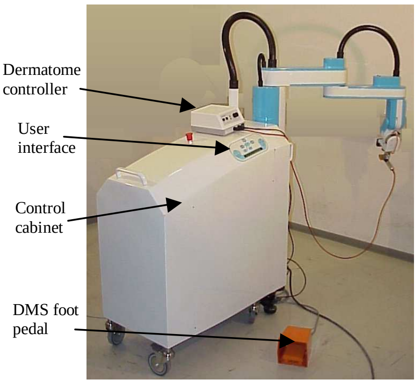


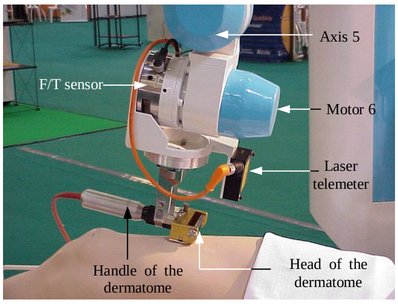
Surface tracking: Skin harvesting with SCALPP

SCALPP (LIRMM/SINTERS)

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

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



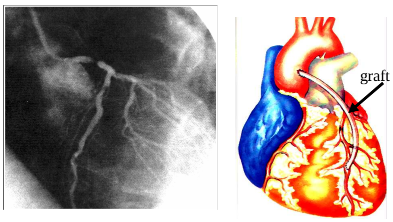


Funding Etat/Région Languedoc-Roussillon

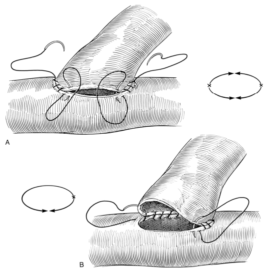
Function: Micro-manipulation

- 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),

- **Advantages of robots:**
  - Teleoperation mode ➔ scaling force & motion
  - compensate for physiological movements of the patient
  - compensate for the natural hand tremor of the surgeon

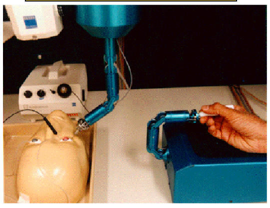


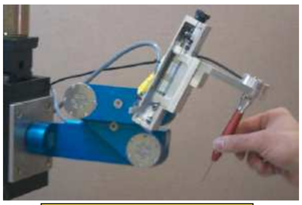
Suturing of the graft to the aorta and the coronary artery



Micro-manipulation : microsurgery

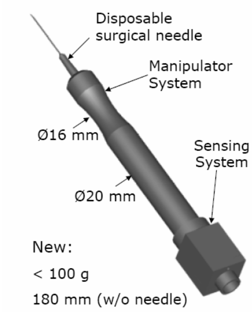
RAMS (Robot Assisted MicroSurgery, JPL- NASA): eye surgery

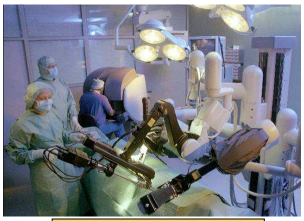




Steady-hand robot (JHU, Baltimore): microsurgery, eye surgery

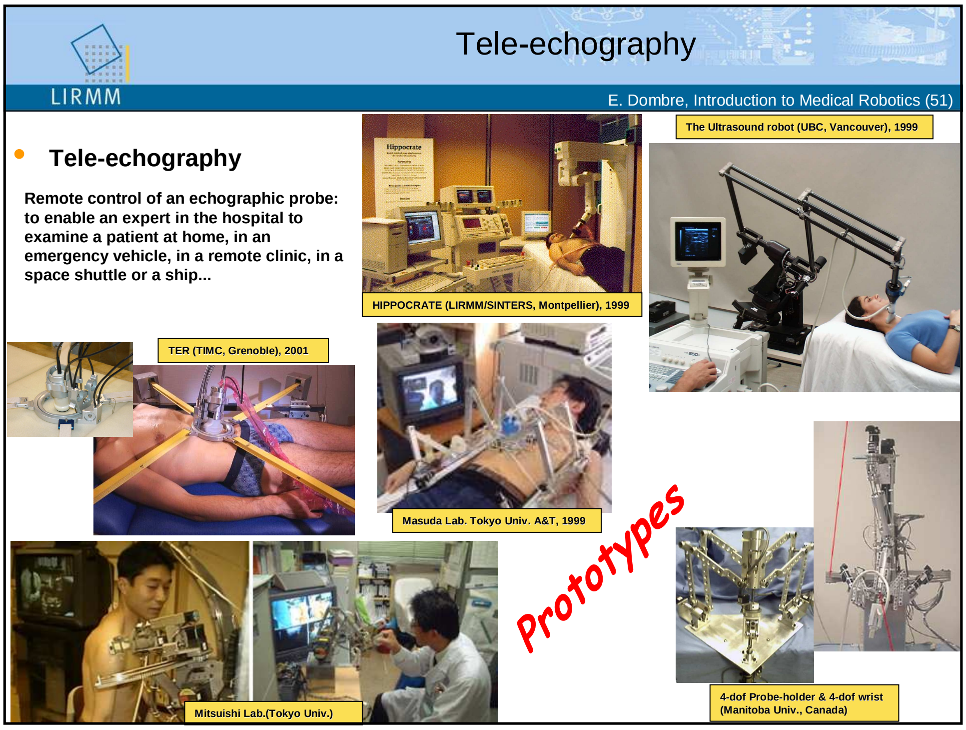
MICRON tremor cancelling instrument (CMU, Pittsburgh): eye surgery



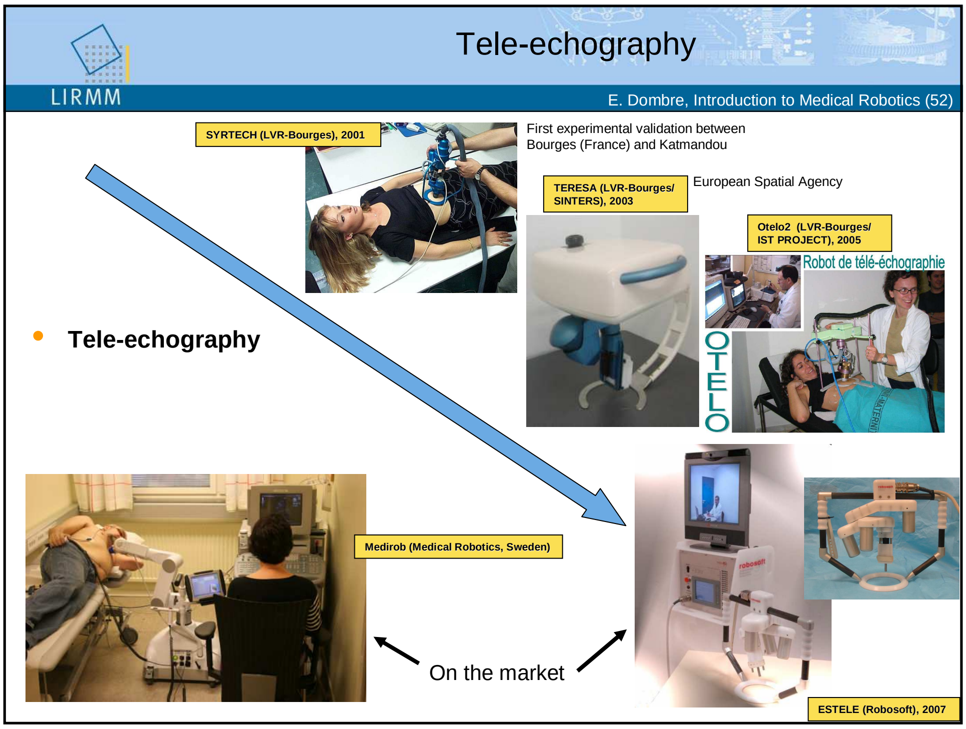


Da Vinci (Intuitive Surgical): urology

- Analysis of some surgical functions:
  - "Machining" (rigid surfaces as bones)
  - Constrained manipulation (through a trocar)
  - Constrained targeting (reach a target through an entry port)
  - Surface tracking
  - Micro-manipulation
- ... and some other "Tele-uses":
  - Tele-echography
  - Tele-surgery
  - Tele-diagnosis

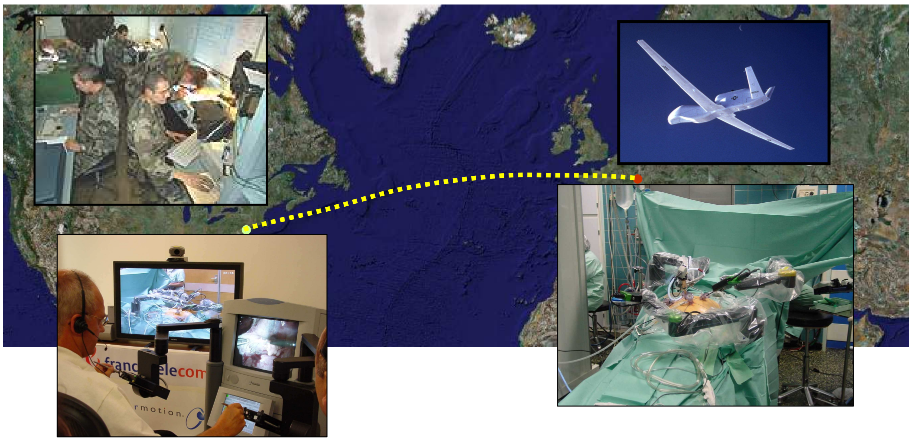


Tele-echography
LIRMM
E. Dombre, Introduction to Medical Robotics (51)
Tele-echography
Remote control of an echographic probe: to enable an expert in the hospital to examine a patient at home, in an emergency vehicle, in a remote clinic, in a space shuttle or a ship...
HIPPOCRATE (LIRMM/SINTERS, Montpellier), 1999
The Ultrasound robot (UBC, Vancouver), 1999
TER (TIMC, Grenoble), 2001
Masuda Lab. Tokyo Univ. A&T, 1999
Prototypes
Mitsuishi Lab.(Tokyo Univ.)
4-dof Probe-holder & 4-dof wrist (Manitoba Univ., Canada)



Tele-echography
LIRMM
E. Dombre, Introduction to Medical Robotics (52)
SYRTECH (LVR-Bourges), 2001
First experimental validation between Bourges (France) and Katmandou
TERESA (LVR-Bourges/ SINTERS), 2003
European Spatial Agency
Otelo2 (LVR-Bourges/ IST PROJECT), 2005
Robot de télé-échographie
OTELO
Tele-echography
Medirob (Medical Robotics, Sweden)
On the market
ESTELE (Robosoft), 2007

Lindbergh operation (Prof. Marescaux, IRCAD Strasbourg, France Télécom, Computer Motion)
September 7th, 2001, New York – Strasbourg (15 000 km), Human cholecystectomy



Robotics + Communication technology

Reprinted from Luc Soler, IRCAD

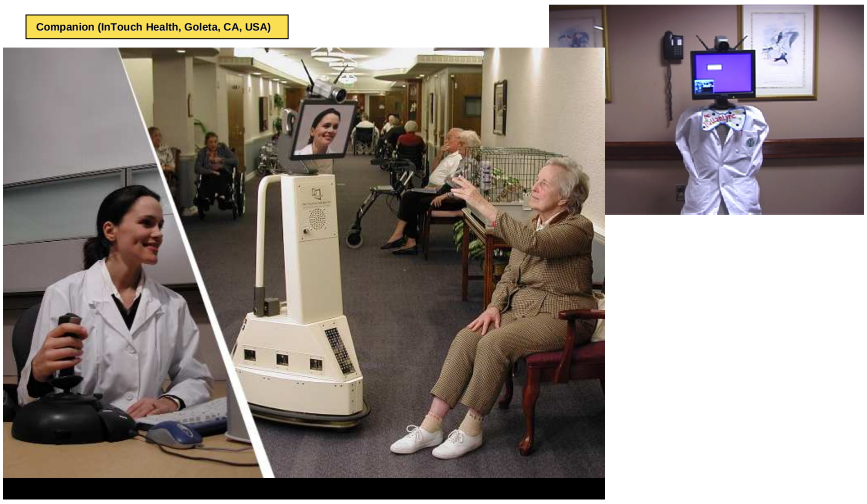
- **Applications:**
  - Patient in remote or non accessible locations
  - Education and training: tele mentoring
  - Telesurgery in the battlefield
  - Telesurgery in space
    - Several projects: ROTEX & ROKVISS projects (DLR), SRI M7 robot,…

M7 robot (SRI , Stanford, USA): micro-gravity experiment in the NASA C-9 airborne parabolic lab.

DARPA Project (BioRobotics Lab., Washington Univ., Seattle, US)

Tele-diagnosis

Companion (InTouch Health, Goleta, CA, USA)



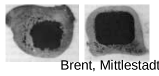
Healthcare through a "Remote Presence" Robot, RP-6: the doctor is projected to another location where the patient is located

Outline

- A short overview on assistive technologies & rehabilitation robotics
- Robotic for surgery, exploration, therapy
  - **A robot… for what?**
    Analysis of some surgical functions (and a few non surgical functions), and the current robotic solutions
  - **Do we need surgeon anymore?**
    Added values and limitations of robots
  - **… and tomorrow?**
    Future directions and technical challenges
- Conclusion

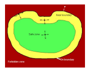
Added values and limitations of robots

- **Improvements that can be expected wrt manual procedures**
  - **Less invasive surgery**
  - **Precise localization** (position and orientation) of instruments with reference to pre-operative or intra-operative imaging
  - **Complex and accurate path following** (e.g. milling a cavity in a bone, targeting a tumor from multiple radiation ports…)
  - **Integration of intra-operative data**:
    - image-guided motion (e.g. needle insertion)
    - visual-servoing (e.g. to compensate for physiological motions and patient's motions)
    - force-controlled motion (e.g. machining, skin harvesting), …
  - **Limitation of risks**: virtual fixtures to constrain the instrument to move into safe regions
  - **Heavy loads** (e.g. linac, microscope…)
  - **Compensation for surgeon's hand tremor**
  - **Motion and force scaling** (e.g. for microsurgery)
  - **Haptic feedback**
  - **Better comfort** for the surgeon
  - **"Tele-uses" for surgery, exploration, therapy,…: to minimize radiation exposure for the surgeon, to treat a patient in a remote or hostile location…**



Brent, Mittlestadt

Acrobot



Added values and limitations of robots

- **Thus a robot is less invasive, more accurate, transcends human limitations…**
- **Many prototypes have been developed…**

LIRMM

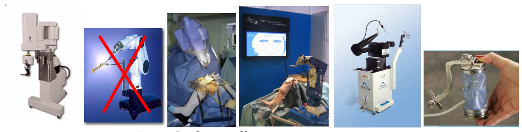
Many prototypes...

LIRMM

Added values and limitations of robots

- **Thus a robot is less invasive, more accurate, transcends human limitations…**
- **Many prototypes have been developed…**
- **… but not yet many robotic systems in the OR**

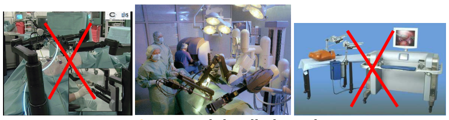
...but not yet many robotics systems in the OR!



- Orthopedics

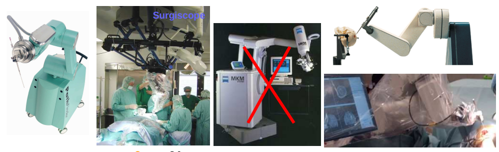
- Interventional radiology

- Endoscope holders and…



- … minimally invasive surgery

- Radiotherapy



- Neurosurgery

- Tele-echography

Today 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 holders: *Surgiscope (ISIS), MKM (Zeiss*)*
  - Neurosurgery / Robots: *Neuromate (Schaerer-Mayfield), PathFinder (Armstrong Healthcare/Prosurgics), ROSA (MedTech)*
  - Orthopedics: *ROBODOC (ISS*, Robodoc), ACROBOT (Acrobot Ltd), MARS/Smart Assist (Mazor Surgical Technologies), BRIGIT (MedTech/Zimmer)*
  - Endoscope holders: *AESOP (Computer Motion**), EndoAssist (Armstrong Healthcare/Prosurgics), FreeHand (Prosurgics), Lapman (Medsys), SoloAssist (AKTORmed)*
  - MIS: *Da Vinci (Intuitive Surgical), ZEUS (Computer Motion**), EndoVia Medical**
  - Interventional radiology: *Sensei (Hansen Medical), CorPath (Corindus)*
  - Radiotherapy: *Cyberknife (Accuray)*
  - Tele-echography: *Estele (LVR / Robosoft)*
  - Tele-diagnosis: *Companion (InTouch Health)*

* out of business
** merged with Intuitive Surgical since March 2003
*** lecture of Y. Patoux, "Evolution of surgical navigation during past decade", http://www.lirmm.fr/UEE05/

Added values and limitations of robots

- **Thus a robot is less invasive, more accurate, transcends human limitations…**
- **Many prototypes have been developed**
- **… but not yet many robotic systems 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

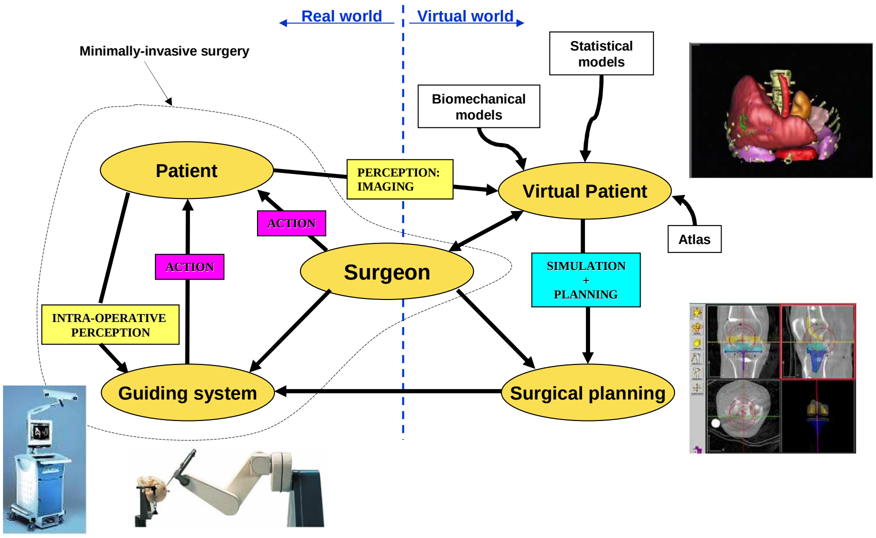
More on some limitations

- **The registration problem**
- **The force measurement challenge**
- **Safety issues**
- **Design specifications**

The registration problem

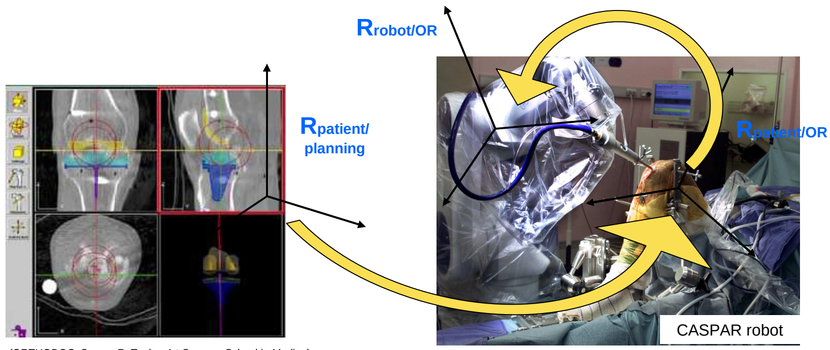
The registration problem

General structure of a Computer-Aided Surgical system: the perception-planning-action loop
(revisited from S. Lavallée, PhD thesis 1989)



The registration problem

- mapping pre-op data and intra-op data of the patient in the robot reference frame
- Still a rather time-consuming and error prone procedure
- Accuracy of the robot action depends on registration



(ORTHODOC. Source R. Taylor, 1st Summer School in Medical Robotics 2003)

Pre-operative data

Intra-operative data

The force measurement challenge

- **To provide haptic feedback to the surgeon**
- **To feedback interaction force information (between instrument and tissue) in a control loop**
- **The force sensor has to be small, easy to mount, sterilizable or disposable (thus low cost)…**

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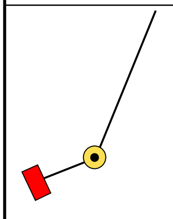
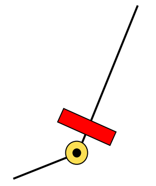
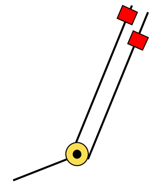
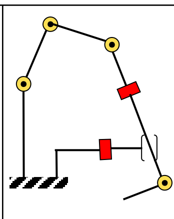
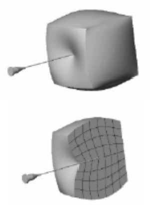
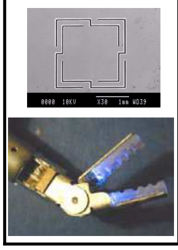
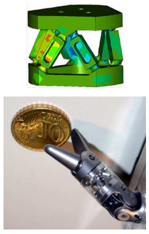
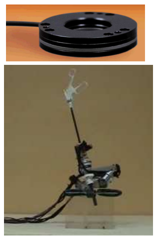
The force measurement challenge

Force sensor				Visual estimation
				
				

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Safety issues

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Safety issues

E. Dombre, Introduction to Medical Robotics (71)

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Safety issues

E. Dombre, Introduction to Medical Robotics (72)

- **Problems:**
  - the robot shares its working space with surgical staff and patient
  - “trail & error” or “doing again” motions are not allowed
  - sterilizability constraints

- **Risk reduction in surgical robotics: pioneer work by B. Davies [Davies, 1993] and Ng [Ng and Tan, 1996] for a robot for prostatectomy**

Safety issues

- **A medical device should be designed considering the following principles:**
  - *redundancy* in control and sensing… but redundancy rises the number of components and increases the complexity of the system, which finally decreases its reliability ➔ a trade-off has to be found between redundancy and reliability
  - *intrinsic safety* obtained with classical components, for instance:
    - actuators with limited power and/or speed
    - high reduction gears such as harmonic drives (for their low backlash and flexibility and for their high efficiency)
    - "Dead Man Switch" (DMS) foot pedal, used by the surgeon to authorize motion of the robot
    - watchdog board checking the activation of the control system
    -
- **At the operation level:** dedicated friendly man-machine interfaces and clear rules for use

Safety: examples of solutions

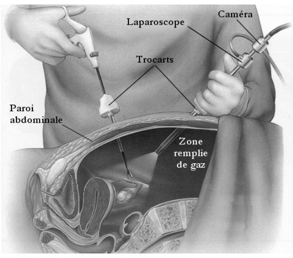
- **Torque control**

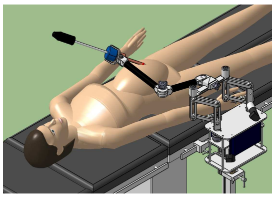
Kinemedics (DLR, Germany)

Design specifications

Design issues

- **Example: trocar constraint and design outcomes of an endoscope holder:**
  - **Compact** and **lightweight**
  - The distal tip of the endoscope should move in a **large intra-abdominal workspace**
  - Quick to install and requiring **minimal adjustments** with respect to the incision
  - no further adjustment should be required if the height or angle of the operation table is changed during the procedure
  - **Backdrivable** to allow a fully manual manipulation of the laparoscope without having to remove it from the robot
  - Ergonomic and intuitive **HMI**: omnidirectional motions, variable speed, position memorisation...
  - **Sterilizable**
  - **Safe**
  - **Low cost**
  - …





B. Herman, Univ. Catholique, Louvain-la-Neuve, 2009

Outline

- A short overview on assistive technologies & rehabilitation robotics
- Robotic for surgery
  - **A robot… for what?**
    Analysis of some surgical functions (and a few non surgical functions), and the current robotic solutions
  - **Do we need surgeon anymore?**
    Added values and limitations of robots
  - **… and tomorrow?**
    Future directions and technical challenges
- Conclusion

Future directions of R&D and technical challenges

- **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, friendly, and safe cooperation between Surgeon and Robot ("Hands-on" / Co-manipulation concept: the surgeon operates the device)…
- **Trends:**
  - Dedicated robotized instruments ("smart" instrument)
  - Autonomy

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

Toward intra-body robotics

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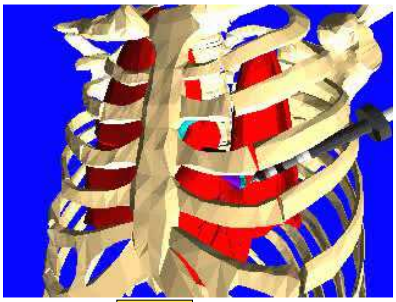
- **Mini-manipulators "inside the body"**
  - could be a device fixed on the trocar or distal part of an instrument
  - high dexterity: they should compensate at most for the loss of mobility due to the trocar
  - size requirements : Ø < 10mm, L = a few cm, small radius of curvature
  - Force capabilities: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



ISIR, Paris

Da Vinci (Intuitive Surgical)

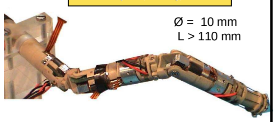
Toward intra-body robotics

LIRMM

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

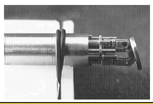
  2 design approaches:

DRIMIS (ISIR, Paris), 2002

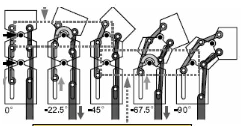


Embedded actuators: mini-serial (or parallel) manipulators made of rigid bodies and discrete joints

bulky, power limitation,
low reliability of actuators



MIPS (INRIA-Sophia), 2002



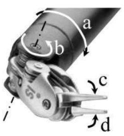
Dohi Lab., Univ. Tokyo

Remote actuators:

➔ Two approaches :
  - **Rigid-linkage mechanisms:** *bulky, complexity*
  - **Wire-driven mechanisms (cables, SMA wires…):** *high dexterity but*

    if cable-drives: backlash, limited reliability

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



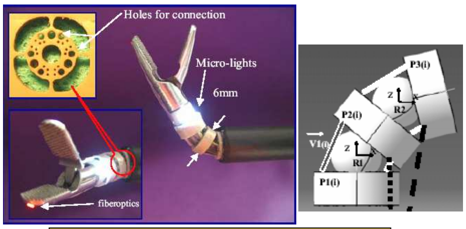
4-dof forceps (da Vinci, Intuitive Surgical)

Toward intra-body robotics

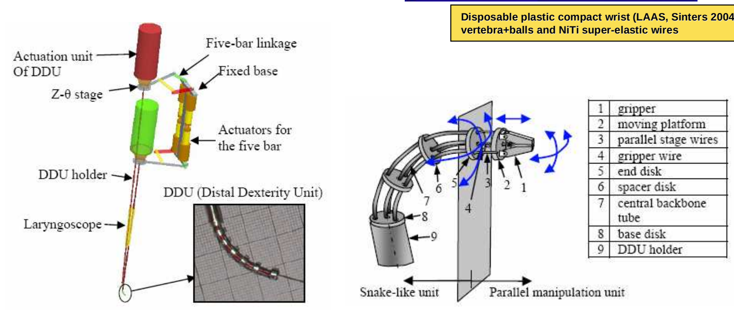
LIRMM

E. Dombre, Introduction to Medical Robotics (81)

- Wire-driven technologies:
  - 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



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

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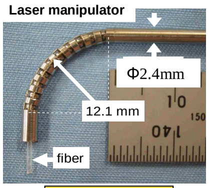
E. Dombre, Introduction to Medical Robotics (82)

- ***Wire-driven mechanisms***

Hydraulic // manipulator (KUL, Leuven), 2000

Laser manipulator

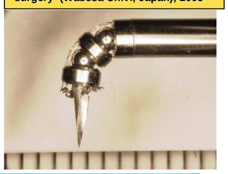


Fujie lab. (Waseda University, Tokyo)

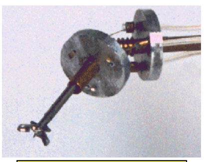
Bending forceps based on rigid linkage mechanism (Univ. Tokyo), 2003

HARP (Robotics Institute, CMU, Pittsburg), 2006

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

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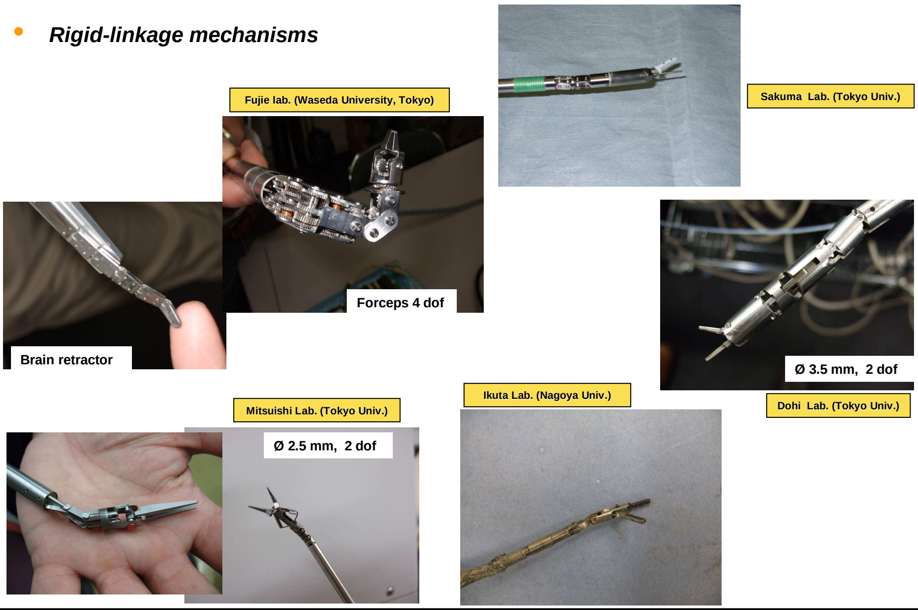
- ***Rigid-linkage mechanisms***

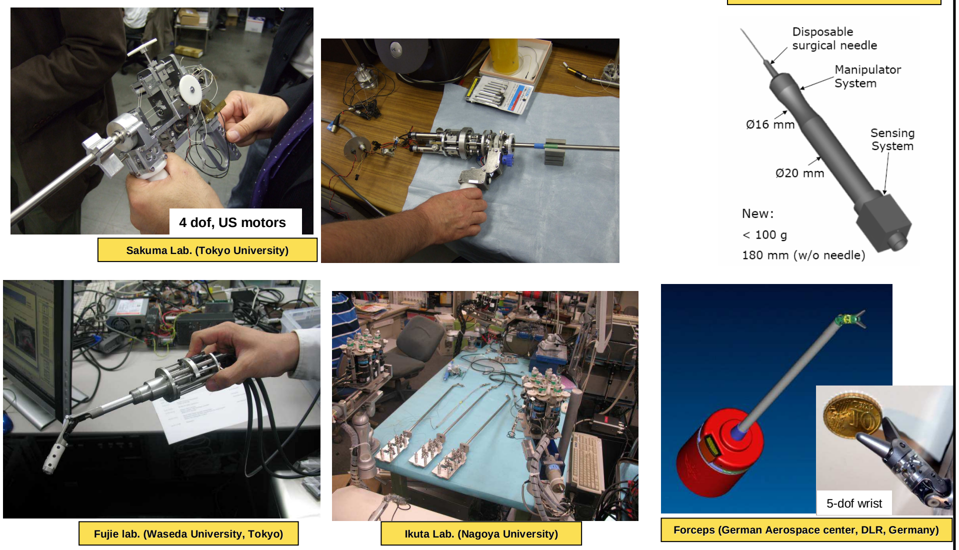


Toward intra-body robotics

LIRMM

- ***Hand-held motorized instruments***

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



Toward intra-body robotics

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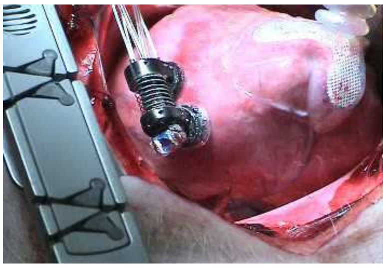
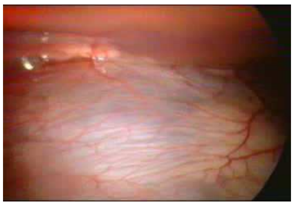
E. Dombre, Introduction to Medical Robotics (85)

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

Version 1





Version 2

HeartLander, Versions 1 et 2 (The Robotics Institute, CMU, Pittsburgh)

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

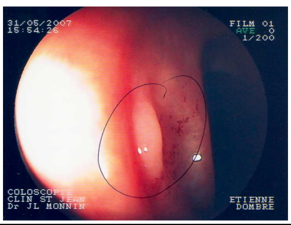
In vivo mobile robot (Robotics & Mechatronics Lab., Univ. Nebraska)

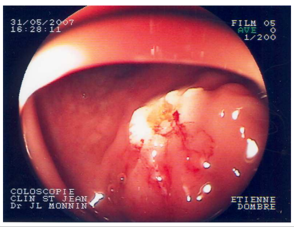
Toward intra-body robotics

LIRMM

E. Dombre, Introduction to Medical Robotics (86)

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

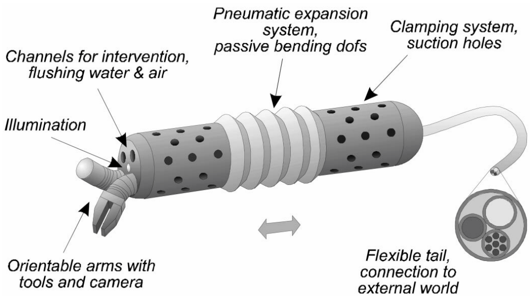




Toward intra-body robotics

LIRMM

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

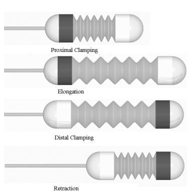


Katholieke Universiteit Leuven, Belgium

Toward intra-body robotics

LIRMM

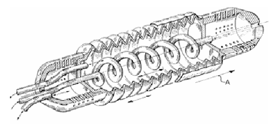
- **Solutions**
  - Semi-autonomous colonoscope: self propelling robot with a tether to transport fluids and energy
  - Autonomous untethered pill swallowed by the patient (thus, the whole tract may be inspected)



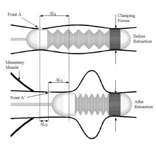
Propulsion based on inchworm locomotion

Ø = 12 mm
Lmin = 115
Lmax = 195

EMIL (SSSA, ARTS Lab., Pise)



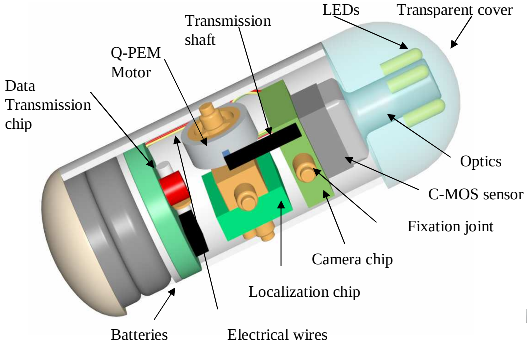
… but colon is collapsible, slippery, has acute bends, which limit traveling capabilities of semi-automatic colonoscopes

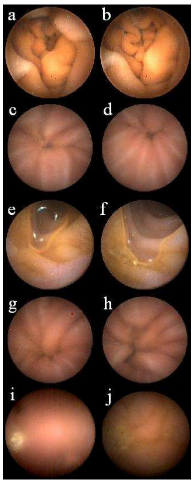


Accordeon effect

Autonomous untethered pill swallowed by the patient

The Endoscopy « Pill », Given Imaging – M2A

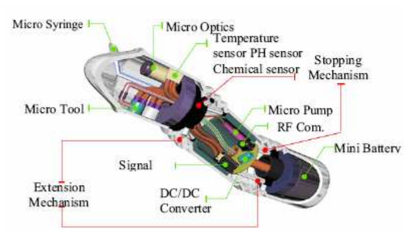


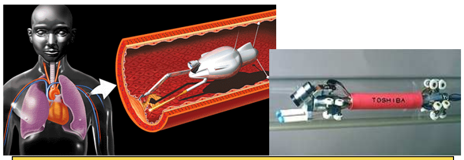


Intracorporeal Video Probe
L = 20 mm, Ø = 8 mm
CMOS technology
RF trasmission data
With steerable camera

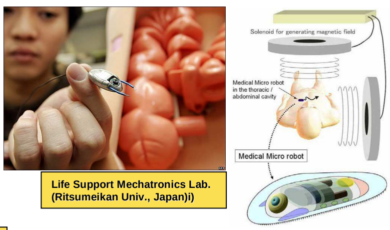
PillCam SB2 :
L = 26 mm, Ø = 11 mm P = 3,7 g
Autonomy : 6h à 8h
2 images / sec. (240x240 pixels)➔> 50000 images to process!

Microcapsule for gastrointestinal diagnosis and therapy (IMC, Korea)





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



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

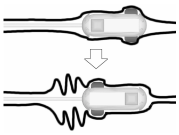
Norika3 et (RFSystem Lab., Japan), 2001

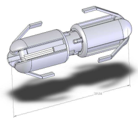
Sayaka, Japan, 2005

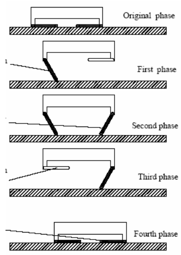
Smart capsule endoscope (Olympus Co., Japan)

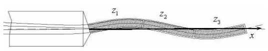
Toward intra-body robotics

- **Pills are promizing but still some technical issues**
  - Energy storage for longer autonomy, miniaturization
  - Active locomotion (wrt natural peristaltic waves of the tract):
    - biomimetic approaches: Inchworm, legs (SSSA), cilia, swimming (fins, tails)
    - sliding clampers
    - paddling
    - inertia impact



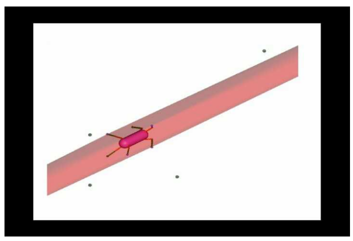






Toward intra-body robotics

SSSA, ARTS Lab., Pise



Toward intra-body robotics

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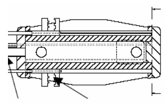
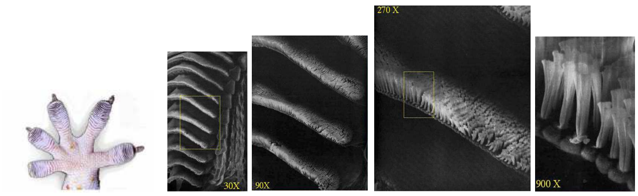
E. Dombre, Introduction to Medical Robotics (93)

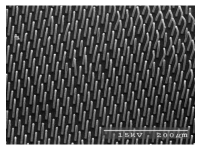
➔ **Pills are promizing but still some technical issues**

- Energy storage for longer autonomy, miniaturization
- 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

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E. Dombre, Introduction to Medical Robotics (94)

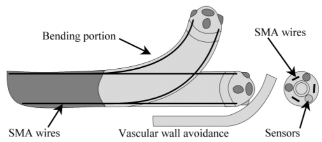
- ### Active catheters
  - Catheter: a tube that can be inserted into a body cavity duct or vessel. Catheters thereby allow drainage or injection of fluids or access by surgical instruments (Wikipedia). Also used for angioplasty, blood pressure measurement...
  - Typical sizes: Ø <2-3 mm, L > 1m
  -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

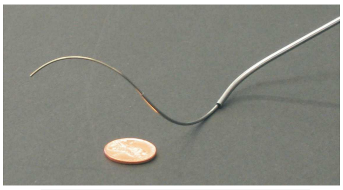
➔ Solution

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

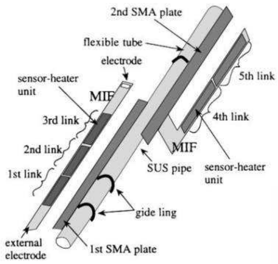
Toward intra-body robotics

- **Active catheters**

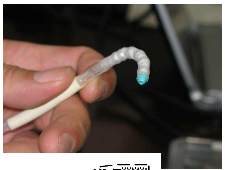


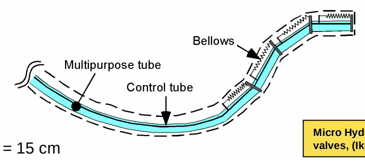


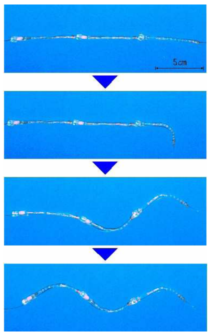
Active canula made of superelasctic nitinol tube (JHU, Baltimore, 2006)



Olympus catheter, Japan, 1999







Ø = 1.5 mm, L = 15 cm

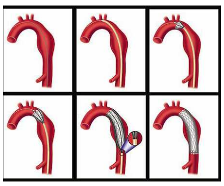
Micro Hydraulic Active Catheter with micro-valves, (Ikuta Lab., Nagoya Univ., Japan)

Toward intra-body robotics

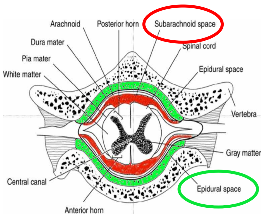
Film..\Conf. Rob Méd\MALICA.avi

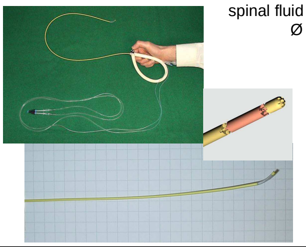
MALICA (LIIA, Paris XII): aneurysm repair

- 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

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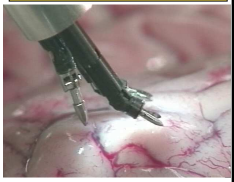
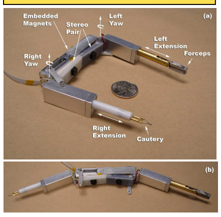
Active catheter: towards transluminal endoscopic surgery

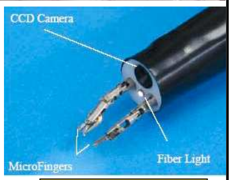
- NOTES : Natural Orifice Transluminal Endoscopic Surgery
- Incisionless surgery
- Through transgastric and transvaginal route
- Justification:
  - reduction or absence of postoperative pain
  - ease of access to some organs
  - absence of trauma to the abdominal wall
  - ideal cosmetic results

Bending forceps (Hitachi, Japan), 2000



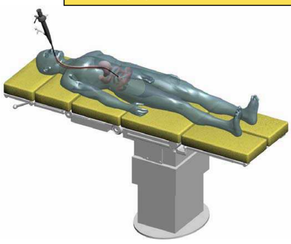
Notes robot (Robotics & Mechatronics Lab., Univ. Nebraska)

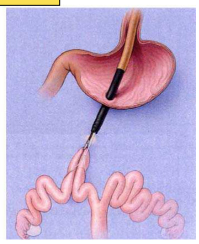


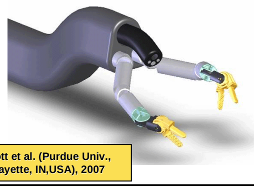


Endoscopy surgery system (Nagoya Univ.), 2004

"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

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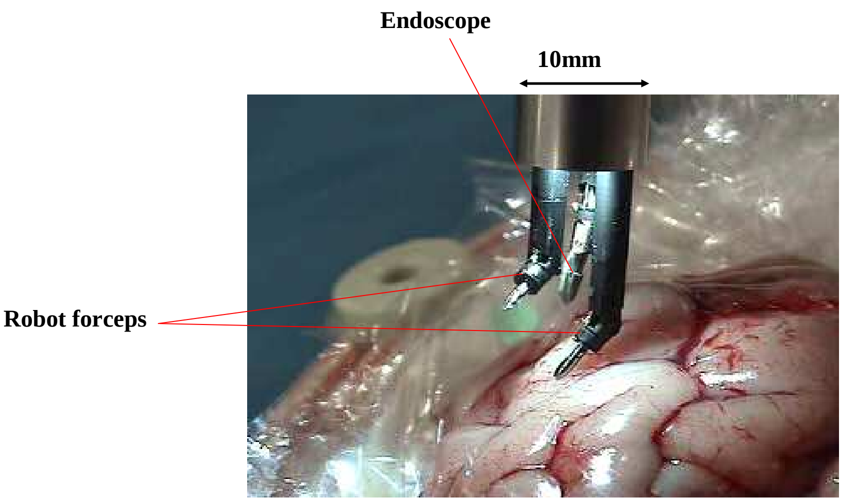
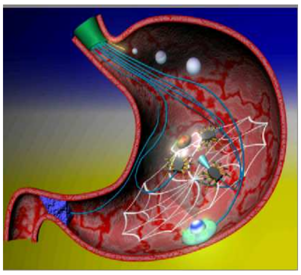
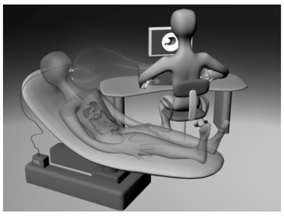


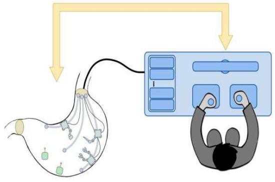
Fujie Lab. (Waseda University, Tokyo)

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)







Outline

- A short overview on assistive technologies & rehabilitation robotics
- Robotic for surgery
  - **A robot… for what?**
    Analysis of some surgical functions (and a few non surgical functions), and the current robotic solutions
  - **Do we need surgeon anymore?**
    Added values and limitations of robots
  - **… and tomorrow?**
    Future directions and technical challenges
- Conclusion

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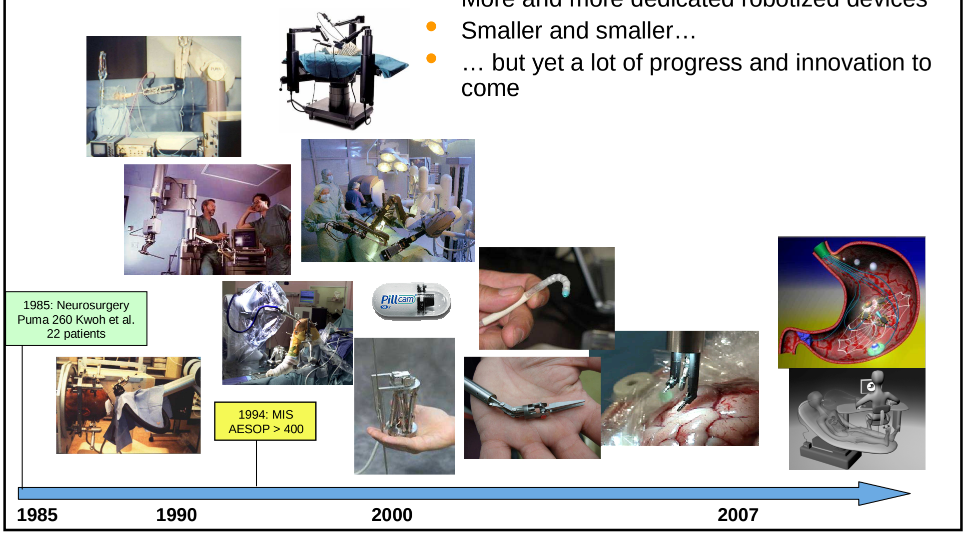
Conclusion

E. Dombre, Introduction to Medical Robotics (101)

- 25 years of research and development
- More and more dedicated robotized devices
- Smaller and smaller…
- … but yet a lot of progress and innovation to come



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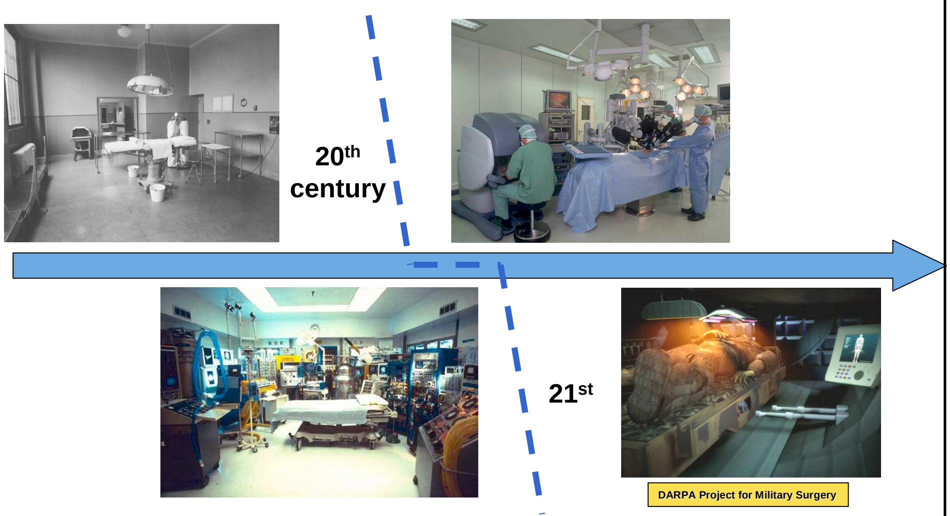
Conclusion

E. Dombre, Introduction to Medical Robotics (102)



Revisited from Jacob Rosen, Univ. Washington, Seattle

- **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 Surgical Robotics, September 2003, Montpellier:** http://www.lirmm.fr/manifs/UEE/accueil.htm
  - **2nd Summer School in Surgical Robotics, September 2005, Montpellier:** http://www.lirmm.fr/UEE2005/
  - **3rd Summer School in Surgical Robotics, September 2007, Montpellier:** http://www.lirmm.fr/UEE2007/
  - 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…