IROS 2012
October 7-12

Intelligent Robots and Systems
IEEE/RSJ International Conference
Vila Moura, Algarve [Portugal]

Robotics for Quality of Life and Sustainable Development

IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 7-12, 2012
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*Celebrating 25 Years of IROS*

# Surgical Robotics: Achievements and Challenges

Paolo Dario

The BioRobotics Institute

Scuola Superiore Sant'Anna, Pisa

and

Italian Institute of Technology, Italy

THE BIOROBOTICS INSTITUTE

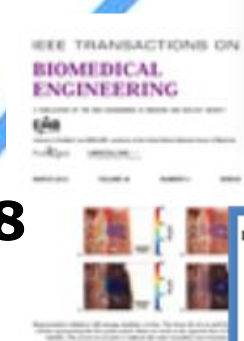
Scuola Superiore Sant'Anna

October 9, 2012

ISTITUTO ITALIANO DI TECNOLOGIA

# I have been around for a while in this field…

**1988**




IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, VOL. 35, NO. 2, FEBRUARY 1988 118

An Advanced Robot System for Automated Diagnostic Tasks Through Palpation

PAOLO DARIO AND MASSIMO BERGAMASCO

**1989**

Demonstrating a robot for assisting disabled persons to Pope John Paul II

**2003**

Special issue on **Medical Robotics**


RUSSELL H. TAYLOR, *Guest Editor*

PAOLO DARIO, *Guest Editor*

JOCELYNE TROCCAZ, *Guest Editor*

**2007**


Guest Editorial
Introduction to the Focused Section on …

*P. Dario and A. Menciassi*

Special issue on **Biomedical Mechatronics**

**2008**

52. Medical Robotics and Computer-Integrated Surgery


Russell Taylor, Arianna Menciassi, Paolo Dario

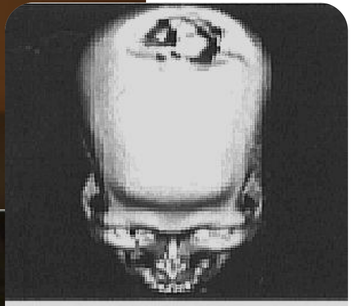
# Outline

- The onset of modern surgery
- The onset of robotic surgery
- Current Scientific and Technological Challenges
- Conclusions

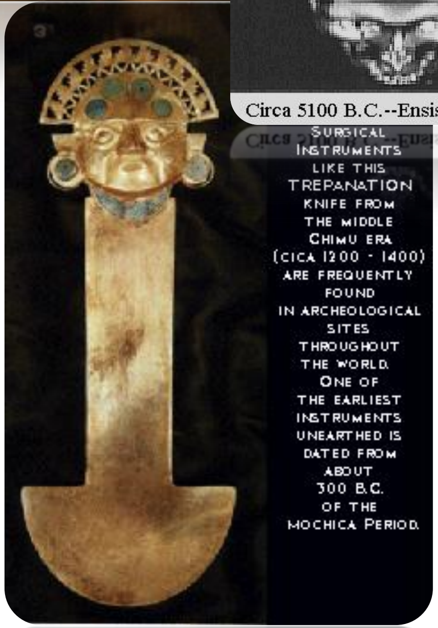
# Pre-Historic Surgery

- **Brain surgery:** the oldest practiced medical art
- **Trephination** or **grind holes in the skull** by using **stone instruments**
- This procedure was aimed at **relieving demon spirits, treating skull fractures,** or **removing bone splinters**
- Ample evidence of brain surgery dating back to the **Neolithic period** (**Late Stone Age – 10,000 B.C.)**
- Unearthed remains of successful brain operations were found in France at one of Europe's noted archeological digs
- Evidence of brain surgery was **not limited to Europe**
- **Pre-Incan** civilization used brain surgery as an extensive practice as early as 2,000 B.C.
- Here too was used for **mental illnesses, headaches, organic diseases, osteomylitis,** as well as **head injuries**

Drilled skull, Iron age.
The perimeter of the hole in the skull is rounded off by in-growth of new bony tissue, indicating that **the patient survived the operation**.



Circa 5100 B.C.--Ensisheim, France



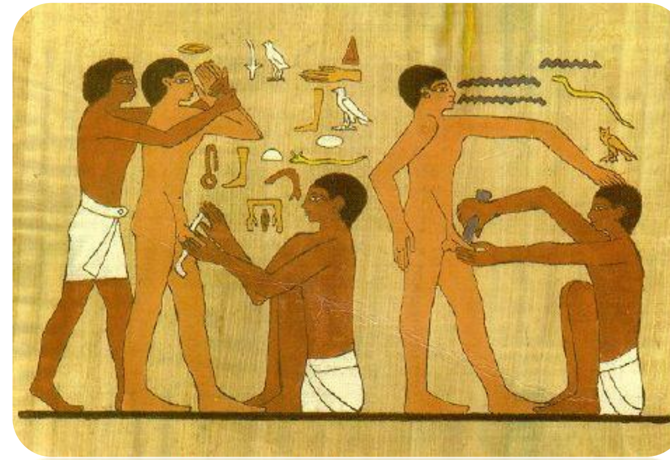
# Egypt, India, Greece, and Roman Empire

- Brain surgery evidences have been found in **Ancient Egypt** papyrus writings (3,000 B.C.)

- Indian physician **Sushruta** (600 B.C.) is known as "**Father of Surgery**" because of his "*Susrutha Samhita*": the oldest known surgical text that describes the examination, diagnosis and treatment of numerous ailments

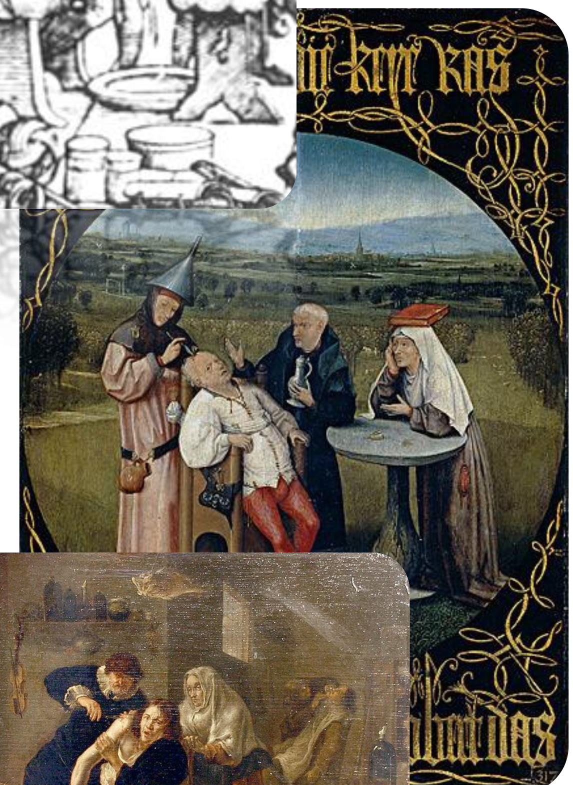
- **Hippocrates** (460–377 B.C.), the father of modern medical ethics, left many texts on brain surgery, and, despite Greek tradition, was **against opening** the body

- Ancient Rome in the 1st century A.D. had its *brain* surgeon star: **Aulus Cornelius Celsus**




# Surgery in the Middle Age

- During the **Middle Ages** in **Europe** there was a **marked regression in surgical knowledge**, and postoperative infection was common. Surgical practice soon fell into the hands of the unskilled and uneducated: the **barber-surgeon**, who performed the usual functions of a barber as well as surgical operations.
- Meanwhile, **Asia** was the home to many talented brain surgeons: **Galenus of Pergamon**, born in Turkey, the physicians of Byzance, such as **Oribasius** (4th century), and **Paul of Aegina**. An **Islamic school of brain surgery** also flourished from 800 to 1200 A.D.



# Declined yet Arrogant (XVI to XIX Centuries)


“Surgery has made immense progress and seems to have reached the highest possible degree of perfection” (**Boyer, 1818 – rather shortsighted**)

“Painless surgery is a chimera that is no longer permitted to pursue”, (**Velpeau, 1838 – very skeptical**)

A rational critical essay about the **poor scientific knowledge** of Luigi XIV period; the satire is **focused on the man won by illusions**.

Moliere paints medical doctor of that period as **selfish, conceited, hypocritical, greedy, and formalist.**

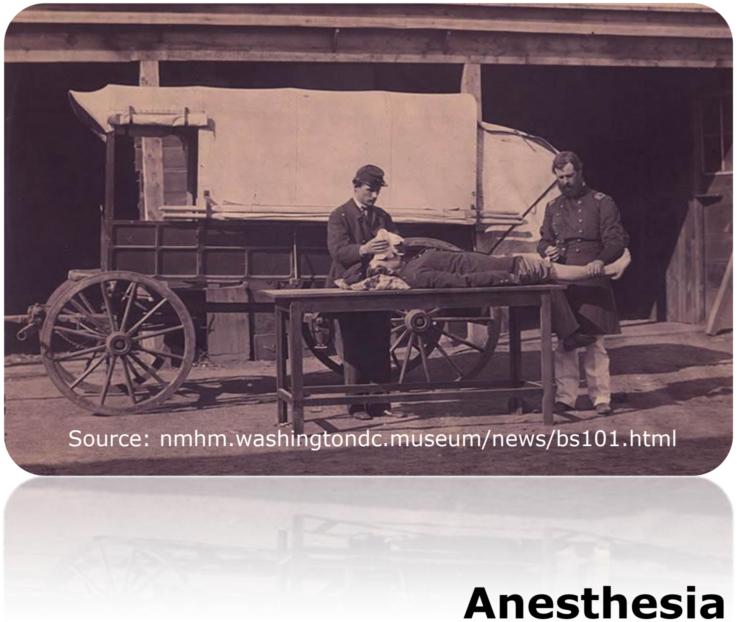
**The Imaginary Invalid (1673)** is a three-act comedy written **by Molière**

# Main Barriers to the Birth of Modern Surgery

Until 19th century surgery was a sort of "craft" and at the same time a very big challenge: suitable anatomical and physiological knowledge as well as enabling technologies like antibiotics, pain therapy, and imaging were still missing.

**Antisepsis** (destruction or inhibition of the growth of microorganisms) was not fully understood **until the discovery of bacteria**. This was the main reason for the **very low rate of survival during surgery**

**From: 'Dances with Wolves', 1990**



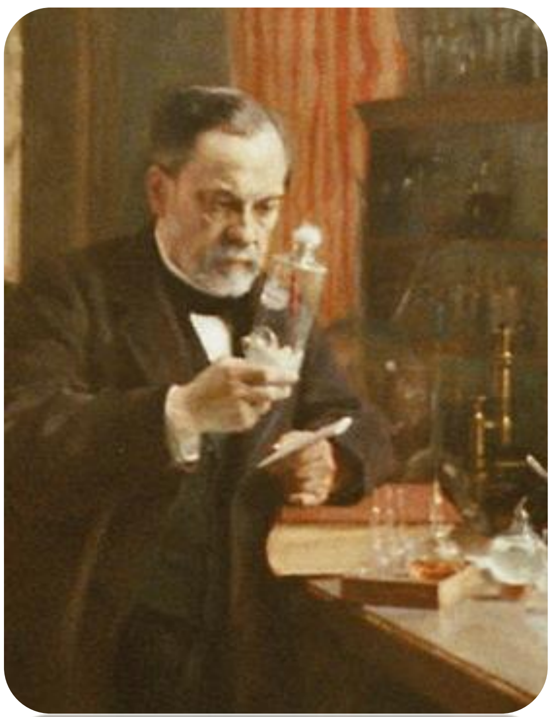
Source: nmhm.washingtondc.museum/news/bs101.html

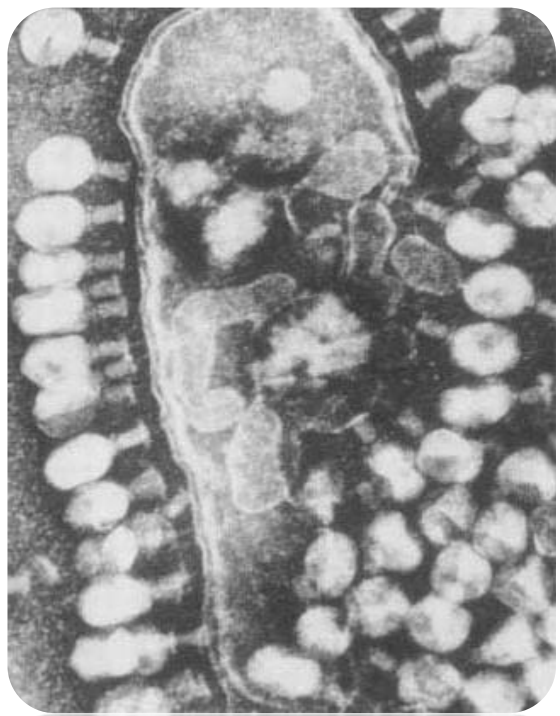
**Amputations** were common in the 1800s especially in the case of compound fractures and had a **40-45% of mortality rate**

**Anesthesia** (1846) **made the problem worse**: more complicated and lengthy surgical operations, **increasing the likelihood of infection**

# Pasteur Breakthrough

- Another deadly form of infection was **puerperal fever**, a streptococcus infection of the uterus that struck women who had just given birth.
- **Louis Pasteur** (France, 1822-1895) discovered the connection between bacteria and disease. Before his studies, **physicians – surgeons in particular – had no concern for cleanliness**. They wore unwashed street clothes or filthy operating gowns, used unclean instruments, and did not wash their hands before examining or operating on patients, even after examining an infected corpse. **Many doctors took pride in the accumulation of blood and pus on their medical garments**.

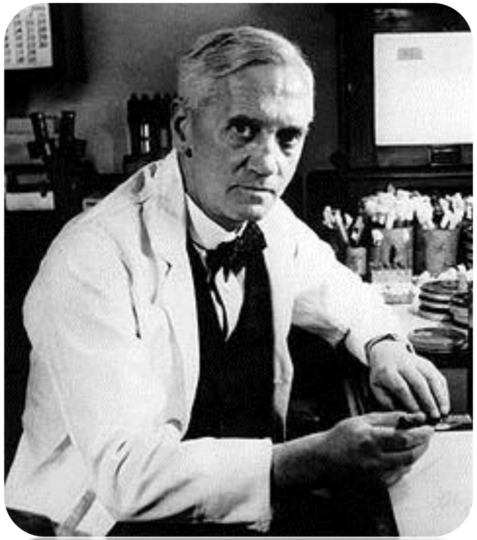




"If I had the honor of being one of them [physician or surgeon], being deeply aware as I am of the danger represented by all the germs and microbes that pervade all things, particularly in hospitals, I would not only use perfectly clean instruments but also, after thoroughly cleaning my hands, I would only use shredded linen, bandages and sponges previously exposed to air brought to a temperature of 150°C. I would only use water that has been brought up to 120°C" ***(Louis Pasteur, 1878)***.

# Fleming Steps Forward

- 1928 **Sir Alexander Fleming** (U.K.) → discovered enzyme lysozyme and the antibiotic substance **penicillin** from the fungus Penicillium notatum [Nobel Prize in Physiology or Medicine, 1945]



**In 1999 *Time* magazine named Fleming one of the <u>100 Most Import People of the 20th Century</u>,** stating: *"The active ingredient in that mould, which Fleming named **penicillin**, turned out to be an infection-fighting agent of enormous potency. When it was finally recognized for what it was, the **most efficacious life-saving drug in the world**, penicillin would alter forever the treatment of bacterial infections"*.

- ✓ Modern methods of preventing infection: infection internally fought .
- ✓ <u>Thereafter attention to cleanliness gradually declined</u> (sterilization against bacteria).

Source: nmhm.washingtondc.museum/news/bs101.html

# Convergence to Modern Surgery

## Where we were: painless & infectiousless surgery

- Anesthetics
- Antiseptics
- Anticoagulants
- Antibiotics
- Analgesics

→ **Modern surgery**

"Surgery has made immense progress and seems to have reached the highest possible degree of perfection" (**Boyer, 1818 – rather shortsighted**)

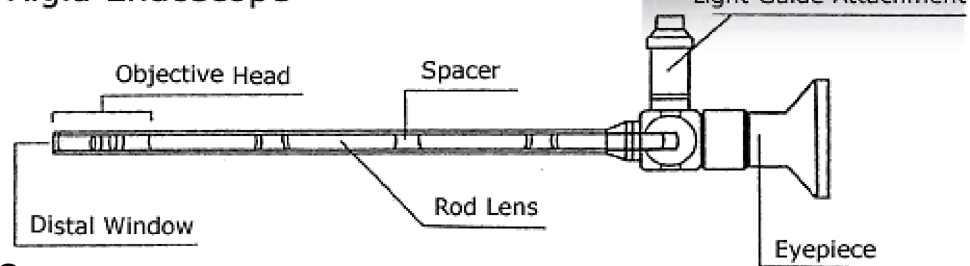
"Painless surgery is a chimera that is no longer permitted to pursue", **(Velpeau, 1838 – very skeptical)**

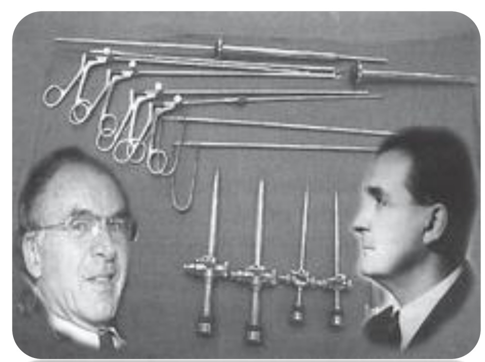
**What they were still missing: tools for diagnosis and approaches for scarless surgery**

# The Birth of Laparoscopic Surgery

- 1954: **Harold H. Hopkins** invented optical fibers and the cylindrical lens
- 1966: **Kurt Semm** introduced an automatic insufflation device capable of monitoring intraabdominal pressures
- 1976: **De Kok** performed the first laparoscopic appendicectomy
- 1985: **Erich Mühe** 1st laparoscopic cholecystectomy
- 1987: **Mouret** in Lyon published the first laparoscopic cholecystectomy using video–technique.

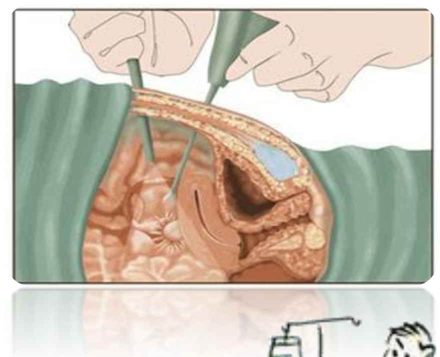

Rigid Endoscope



# The Birth of Laparoscopic Surgery


"When the first laparoscopic cholecystectomy was performed, how many of surgeries believed that there was any future in this new approach? Although the first publications were greeted with more criticisms than compliments – A futureless technique, circus surgery, the mediatized show of a tight-rope dancer totally careless of the risks for the patients-", **(Jacques Perissat – on inveterate skepticals)**.



"Someday in the future, people will look back at a regular surgical incision as something archaic and barbaric", **(Dr. Paul A. Wetter – on the open-minded side …)**.

# Just 10 years later in the US (for skepticals!)

Table 1. Number and type of laparoscopic procedures performed annually in the U.S.*

| Type of Procedure | Total Procedures | Number (%) performed laparoscopically |
|---|---|---|
| ***General Surgery Procedures:*** | | |
| Cholecystectomy | 1,084,882 | 922,150 (85) |
| Adhesiolysis | 215,760 | 155,347 (72) |
| Hernia repair | 820,191 | 114,827 (14) |
| Appendectomies | 334,388 | 73,565 (22) |
| Nissen fundoplication | 47,087 | 44,733 (95) |
| Colon resection | 380,000 | 26,600 (7) |
| ***Gynecology Procedures:*** | | |
| Adnexa removal | 350,059 | 227,538 (65) |
| Sterilization | 684,000 | 342,000 (50) |
| Hysterectomies | 582,000 | 87,300 (15) |
| Myomectomy | 64,977 | 45,484 (70) |
| **Urology Procedures** | | |
| Pelvic floor reconstruction | 160,000 | 64,000 (40) |
| **Total** | **4,723,344** | **2,103,544** |

85% of total cholecystectomies were performed laparoscopically

95% of total Nissen fundoplications were performed laparoscopically

Available from: URL: http://www.fda.gov/medicaldevices/safety/alertsandnotices/ucm197339.htm

# Minimally Invasive Surgery

Anesthetics

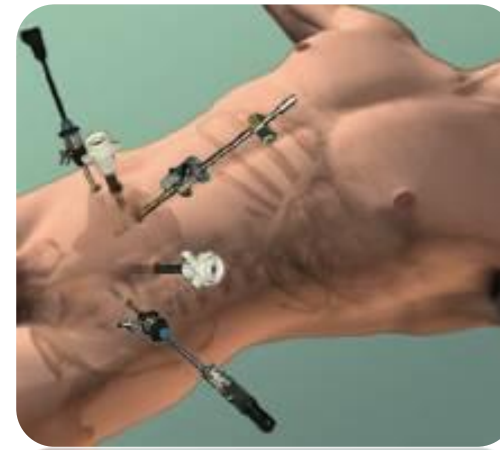
Antiseptics

Anticoagulants

Antibiotics

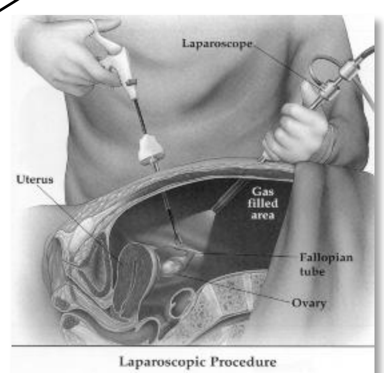
Analgesics

Endoscopic instruments

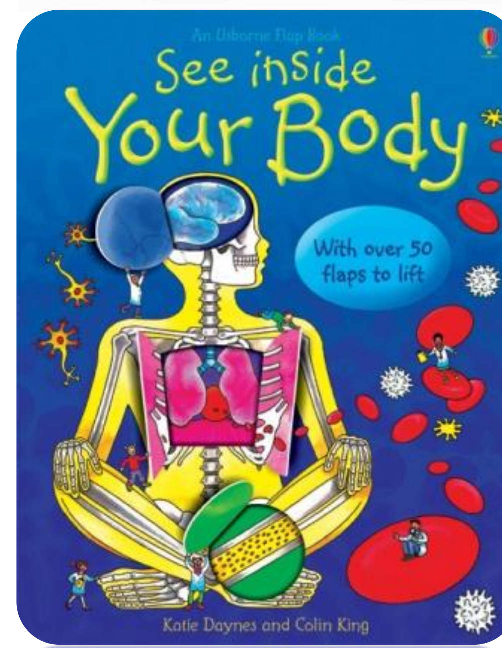


Modern surgery

Minimally invasive Surgery




**Quest for diagnosis techniques not relying on open procedures**



# The Role of Imaging in the Evolution of Surgery

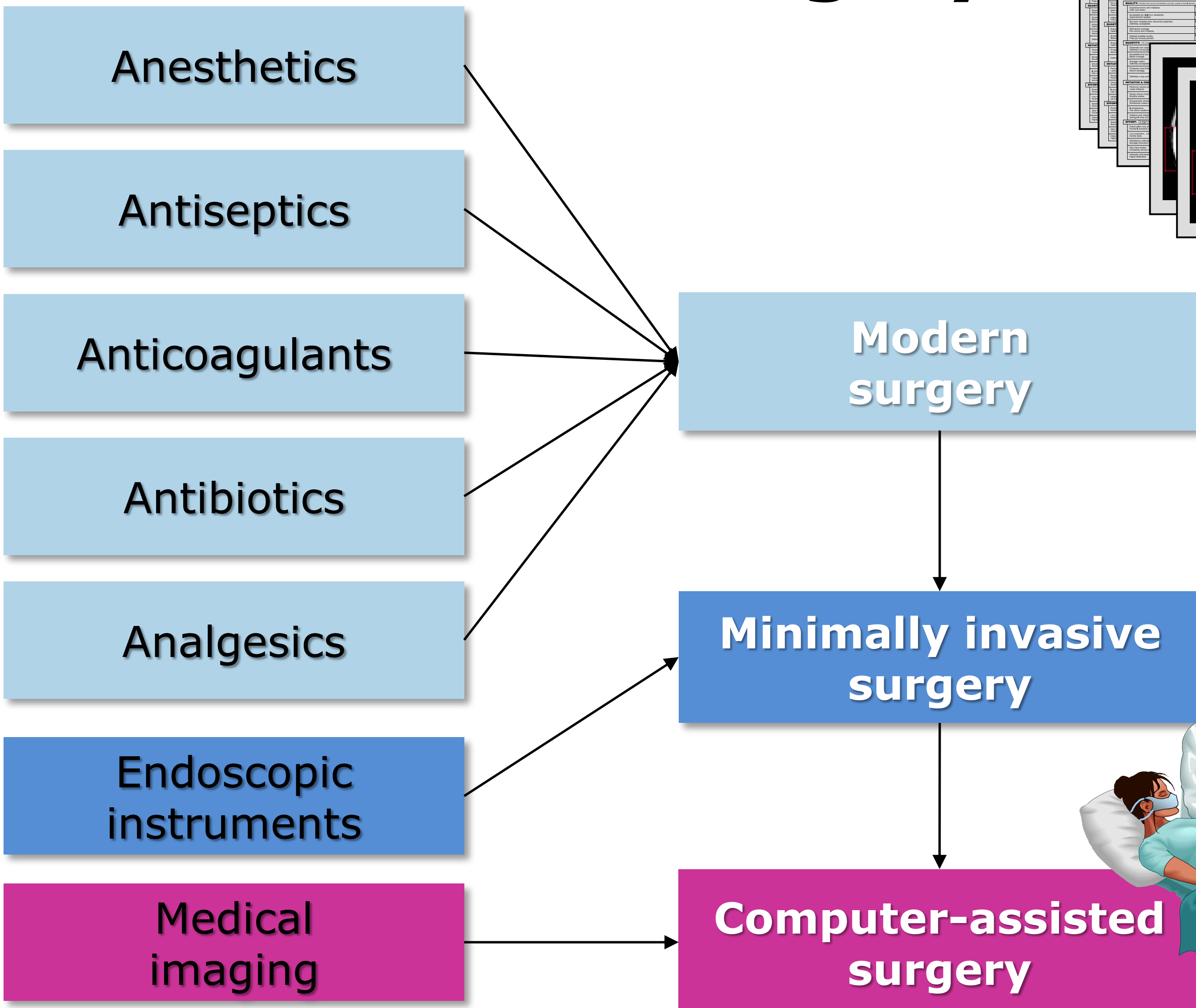
- **1895: Röntgen** (accidentally) discovered an image cast from his cathode **X-ray** generator

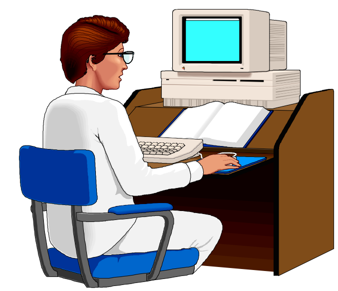
- **1947**: **Ultrasonic** energy was first applied to the human body for medical purposes by **George Ludwig** at the Naval Medical Research Institute, Bethesda (MD)

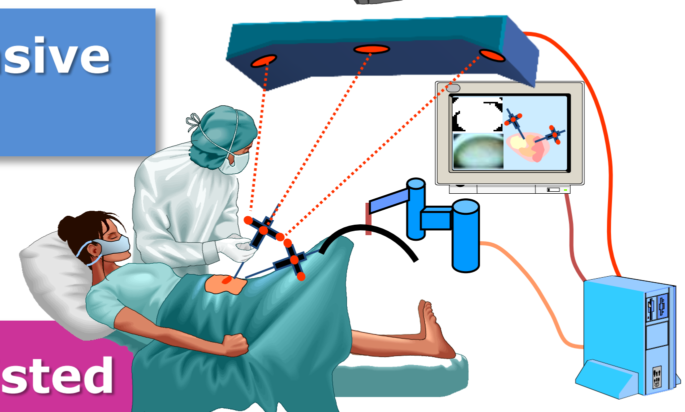
- **1975**: **Robert S. Ledley** patent #3,922,552 was granted for a "diagnostic X-ray systems" also known as whole body **CT-**Scans

- **1977**: first image of in vivo human anatomy using **MRI**, a cross section through a finger

# Convergence to Computer Assisted Surgery

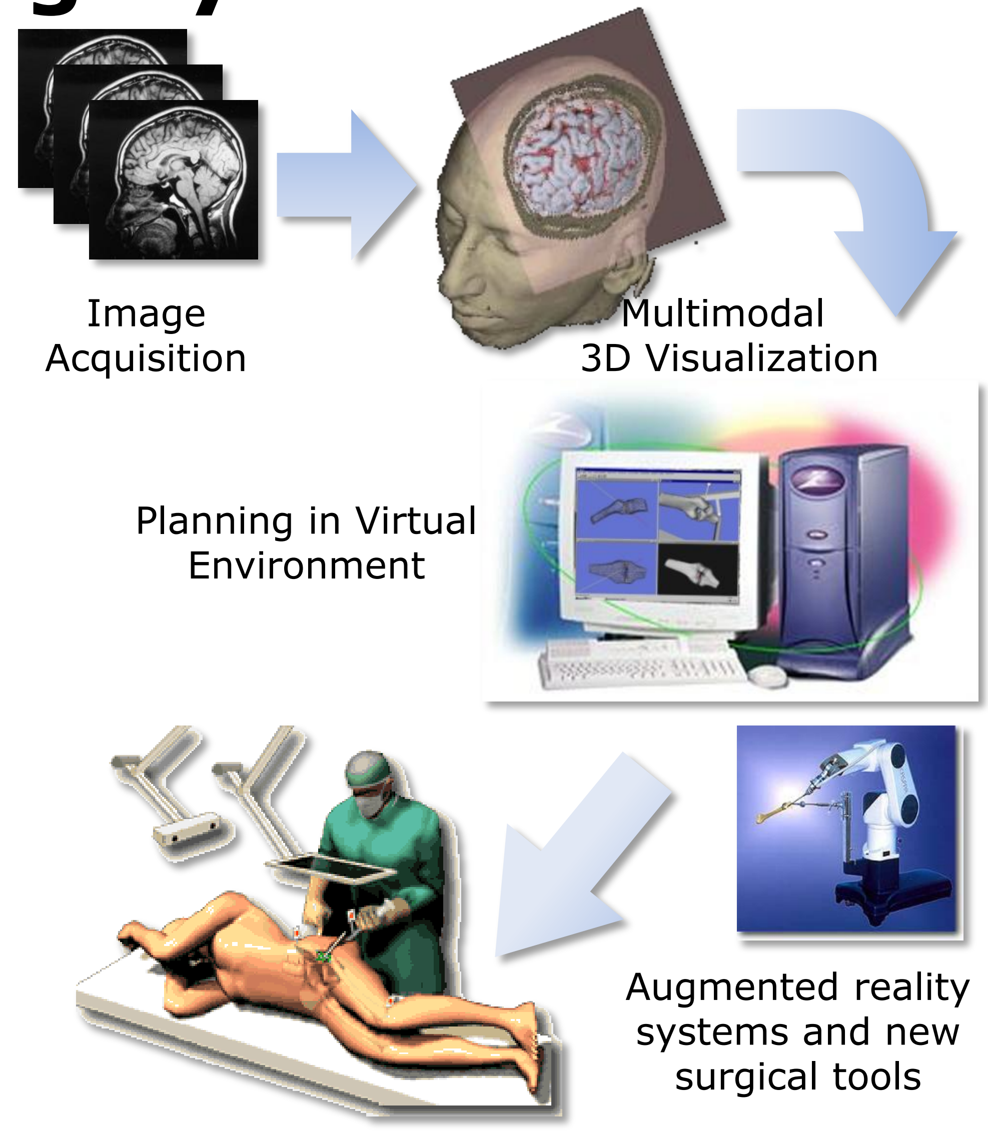




# From Traditional to Computer-Assisted Surgery

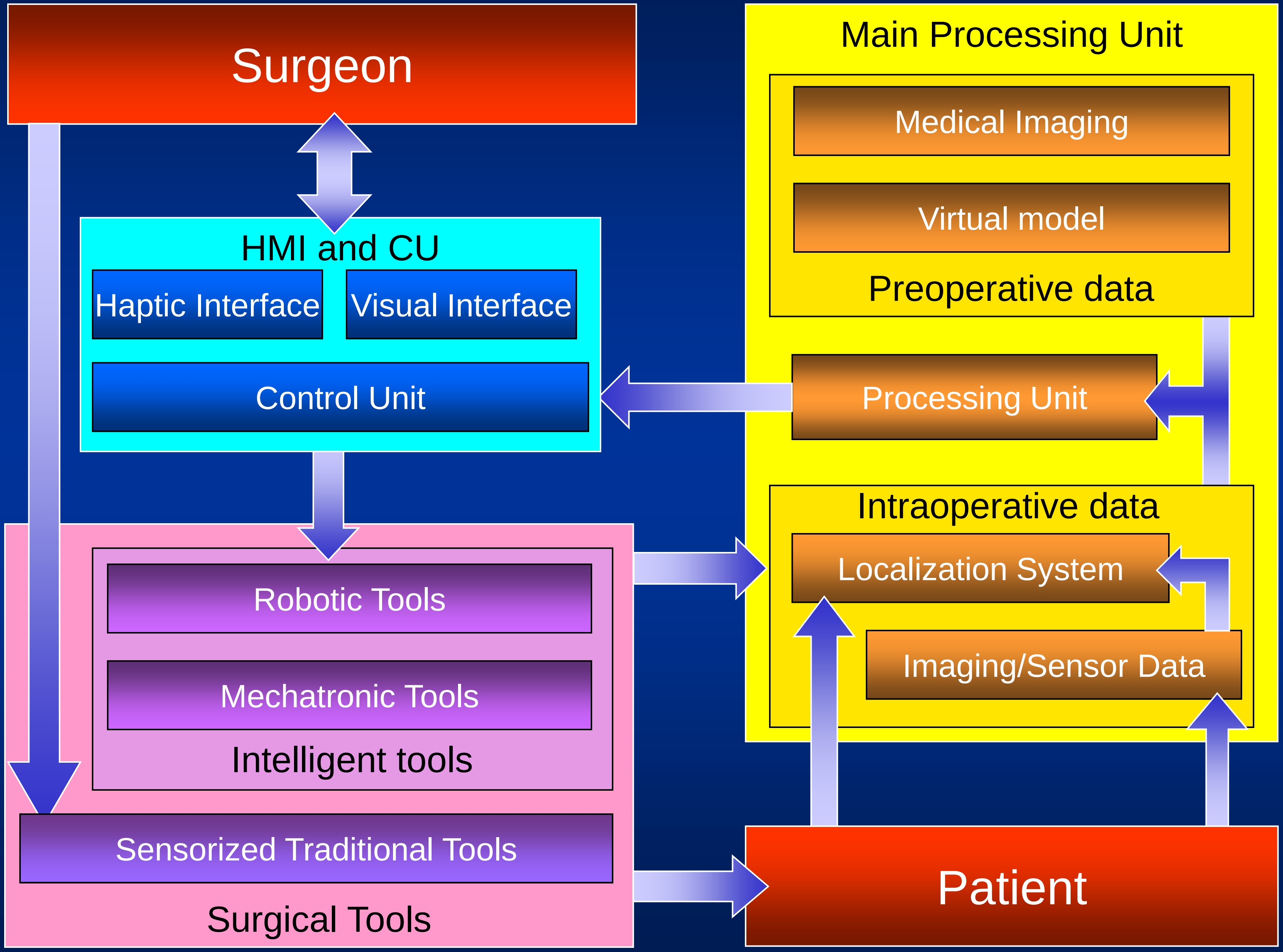

**Traditional "Mental" Registration**




**Multimodal Data Integration**


# Robotic-assisted-dedicated Operating Room

# Computer Assisted Surgery: Functional Scheme



# Outline

- The onset of modern surgery
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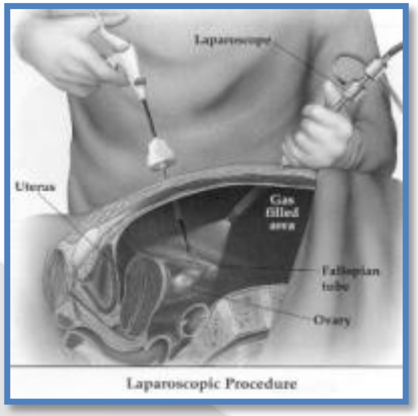
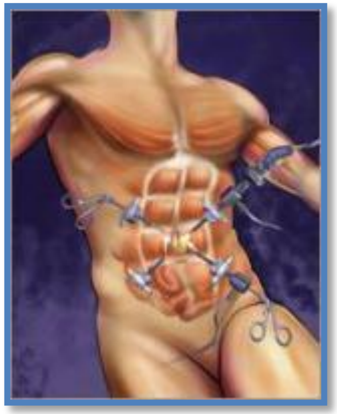
# The Evolution of Surgery

**TRADITIONAL TECHNIQUES**



**LAPAROSCOPIC SURGERY**


Access Trauma Reduction & Increased Internal Dexterity


**ROBOTICS SURGERY**

**+ Accuracy**
**+ Predictability**
**+ Repeatability**

= Quality

# History of Robotics Surgery

- 1985: Erich Mühe
  1st laparoscopic cholecystectomy
- **1985: Kwoh, Young et al.**
  **1st robot in <u>neuro</u>surgery (Puma 560)**
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- **1989: Benabid, Lavallée, Cinquin et al.**
  **1st patient in <u>neuro</u>surgery (Neuromate)**


**NEUROMATE (currently by Renishaw company)**

Neuromate® has been used in thousands of electrode implantation procedures for Deep Brain Stimulation, and Stereotactic Electroencephalography, as well as stereotactic applications in neuro-endoscopy, radiosurgery, biopsy, and Transcranial Magnetic Stimulation.

IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, VOL. 35, NO. 2, FEBRUARY 1988 153

A Robot with Improved Absolute Positioning Accuracy for CT Guided Stereotactic Brain Surgery

YIK SAN KWOH, MEMBER, IEEE, JOAHIN HOU, EDMOND A. JONCKHEERE, SENIOR MEMBER, IEEE, AND SAMAD HAYATI

118 IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, VOL. 35, NO. 2, FEBRUARY 1988

An Advanced Robot System for Automated Diagnostic Tasks Through Palpation

PAOLO DARIO AND MASSIMO BERGAMASCO

**IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, 1988**

# Scientific and Technological Milestones in Robotics Surgery

IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, VOL. 35, NO. 2, FEBRUARY 1988 153

## A Robot with Improved Absolute Positioning Accuracy for CT Guided Stereotactic Brain Surgery

YIK SAN KWOH, MEMBER, IEEE, JOAHIN HOU, EDMOND A. JONCKHEERE, SENIOR MEMBER, IEEE, AND SAMAD HAYATI

*Abstract*—In this paper, we describe how a U
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mounted at its end effector, can be used for C
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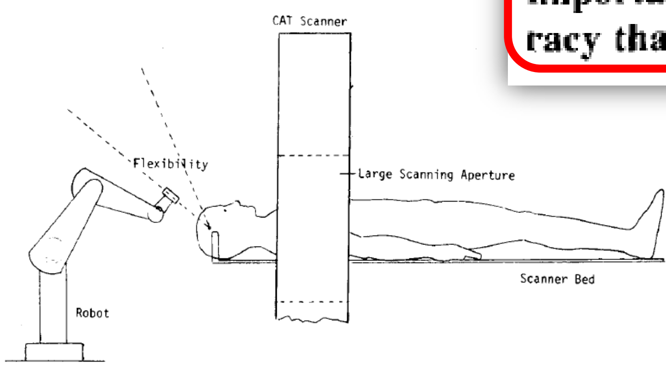
than one with a manually adjustable frame.
important advantage, as we show in this paper
racy that can be reached by proper calibration

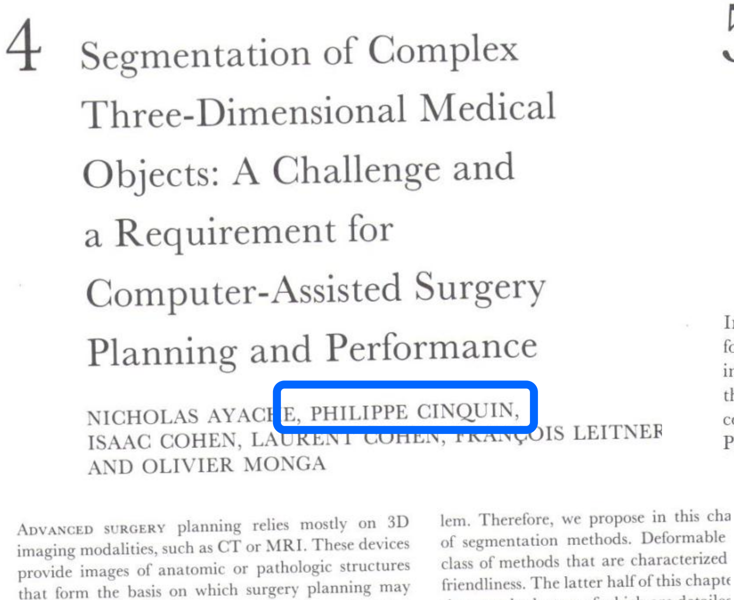
*Abstract*—In this paper, we describe how a Unimation Puma 200 robot, properly interfaced with a CT scanner and with a probe guide mounted at its end effector, can be used for CT-guided brain tumor biopsies. Once the target is identified on the CT picture, a simple command allows the robot to move to a position such that the end effector probe guide points towards the target. This results in a procedure faster than one with a manually adjustable frame. But probably the most important advantage, as we show in this paper, is the improved accuracy that can be reached by proper calibration of the robot.




**Y. S. Kwoh**, CT Research, Department of Radiology, Memorial Medical Center, Long Beach, CA, USA

# Scientific and Technological Milestones in Robotics Surgery

Stephane Lavallè,
Grenoble, France



4 Segmentation of Complex Three-Dimensional Medical Objects: A Challenge and a Requirement for Computer-Assisted Surgery Planning and Performance

NICHOLAS AYACHE, PHILIPPE CINQUIN, ISAAC COHEN, LAURENT COHEN, FRANÇOIS LEITNER AND OLIVIER MONGA

ADVANCED SURGERY planning relies mostly on 3D imaging modalities, such as CT or MRI. These devices provide images of anatomic or pathologic structures that form the basis on which surgery planning may be performed. Quantitative decisions (e.g., direction

lem. Therefore, we propose in this cha of segmentation methods. Deformable class of methods that are characterized friendliness. The latter half of this chapte these methods, two of which are detailec

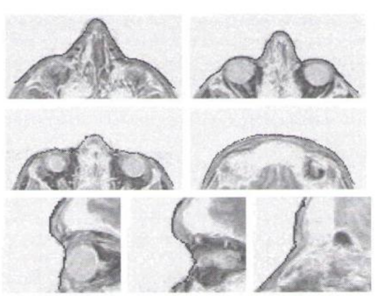
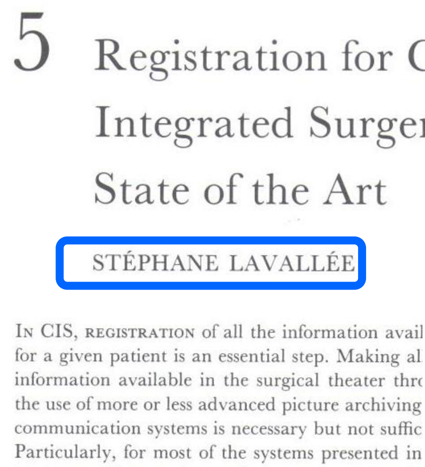


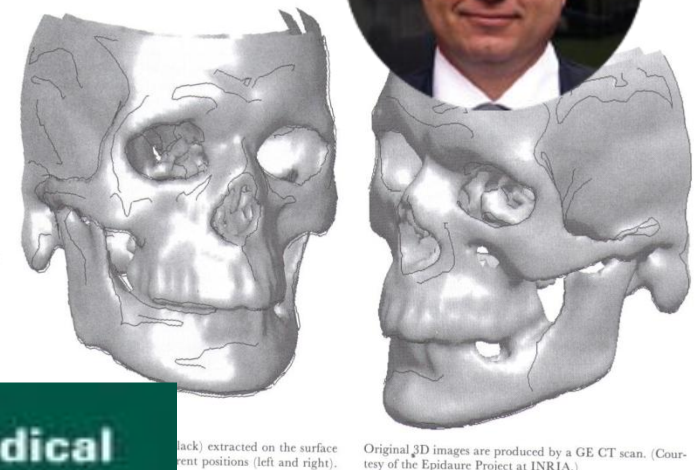
FIGURE 4.2 Here we represent the surface once we have reached a minimum of the energy $E$. Some vertical and horizontal cross-sections of the surface are given. They show an accurate localization of the surface at the edge points.



5 Registration for Computer-Integrated Surgery: Methodology, State of the Art

STÉPHANE LAVALLÉE

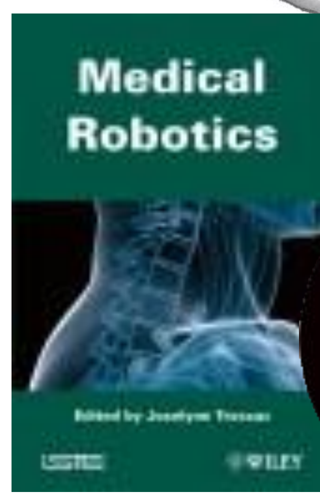
IN CIS, REGISTRATION of all the information avail for a given patient is an essential step. Making al information available in the surgical theater thro the use of more or less advanced picture archiving communication systems is necessary but not suffic Particularly, for most of the systems presented in



lack) extracted on the surface ent positions (left and right).

Original 3D images are produced by a GE CT scan. (Courtesy of the Epidaure Project at INRIA.)

Philippe Cinquin,
Grenoble, France




Jocelyne Troccaz,
Grenoble, France

# History of Robotic Surgery

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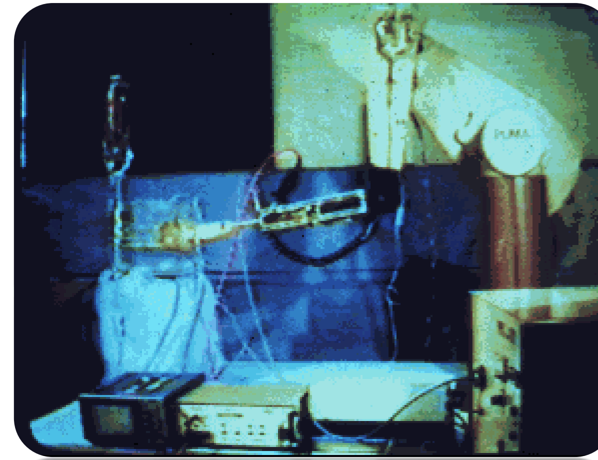
  1st laparoscopic cholecystectomy
- 1985: Kwoh, Young et al.
  1st robot in neurosurgery (Puma 560)
- 1987: 1st video-laparoscopic cholecystectomy
- 1989: Benabid, Lavallée, Cinquin et al.
  1st patient in neurosurgery (Neuromate)
- **1991: Davies et al.**
  **1st patient for prostate surgery (Puma 560)**

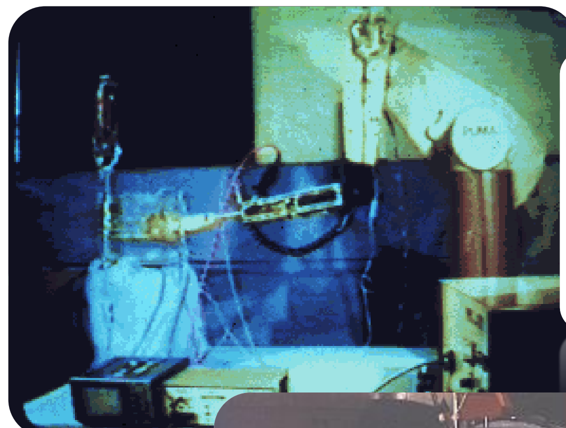


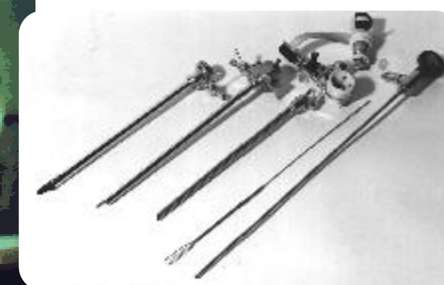
# Surgeon Assistant Robot for Prostatectomy (SARP)

- Developed at Imperial College, London, UK, in 1991 (B. Davies)
- Derived from a **six-axis PUMA robot**, modified by adding a prismatic axis for moving a resectoscope
- Designed to conduct transurethral resection of the prostate (TURP)

**Professor Brian Davies**
Imperial College, London, UK

- **1988**: Preliminary experiment with PUMA





- **1991**: motorized frame SARP, in use on a live patient

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  1st robot in neurosurgery (Puma 560)
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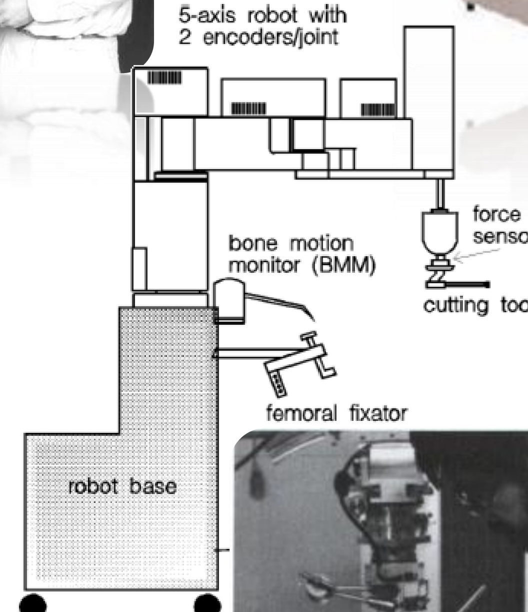
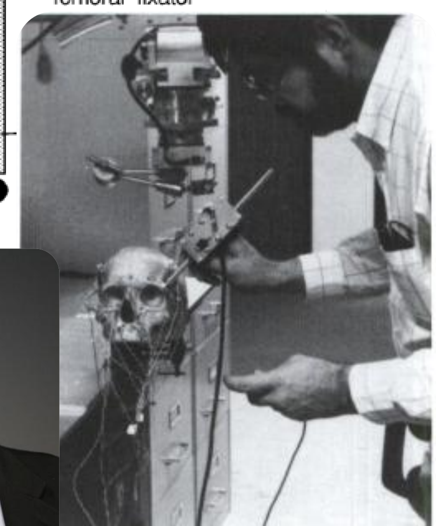
- 1989: Benabid, Lavallée, Cinquin et al.
  1st patient in neurosurgery (Neuromate)
- 1991: Davies et al.
  1st patient for TURP (Puma 560)
- **1992: Taylor et al. Integrated surgical systems 1st <u>hip</u> surgery with ROBODOC**



# The birth of **RoboDoc**

‘There **were two surgeons at the University of California at Davis**, **Bill Bargar** and **Howard Pau**l, who were doing research **on custom hip implants**…
they asked themselves: ‘Gee, here we are designing orthopaedic implants for custom use to a precision of a tenth of a mm or better, five one thousandths of an inch, but **this hole is very crude**, and is nowhere, and only maybe 25% of the implant is even in contact with bone, and we can’t really control where it is, and there are large gaps, and so, if we expect the bone to grow into the implant, this is a very hit-or-miss, uncontrolled process.” And so **they began to wonder if you could use a robot to machine the cavity for the hip implant**.

**Howard Paul (center)** and Peter Kazanzides (right)

**William L. Bargar, M.D.**

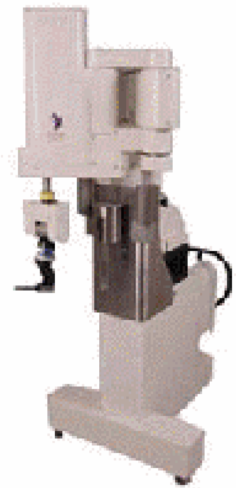
# The birth of RoboDoc and of ISS Inc.

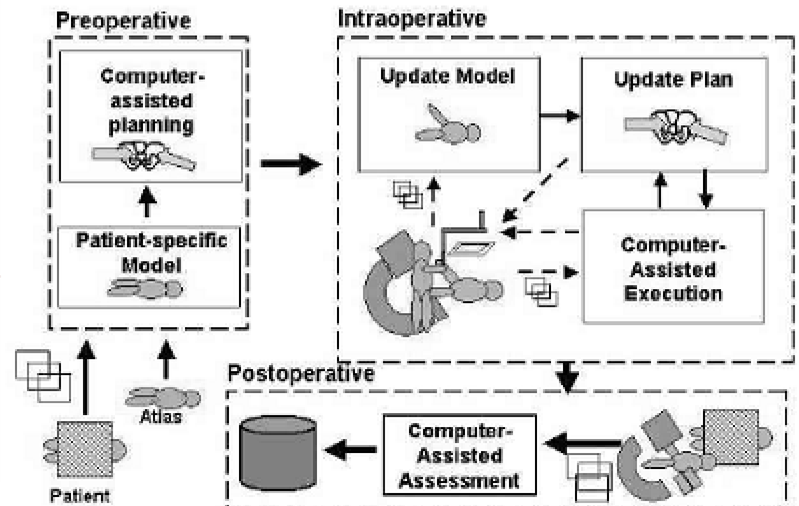
…They went to **a number of robot manufacturers** and the **only one they could get interested was IBM**. Essentially, the project bounced around a bit in IBM Research until **eventually it got to the right place, which was my Automation Technology Department**. After about a year, I decided that I wanted to take an internal sabbatical inside IBM to develop a complete system. I hired two post-docs: Peter Kazanzides, who worked on Robodoc, and Yong-Yil Kim, who worked on surgical navigation for craniofacial osteotomies. Peter and I developed the prototype Robodoc system, along with a couple people from UC Davis and IBM Palo Alto. I led the development effort. Subsequently, **the surgeons started Integrated Surgical Systems (ISS) to make a clinical product.** Peter joined ISS and I stayed at IBM Research to start the Computer-Assisted Surgery group, which I led until I moved to JHU in 1995. **ISS did the actual testing on dogs and developed the human version**.

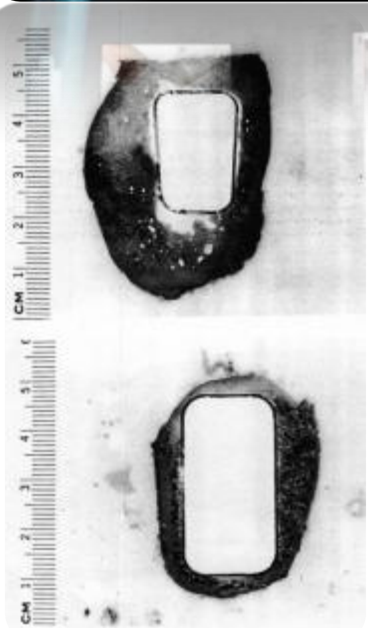
**Russell Taylor**

**Peter Kazanzides**

# The ROBODOC Integrated Surgical Systems, Inc.





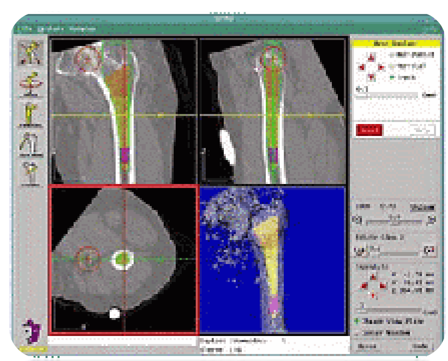



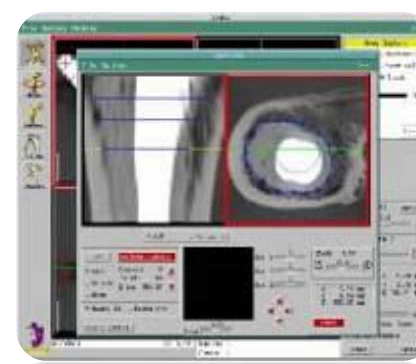
## Bone implant comparison

Manual broach method
20% contact surface
1-4 mm gap size

ROBODOC method
96% contact surface
0.05 mm gap size

ORTHODOC Pre-surgical planning station





INTEGRATED SURGICAL SYSTEMS
*Redefining Surgery...*

http://www.robodoc.com

# ROBODOC Premieres

2 May 1990. 1st Dog surgery with **Hap Paul** in the foreground and **Brent Mittelstadt** in the background.

1 November 1992. 1st Human surgery performed by **Dr. Bill Bargar** (Peter Kazanzides also attending).

Courtesy of Peter Kazanzides and Russell Taylor

INTEGRATED SURGICAL SYSTEMS
*Redefining Surgery...*

# ROBODOC: from riches... to rags...

**From Technical Wonder to Malpractice Liability**

**In 1998, a patient, after receiving an artificial hip, said: "It fits real well, but I can't walk any more"**

- **(1997) The combined experience of the United States Food and Drug Administration multicenter trial and the German postmarket use of ROBODOC on over than one thousand patients lead to this expression: "The ROBODOC system is thought to be safe and effective in producing radiographically superior implant fit and positioning while eliminating femoral fractures"**

**ISS ceased operations in mid-2005 because of lawsuits and lack of funding**

# ROBODOC: ...and back to riches?

INTEGRATED SURGICAL SYSTEMS
*Redefining Surgery...*

CUREXO TECHNOLOGY CORPORATION LAUNCHES ITS ROBODOC® SURGICAL SYSTEM AT UPCOMING ORTHOPAEDIC CONFERENCE IN LAS VEGAS, SACRAMENTO, Calif. [February 23, 2009]

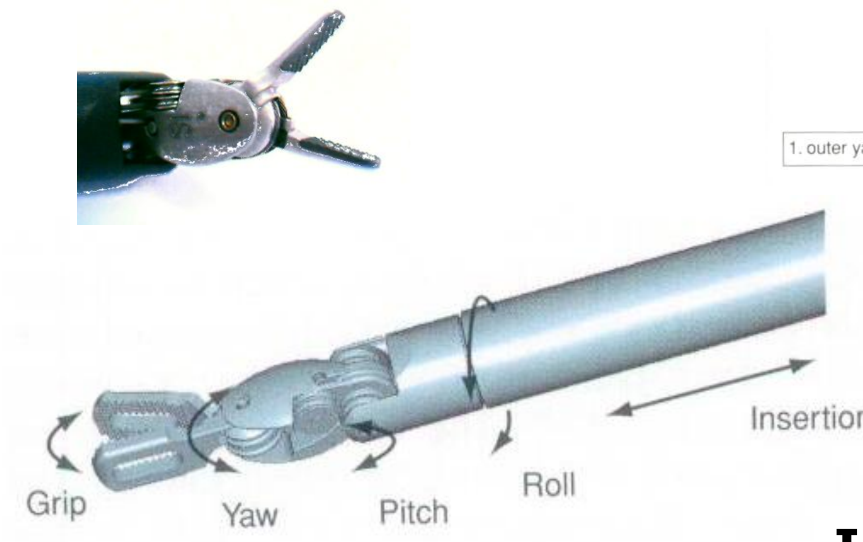
Curexo Technology Corporation develops, manufactures, and markets an image-directed surgical robotic system for orthopaedic surgery. **The ROBODOC® Surgical System is the only active robotic system cleared by the FDA for orthopedic surgery. To date the system has been used in over 24,000 combined TKA and THA surgical procedures worldwide.** ROBODOC® and ORTHODOC®, are registered trademarks of Curexo Technology Corporation.

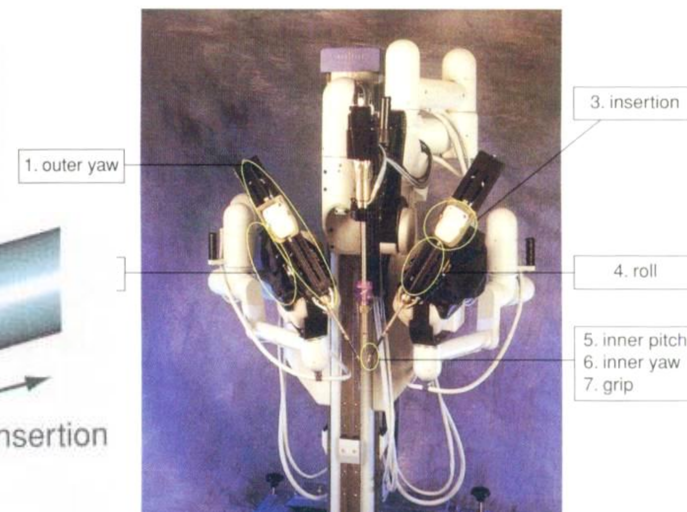

ROBODOC
Curexo Technology Corporation

# History of Robotics Surgery

- 1985: Erich Mühe
  1st laparoscopic cholecystectomy
- 1985: Kwoh, Young et al.
  1st robot in neurosurgery (Puma 560)
- 1987: 1st video-laparoscopic cholecystectomy
- 1989: Benabid, Lavallée, Cinquin et al.
  1st patient in neurosurgery (Neuromate)
- 1991: Davies et al.
  1st patient for TURP (Puma 560)
- 1992: Integrated surgical systems
  1st hip surgery with ROBODOC
- **1995: Intuitive Surgical Inc. was founded**
- **1998: Intuitive Surgical Inc.**
  **1st totally endoscopic coronary artery bypass grafting using the da Vinci ROBOTIC SYSTEM**

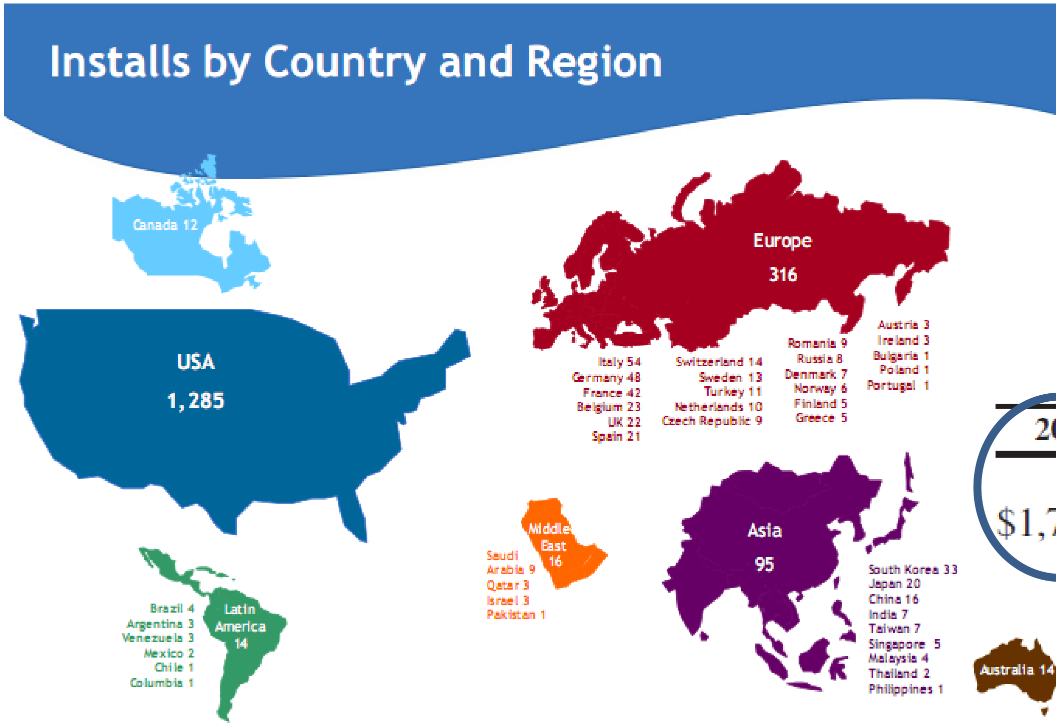
# A success story in surgical robotics: the "daVinci" system


**Intuitive "Endowrist"**

# Da Vinci Robot and Intuitive Surgical at-a-glance



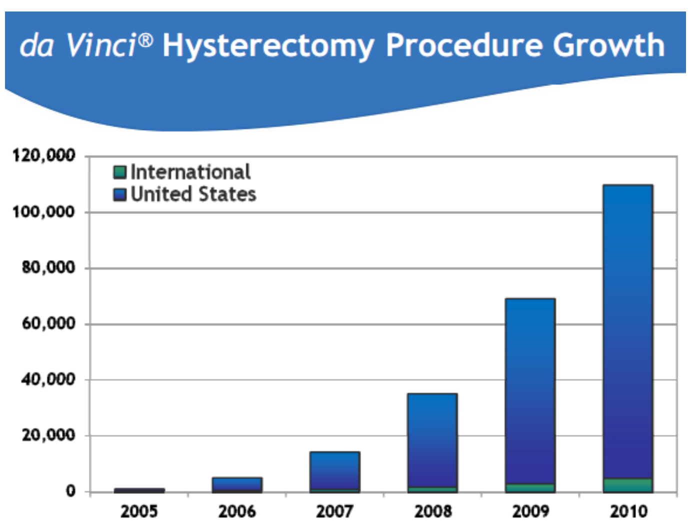

## 1840+ systems installed in 1450+ hospitals

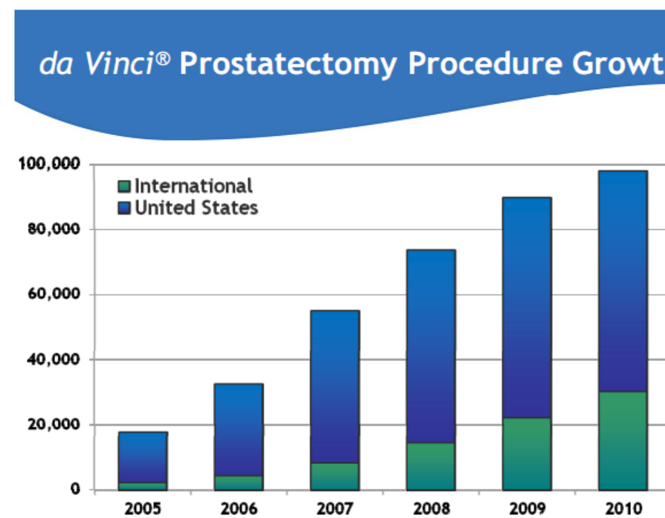
## 1700+ employees

**Revenue**

| Year Ended December 31, | | | |
|---|---|---|---|
| 2011 | 2010 | 2009 | 2008 |
| (In millions, except per share amounts and headcount) | | | |
| $1,757.3 | $1,413.0 | $1,052.2 | $ 874.9 |

## DaVinci Worldwide Installations (2010)

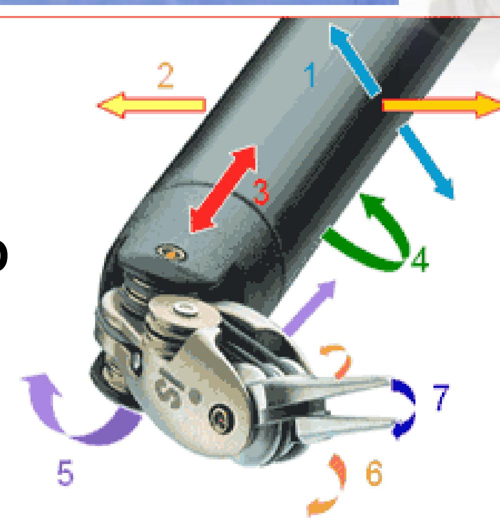



SOURCE: www.intuitivesurgical.com

# The "Secrets" of the DaVinci Robot Success: Accuracy, Dexterity, Intuitiveness


- Outstanding mechanical design
- Excellent optics (2D and 3D vision)
- Smart and friendly interfaces




# The Image-Guided CyberKnife System by AccuRay (Sunnyvale, CA, USA) for Computer-Assisted Radiotherapy

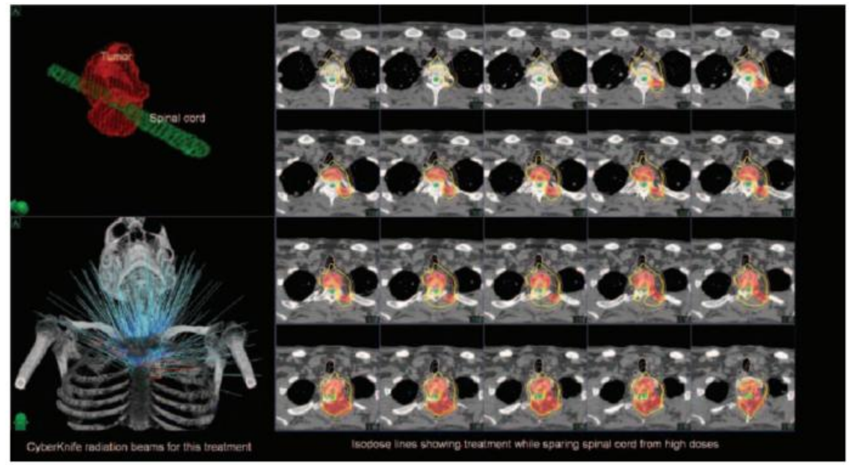
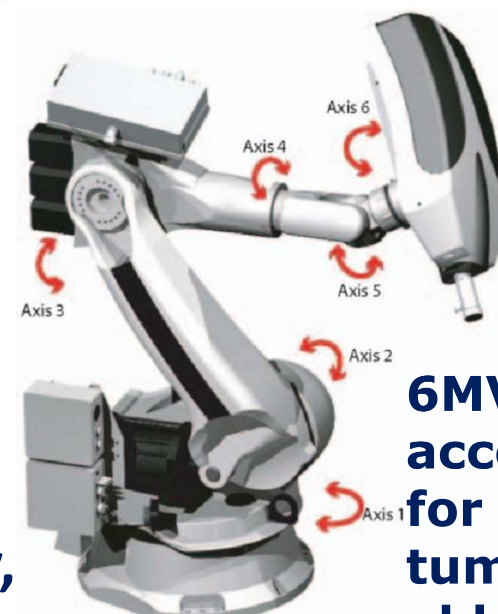




**Figure 4** Top left image: the patient model with the tumour to be targeted and the spinal cord radiosensitive area. Bottom left: CyberKnife radiation beams for treatment. Right: Isodose lines for treatment.

The main reasons for success:

- **Accuracy**
- **Tracking system for motion compensation**




**6MV linear accelerator for X-ray tumor ablation**

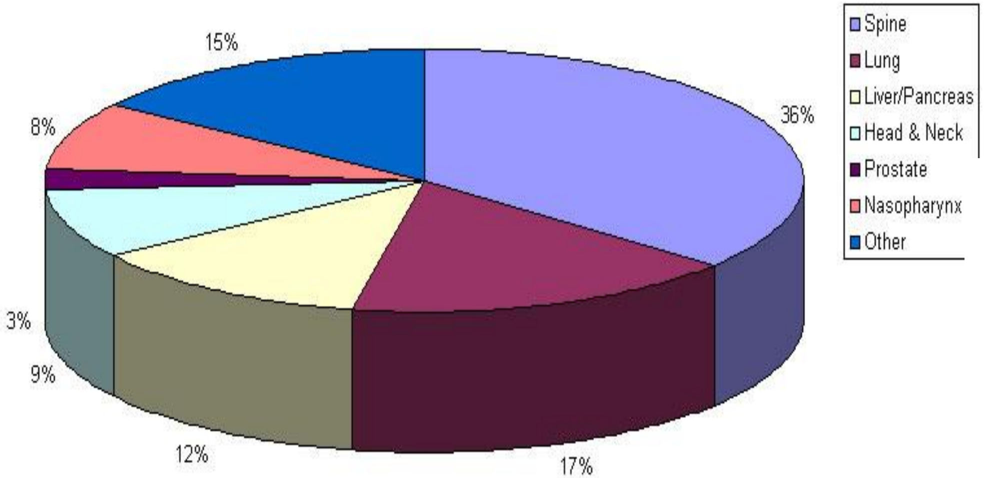
**J.R. Adler, M.J. Murphy, S.D. Chang, S.L. Hankock: Image guided robotic radiosurgery, Neurosurgery 44(6), 1299–1306 (1999)**

# CyberKnife: Clinical Use

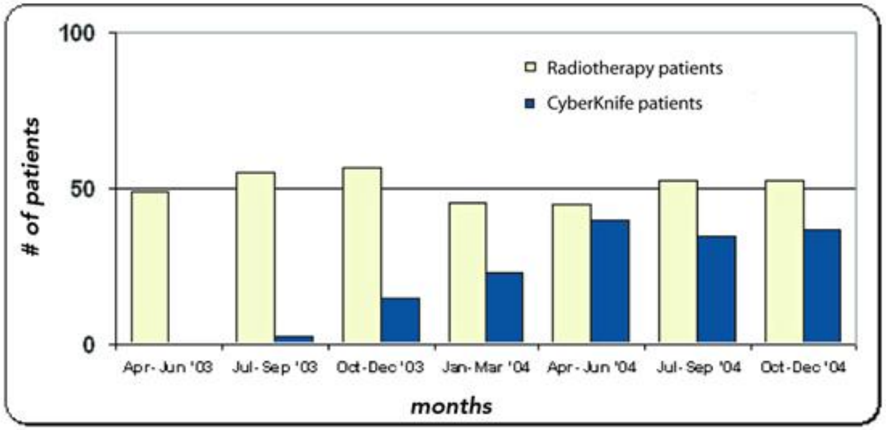
- 20,000+ patients worldwide
- Treatments last 30 to 90 minutes, depending on the tumor's complexity and shape. Patients require no anesthesia.

2011 AccuRay Data

- 642 systems installed
- 1000+ employees
- 330+ patents
- 2011 revenue: 219 M$




Total CyberKnife System Treatments by Tumor Location




Patient Population

Source: www.accuray.com

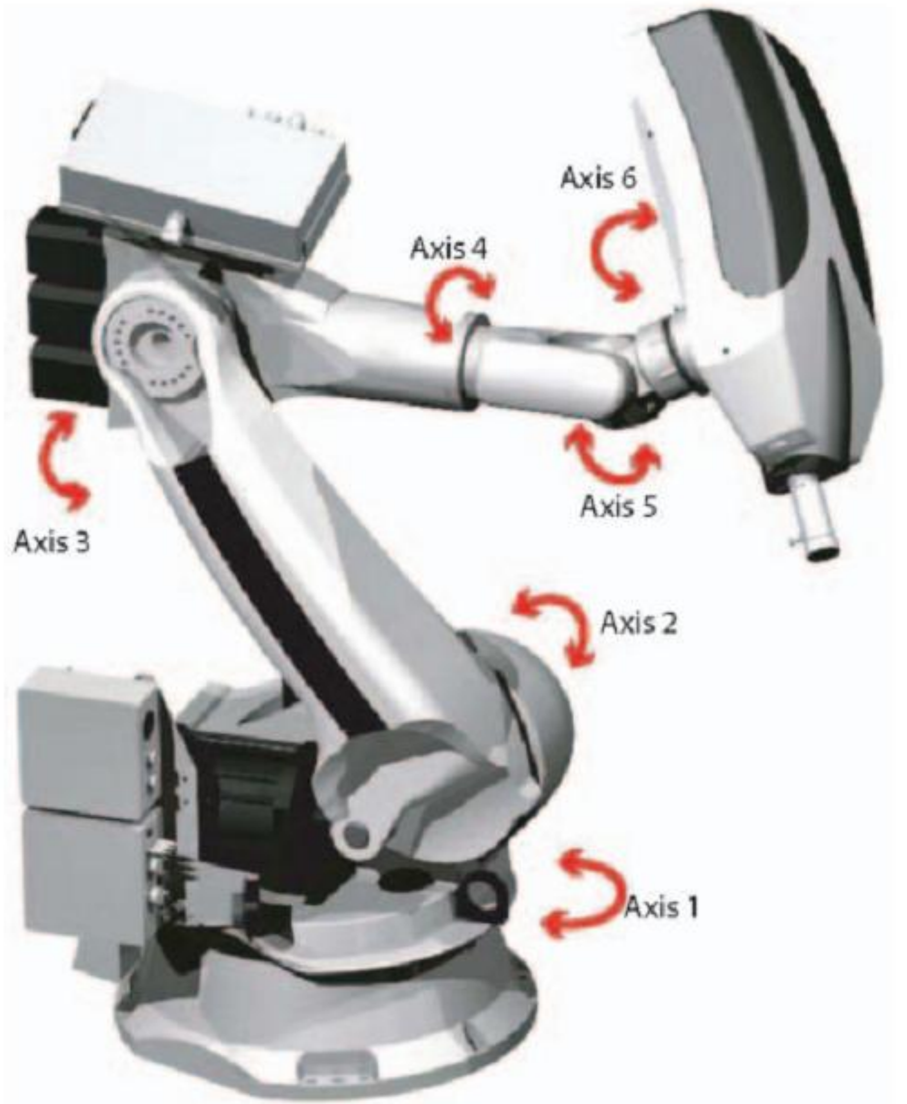
# The CyberKnife Robot

## 6-dof KUKA Robot

- Robotic targeting precision <0.2mm
- Payload: 150 kg
- Max. reach: 2700/2900/3100 mm
- Weight: 1285 kg

## Overall precision of treatment

- <0.95mm for cranial and spinal lesions
- 1.5mm for moving targets with respiratory tracking

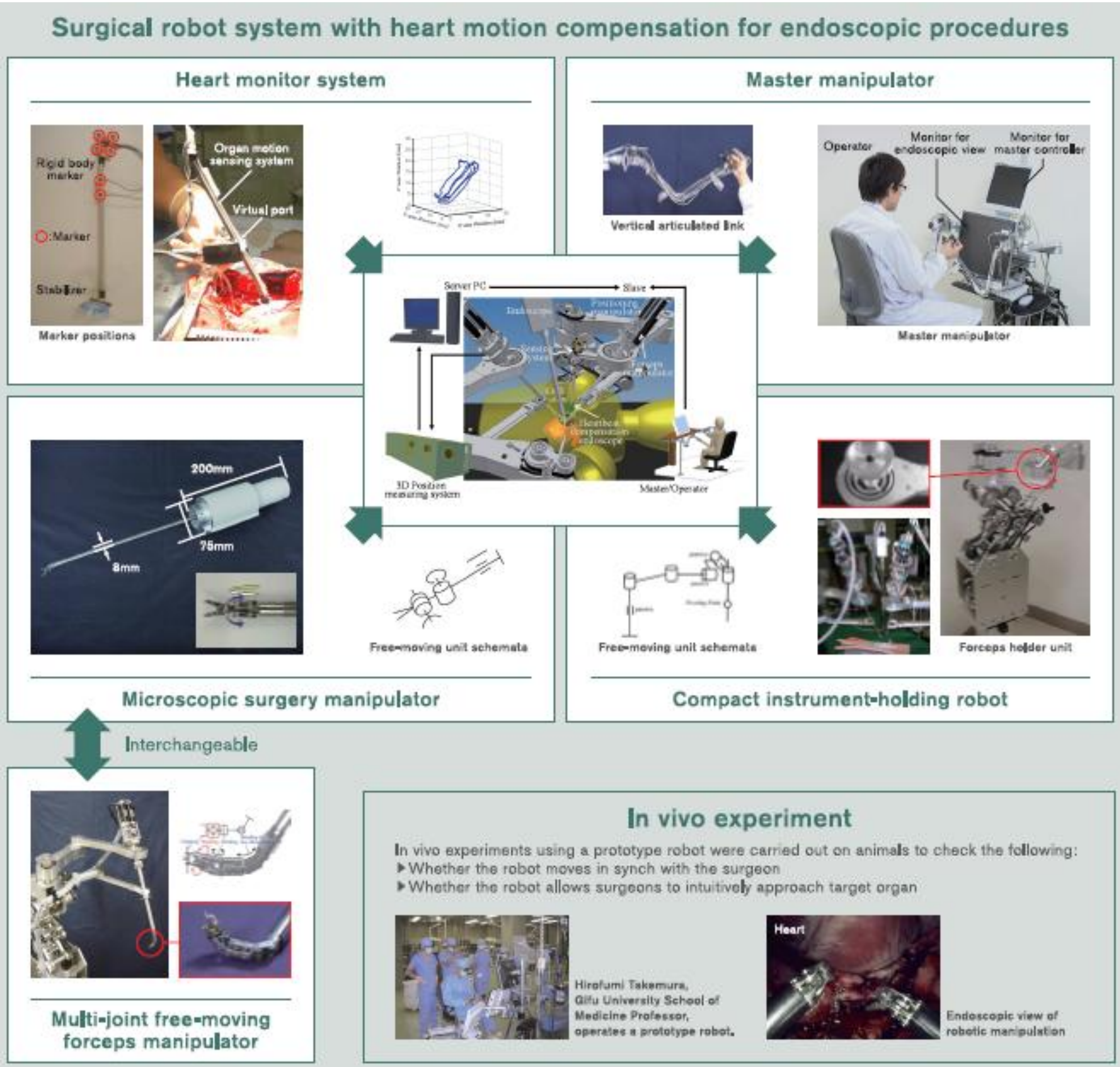


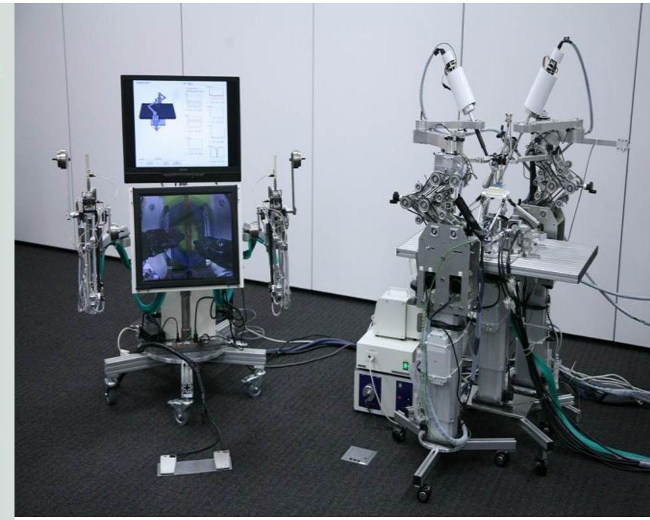
# The Synchrony Tracking System


**1.5mm ACCURACY for moving targets with respiratory tracking**

Correspondence model of LEDs and fiducial positions is created intra-operatively. LED position is then tracked in real-time

# Heart Motion Compensation for Endoscopic Procedures



Fujie Laboratory,
Waseda University,
Tokyo, Japan

# Achievements of Robotics Surgery

- Game-changing applications
- Technically advanced and dependable systems
- Widely accepted and used in clinical practice by surgeons, by patients and by hospital administrations: 220.000+ surgical interventions worldwide just since the beginning of 2012
- Real IMPACT on health, and on economy (real products, real jobs)

# Robotics Surgery: Lessons Learned

- **Real application domains** and procedures that benefit
- **Cost/benefit** clearly proved
- **Time of intervention** kept short
- **Time and complexity for set-up** to be **minimized**

# Surgeon's Opinion

- External surgical master-slave manipulators (robots) are here to stay and robotic assistance will become the preferred approach, but only for advanced certain operations

- Operations which involve intra-corporeal anastomosis of small vessels and ducts (3mm) & operations where the operative space is restricted benefit from Robotic Assisted Surgery

- In these operations robotic assistance increases 'effectiveness' = reduces the level of difficulty and thus increases the number of surgeons who can perform these operations well and with safety (not just the very gifted master surgeons)

- Cost efficacy will increase with competition and increased multi-disciplinary usage in high volume centres

- Internal **mini-robots** are predicted to replace flexible endoscopy as we know it

**Professor Sir Alfred Cuschieri, MD**
Director of the Institute of Medical Science and technology in Dundee and St Andrew's Universities
Pioneer of endoscopic surgery

# Outline

- The onset of modern surgery
- The onset of robotic surgery
- Current Scientific and Technological Challenges
- Conclusions

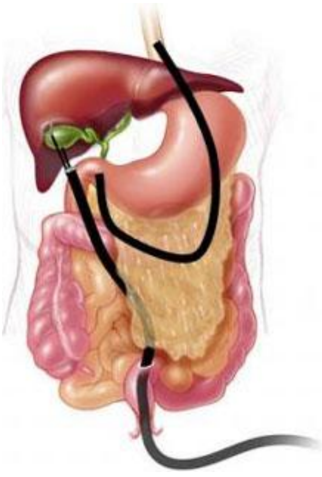
# What’s next?

- Consolidating the success story of Robotics Surgery by addressing the still many open research issues and technical/clinical/ industrial limitations
- Simplifying the complexity and reducing the cost of procedures
- Exploring new avenues and paradigms (one more ‘game change’ in surgery with robots?)

# Some examples

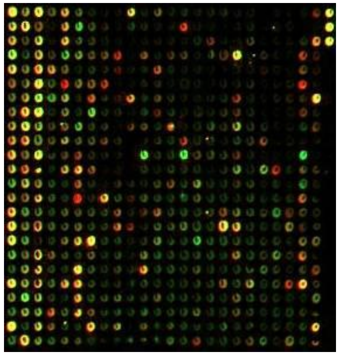
Needle steering

Capsular endoscopy and therapy

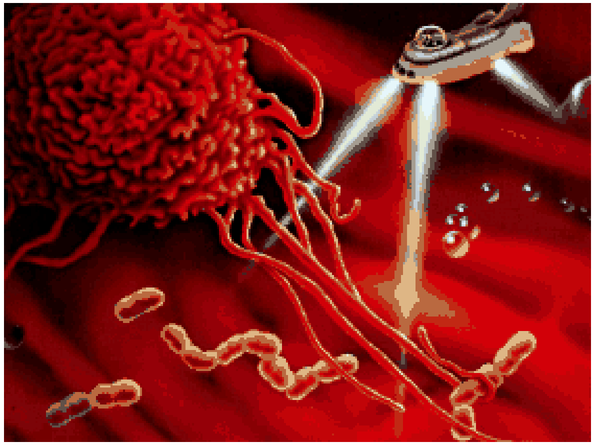


From Minimally Invasive to Visible Scareless procedures

Fetal surgery



Early diagnosis by DNA chips



Ultimately... Fantastic Voyage

# Why a Change of Paradigm is INEVITABLE

**Professor Sir Alfred Cuschieri, MD**

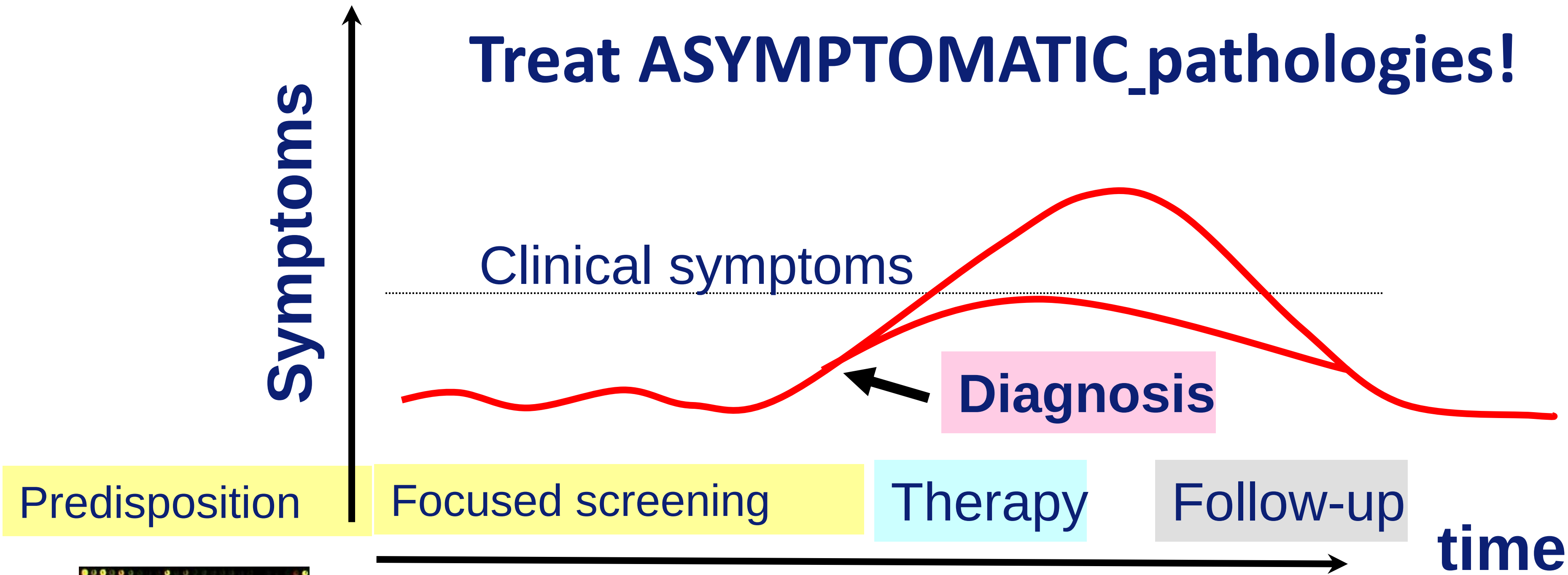
Director of the Institute of Medical Science and technology in Dundee and St Andrew's Universities. Pioneer of endoscopic surgery

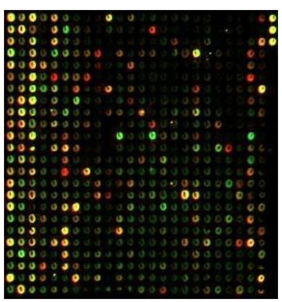
***The operating room of the year 2030 will be a totally different environment than today***

***MASS Screening and EARLY diagnosis will have a major impact on the type and invasiveness of required surgical procedures***

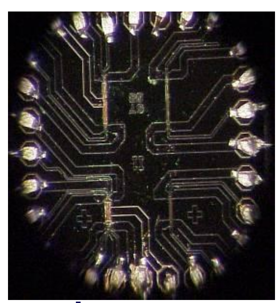
**The combination of micro/nano technologies, chemistry, physics and robotics/microrobotics will be key technologies enabling future high quality (accurate and repeatable), early and minimal invasive surgery**

# Prevention: the challenge of modern medicine

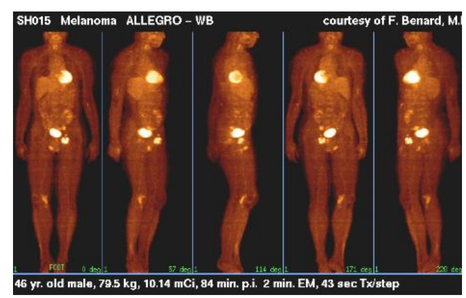


Gene Chip



Biosensor

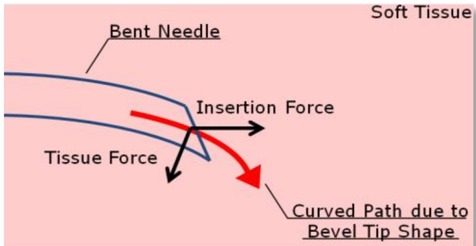


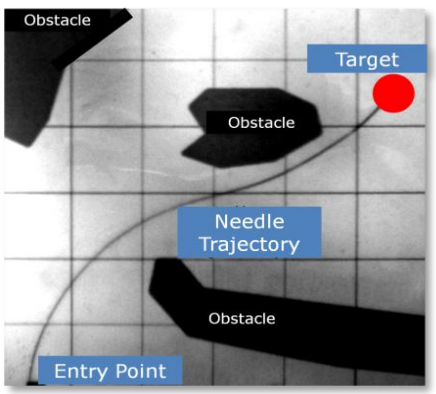

PET-CT
Molecular Imaging

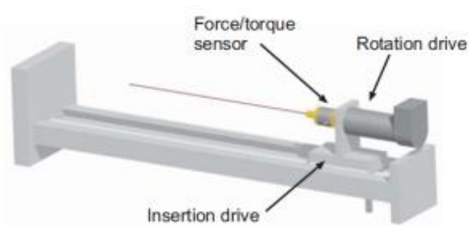
Molecular Diagnostics

***Courtesy by Philips***

# Robotic Needle Steering: Trying to Catch a Rather Elusive Target




## An elegant approach:

- Simple mechanical design (1D, no compartimentalization, no on-board electronics)
- Targeting only achieved by tip-tissue interaction and control strategies for insertion
- Minimally invasive, low cost solution

## Main challenges:

- Accurate targeting (e.g. for controlled obstacle avoidance)
- Tissue compliance leading to target displacement: quest for insertion path update (to prevent/minimize damage)

# Micro-active Endoscopes and Needle Steering

Prof. Koji Ikuta

IEEE ICRA 2012 Needle Steering Workshop

**Pathways to Clinical Needle Steering: Recent Advances and Future Applications**

Prof. Jaydev Desai

Prof. Rajni Patel

Prof. Moshe Shoham

Prof. Mamoru Mitsuishi

Lecture Notes in Computer Science
Volume 2878 2003

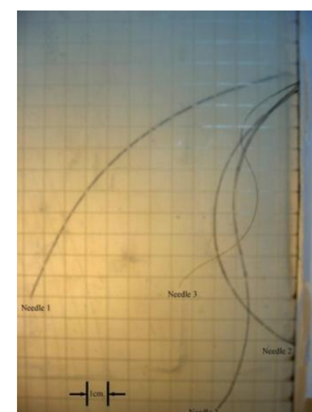
Medical Image Computing and Computer-Assisted Intervention - MICCAI 2003

**MICCAI 2008 Workshop**
**Needle Steering: Recent Results and Future Opportunities**

Prof.Tim Salcudean

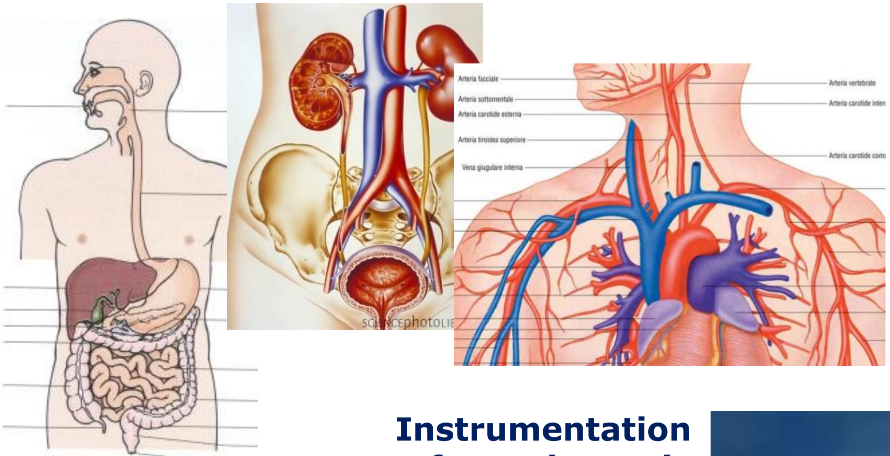
P. Pierre Dupont


Prof. Allison Okamura



# Endoluminal Therapy and Surgery

Endoluminal procedures consist of bringing a set of advanced therapeutic and surgical tools to the area of interest by navigating in the *lumens* of the human body, such as the gastrointestinal tract, the urinary apparatus, the circulatory system, etc.



**PillCam for GI tract endoscopy**

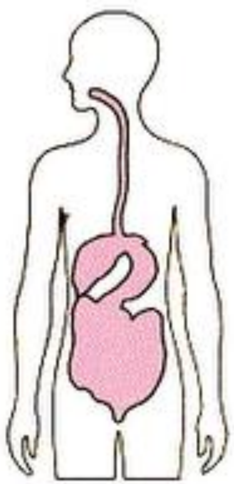

**Clip for endoscopic surgery**

**Instrumentation for endoscopic surgery and NOTES (Natural Orifices Transgastric Endoscopic Surgery)**

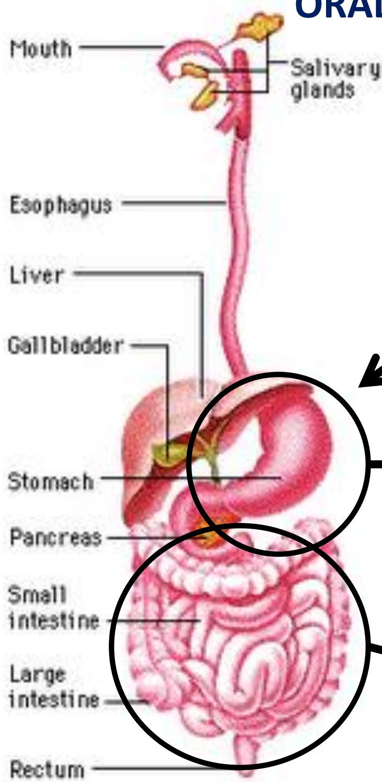
# Endoluminal endoscopy and therapy in the gastrointestinal tract: different possible accesses

**Gastrointestinal Tract (from esophagus to rectum) : Ø = 10 to 30 mm**

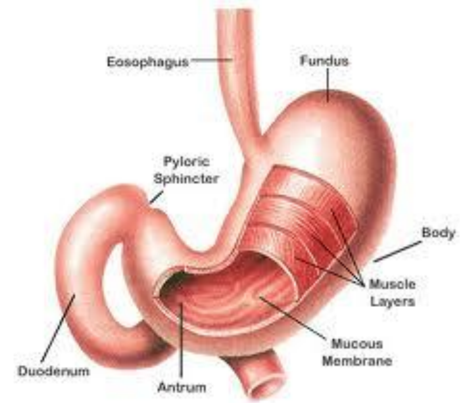
| | |
|---|---|
| Small diameter | → Miniaturization |
| Physiological curvature | → Dedicated/Conformable shape |
| Collapsed tissues | → Active mechanism needed for locomotion |



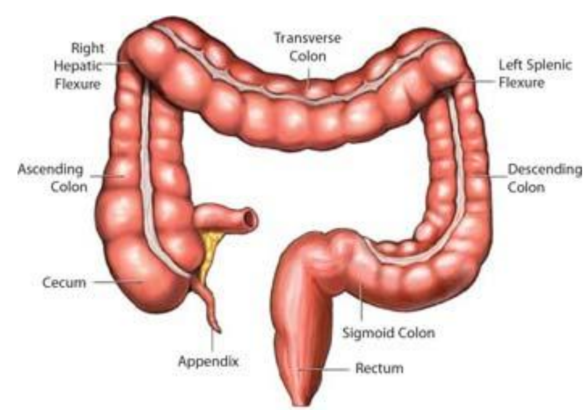
**ORAL ACCESS**




**ABDOMINAL AND UMBILICAL ACCESS**




**Stomach**

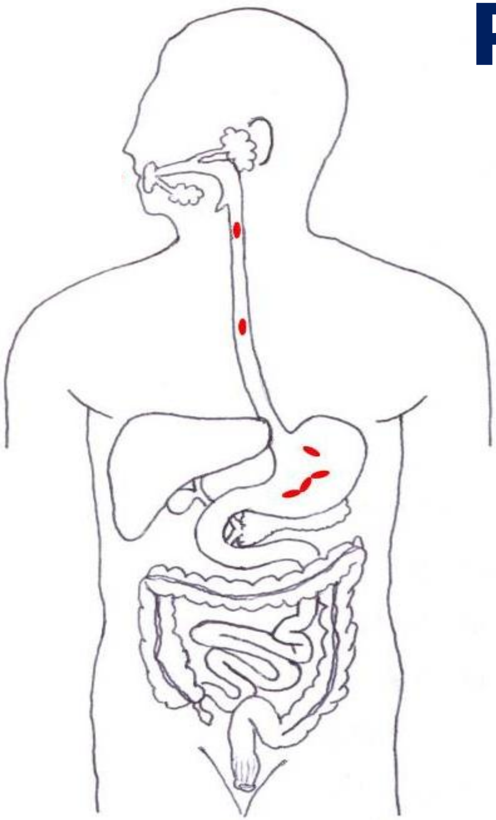


Anatomy of Large Intestine

**RECTAL ACCESS**

**Colon**

# Passive wireless capsules for gastrointestinal endoscopy




***May 2000: Given Imaging (now PillCam) capsule for endoscopy***

The NEW ENGLAND JOURNAL of MEDICINE

ORIGINAL ARTICLE

**Capsule Endoscopy versus Colonoscopy for the Detection of Polyps and Cancer**

André Van Gossum, M.D., Miguel Munoz Navas, M.D., Iñaqui Fernandez-Urien, M.D., Cristina Carretero, M.D., Gérard Gay, M.D., Michel Delvaux, M.D., Marie Georges Lapalus, M.D., Thierry Ponchon, M.D., Horst Neuhaus, M.D., Michael Philipper, M.D., Guido Costamagna, M.D., Maria Elena Riccioni, M.D., Cristiano Spada, M.D., Lucio Petruzziello, M.D., Chris Fraser, M.D., Aymer Postgate, M.D., Aine Fitzpatrick, M.D., Friedrich Hagenmuller, M.D., Martin Keuchel, M.D., Nathalie Schoofs, M.D., and Jacques Devière, M.D.

***Low sensitivity for detecting colonic lesions*** (64% for lesions 6 mm or bigger, compared with the use of standard colonoscopy)

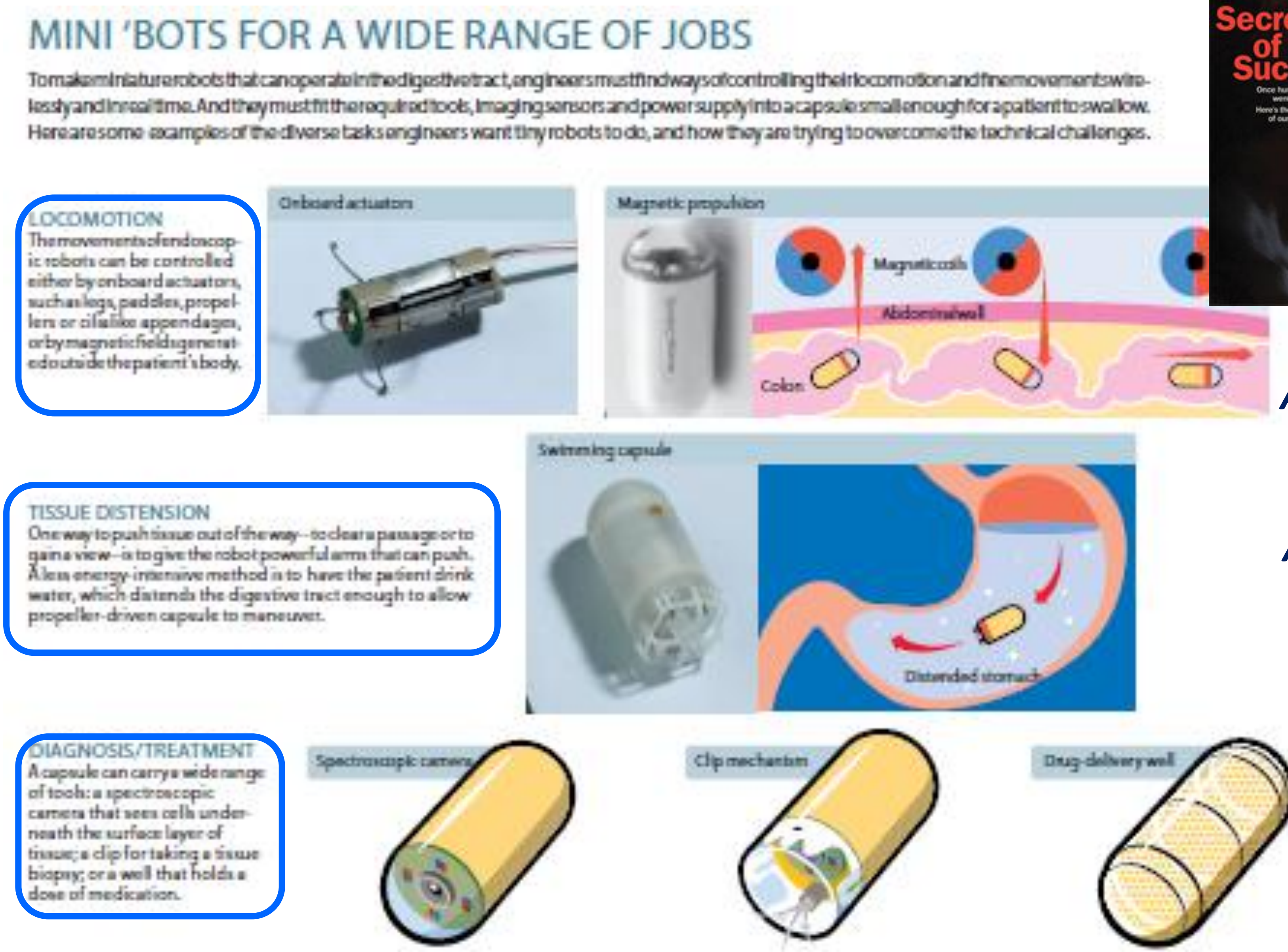
Benefits:

- Small system dimension
- Low invasiveness procedure
- Access to small bowel

Limitations:

- **Passive locomotion** (no controlled halts: capsule movement by peristalsis)
- Some false negative results

# Overcoming the Limitations of Passive Endoscopic Capsules


MINI 'BOTS FOR A WIDE RANGE OF JOBS

To make miniature robots that can operate in the digestive tract, engineers must find ways of controlling their locomotion and fine movements wirelessly and in real time. And they must fit the required tools, imaging sensors and power supply into a capsule small enough for a patient to swallow. Here are some examples of the diverse tasks engineers want tiny robots to do, and how they are trying to overcome the technical challenges.

LOCOMOTION
The movements of endoscopic robots can be controlled either by onboard actuators, such as legs, paddles, propellers or cilialike appendages, or by magnetic fields generated outside the patient's body.

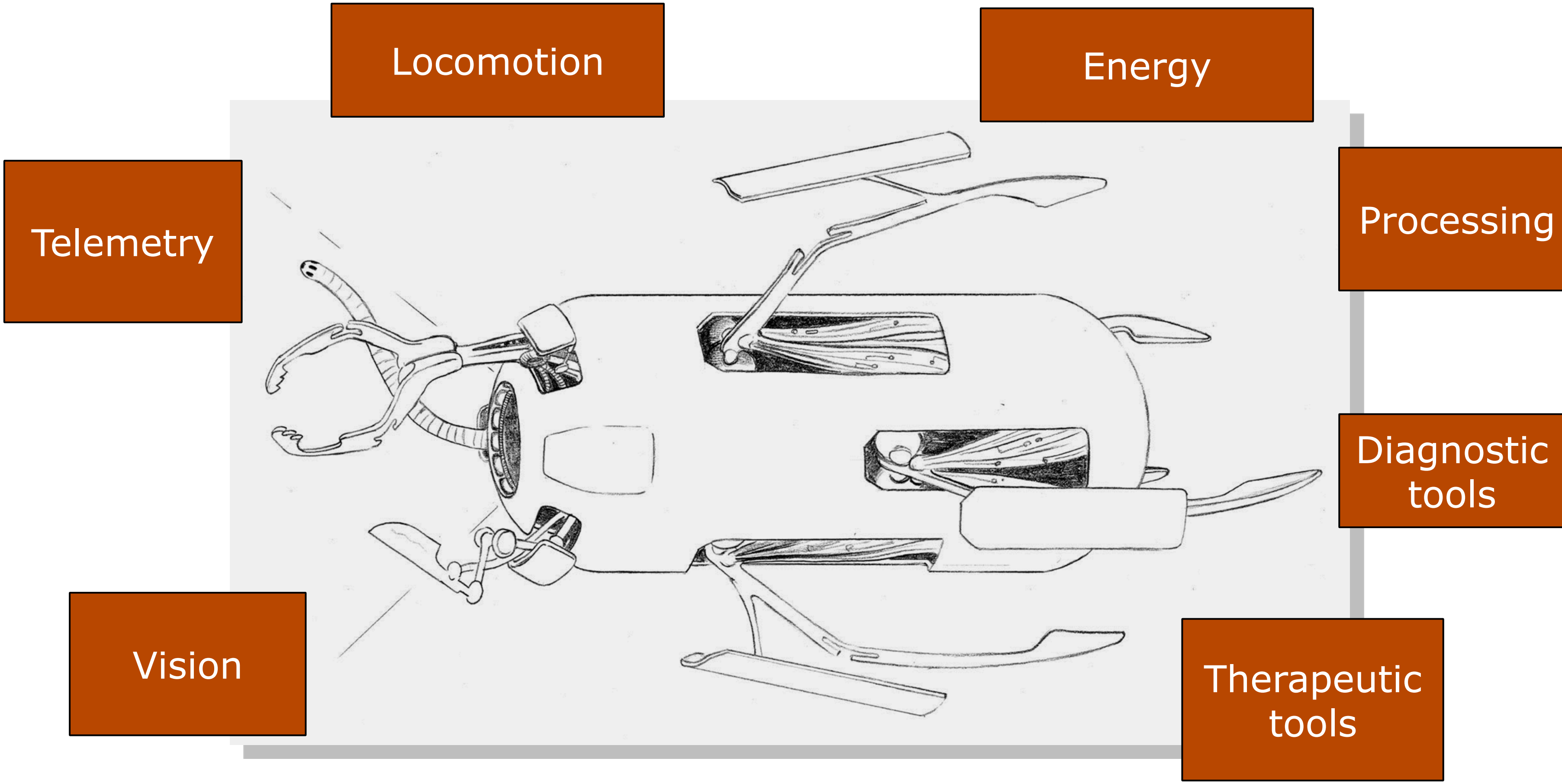
TISSUE DISTENSION
One way to push tissue out of the way—to clear a passage or to gain a view—is to give the robot powerful arms that can push. A less energy-intensive method is to have the patient drink water, which distends the digestive tract enough to allow propeller-driven capsule to maneuver.

DIAGNOSIS/TREATMENT
A capsule can carry a wide range of tools: a spectroscopic camera that sees cells underneath the surface layer of tissue; a clip for taking a tissue biopsy; or a well that holds a dose of medication.



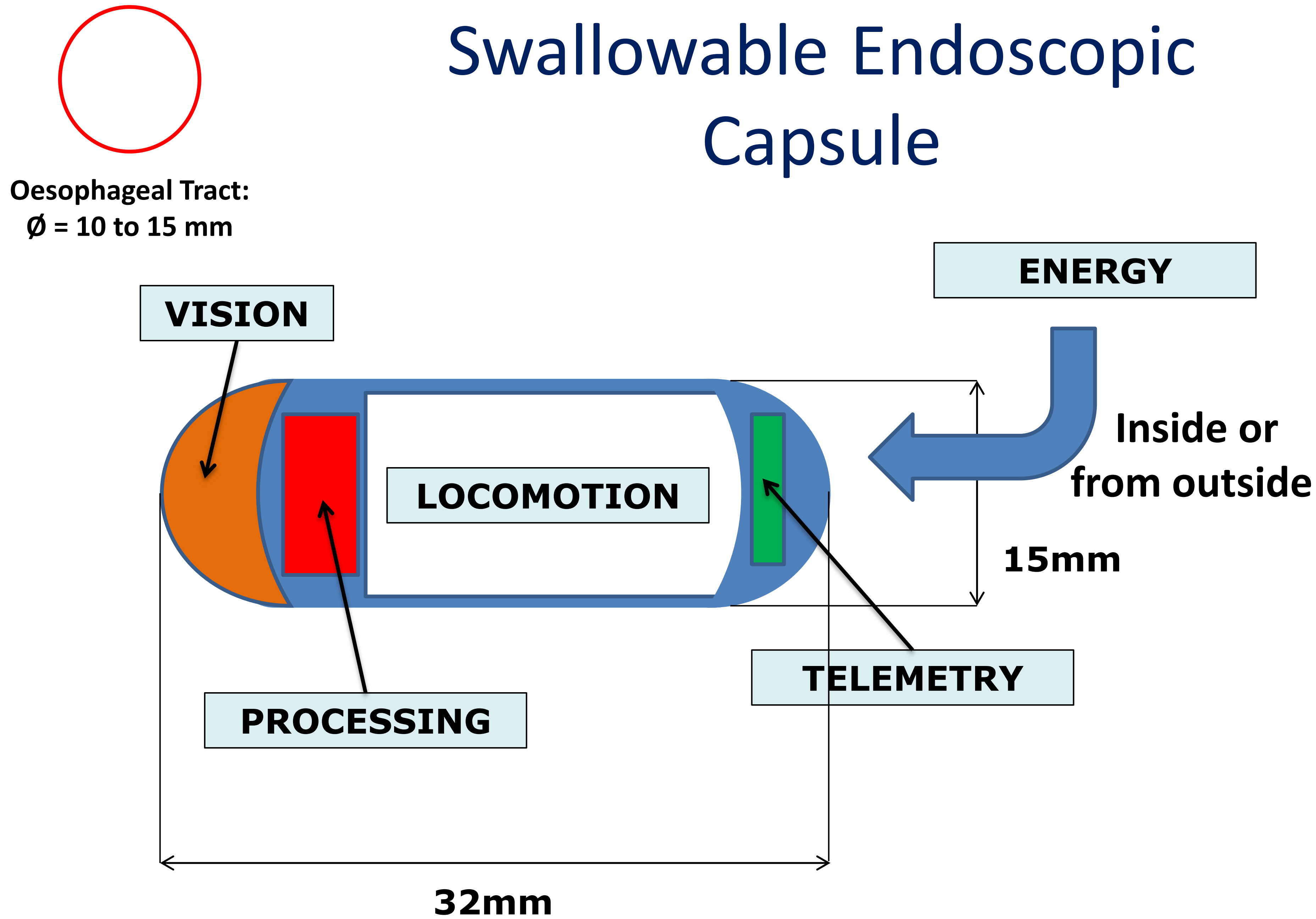

*P. Dario and A. Menciassi Scientific American, August 2010*

# **ACTIVE** WIRELESS Capsule for Endoscopy



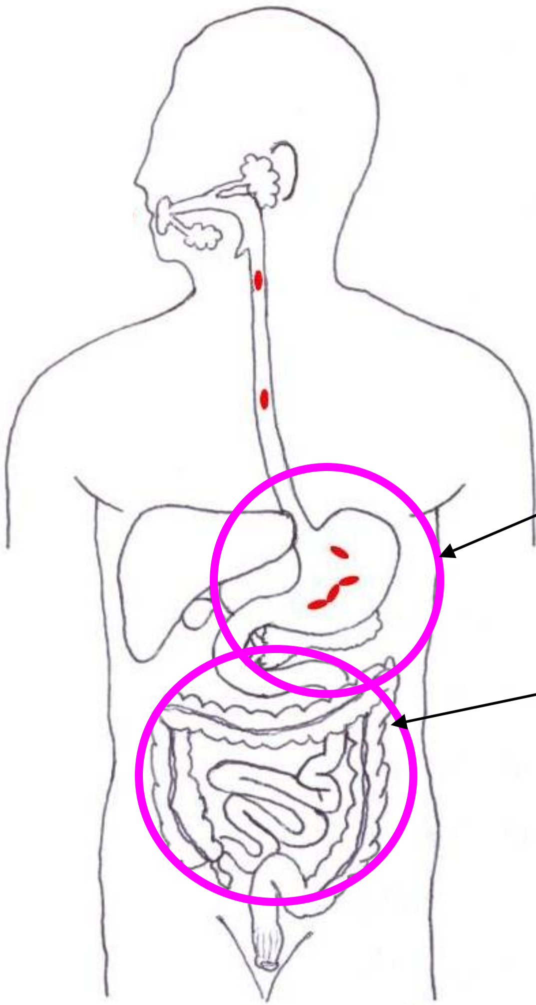

The engineering design challenge: all components MUST fit in a **swallowable** size (**Ø ~12 mm x L~ 32 mm**)

# Swallowable Endoscopic Capsule



# Active Endoscopic Capsules

Examples of locomotion strategies optimized for two targeted districts: stomach and colon

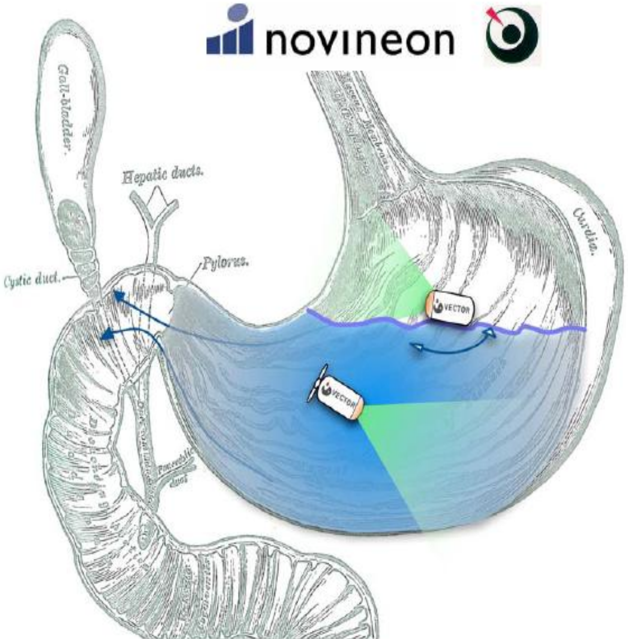


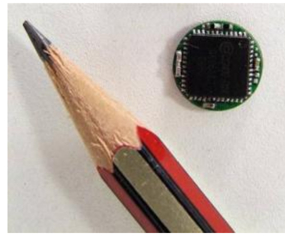
Locomotion in the Stomach:
The capsule **swims** in a liquid environment

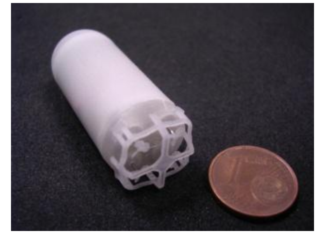
Locomotion in the Colon:
The capsule moves by legs

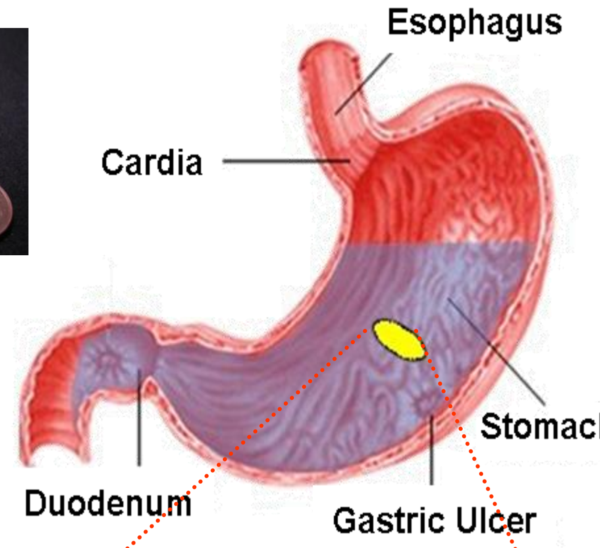
# Wireless Capsule for PAINLESS GASTROSCOPY

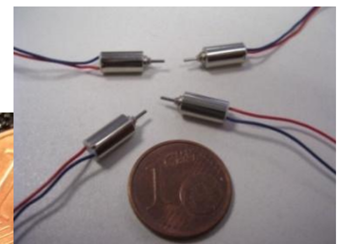
Ingestion of liquid in context with the examination allows to obtain organ distension, thus making possible a low power 3D locomotion in the stomach

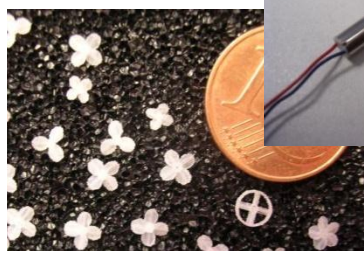


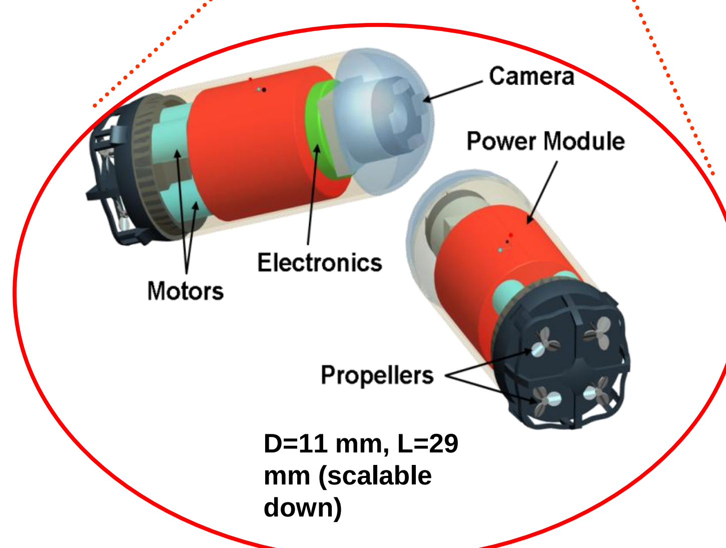







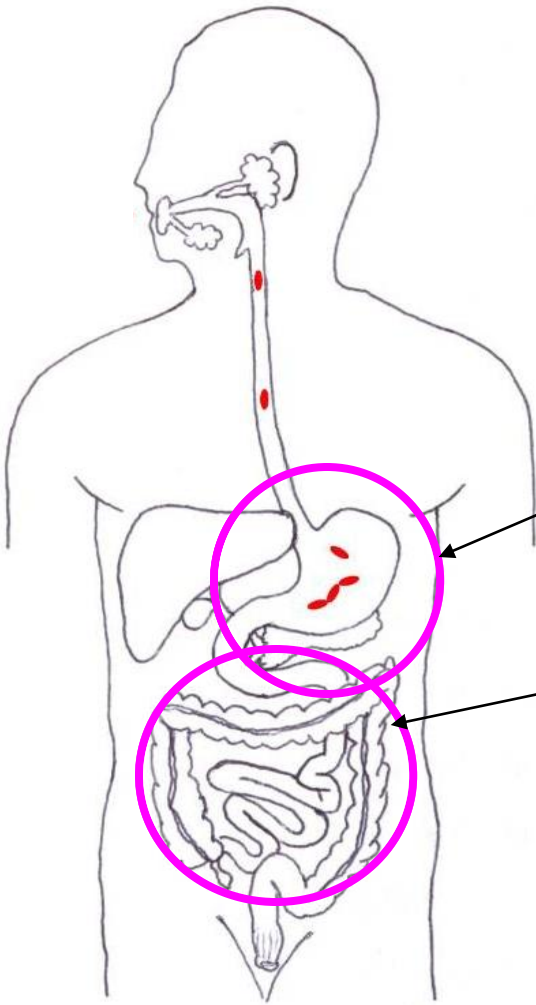








# Active Endoscopic Capsules

Examples of locomotion strategies optimized for two targeted districts: stomach and colon

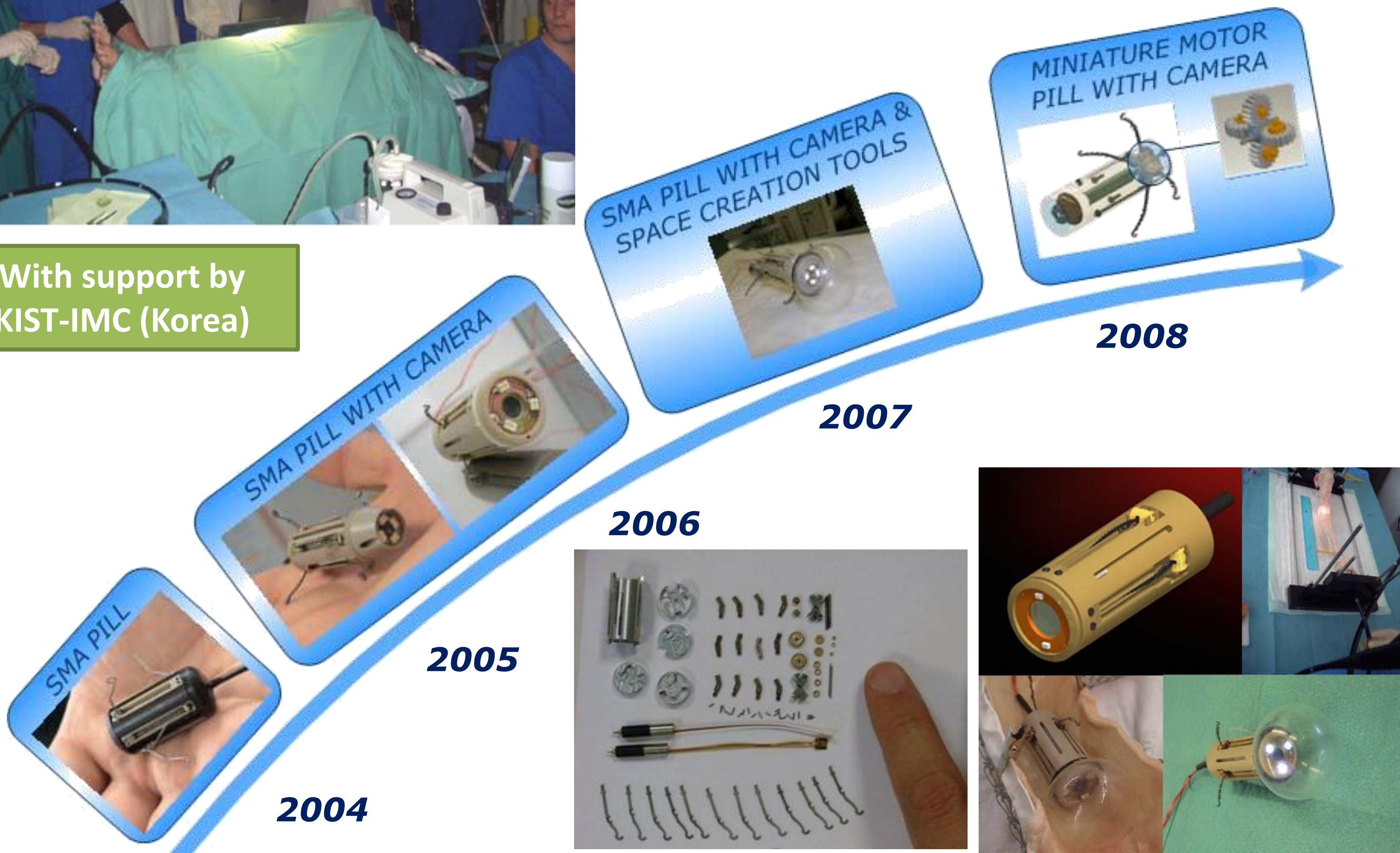


Locomotion in the Stomach:
The capsule **swims** in a liquid environment

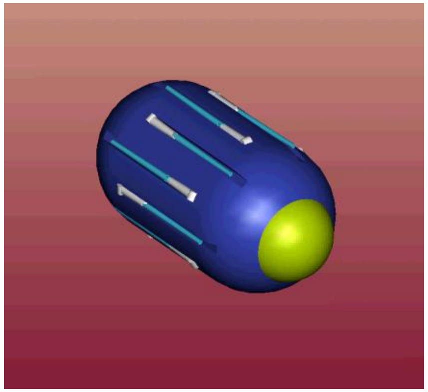
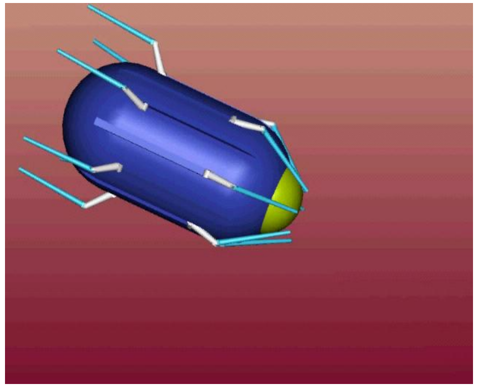
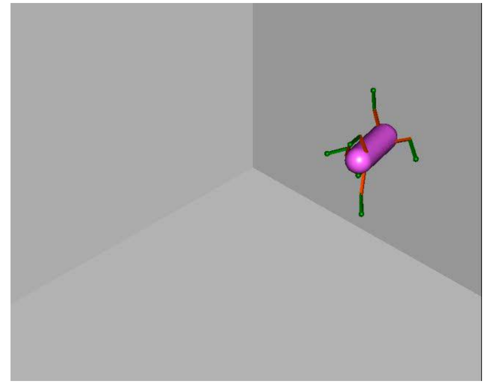
Locomotion in the Colon:
The capsule **moves by legs**

# Developing a Legged Locomotion System

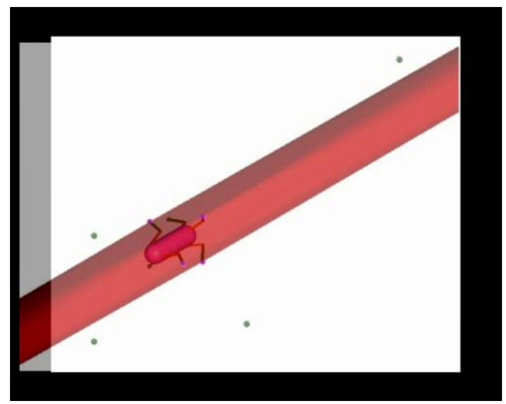
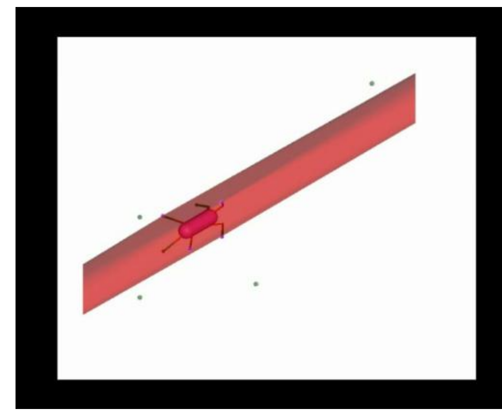
**With support by KIST-IMC (Korea)**



# Legged Endoscopic Capsules for Tubular Organs

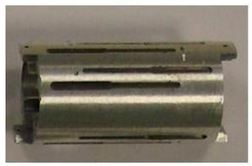

**Features: 12 legs (6 in the front and 6 in the rear part)**
**Dimensions: Φ11 mm; L30 mm**
**Average speed: 5 cm/minute**
**Pulling force: 3.8 N → 0.66 N per leg**


1. A. Moglia, et al. **THE LANCET**, Vol 370 July 14, 2007, pp. 114-116
2. P. Valdastri, R. J. Webster III, C. Quaglia, M. Quirini, A. Menciassi, P. Dario, "*A New Mechanism for Meso-Scale Legged Locomotion in Compliant Tubular Environments*", **IEEE Transactions on Robotics**, 2009, Vol. 25, No. 5, pp. 1047-1057.
3. C. Quaglia, E. Buselli, R. J. Webster III, P. Valdastri, A. Menciassi, P. Dario, "*An Endoscopic Capsule Robot: A Meso-Scale Engineering Case Study*", **Journal of Micromechanics and Microengineering**, 2009, Vol. 19, No. 10, 105007.
4. E. Buselli, P. Valdastri, M. Quirini, A. Menciassi, P. Dario, "*Superelastic leg design optimization for an endoscopic capsule with active locomotion*", **Smart Materials and Structures**, Vol. 18, No. 1, January 2009.

# Optimization of capsule legs design and fabrication in terms of degrees of freedom, number and friction enhancement areas

**The body**
- 25 mm in length
- 12 mm in diameter
- Aluminium
- Fabricated by CNC micromachining



**The motor**
- 2 DC brushless motor (Namiki Precision Jewel)
- 4 mm in diameter
- 17.4 mm in length
- Max output torque:10.6 mN

**The bushings**
- Reduces the friction between the elements
- Fabricated by turning lathe machine

**Main components of the 12-leg capsule**

**The gear**
- Transmits and reduces the motor motion
- Bronze: increases resistance and reduces friction

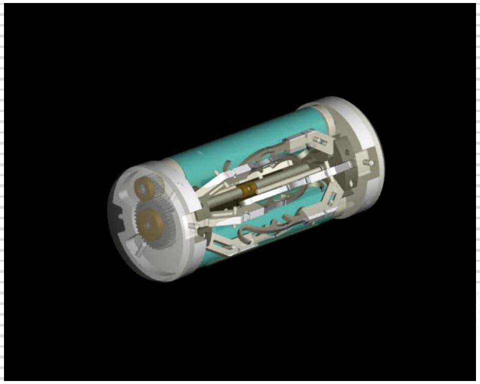
**The legs**
- 10 mm in length
- 0.5 mm in thickness
- Shape Memory Alloy
- Fabricated by Wire Electrical Discharge Machining

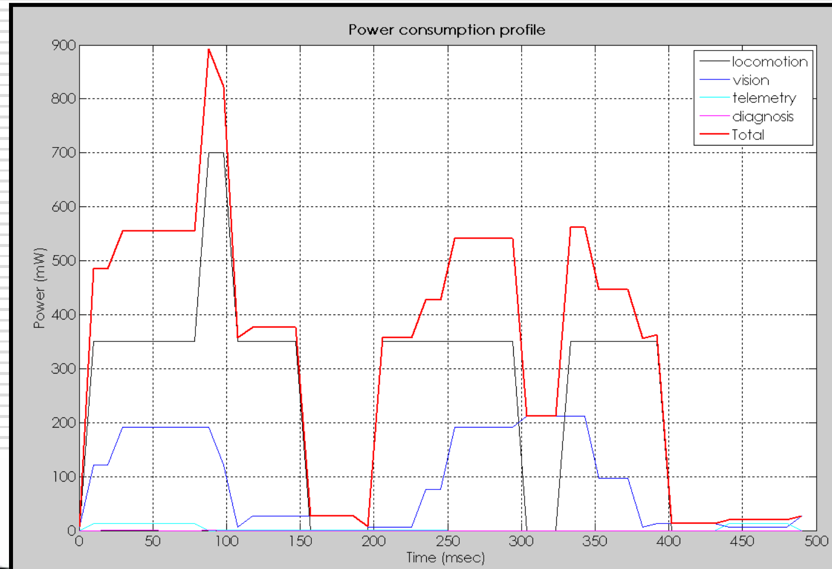
**The leg holder**
- Transmits the motion to the legs
- Fabricated by Electrical Discharge Machine

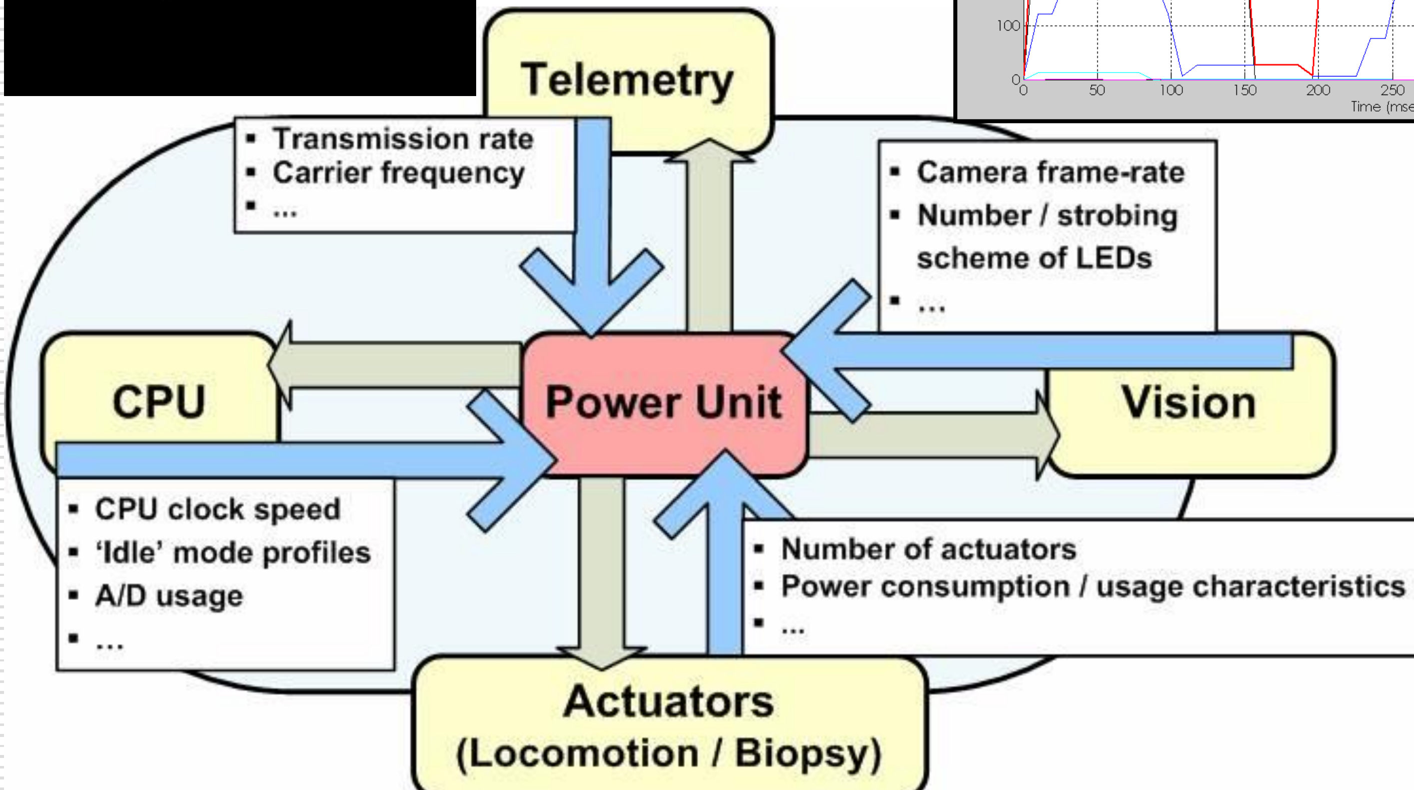
**The nut**
- Transmits the motion to the leg holder.
- Fabricated by CNC micromachining and Electrical Discharge Machine

# The MAJOR problem for active, legged endoscopic capsules

# POWER!

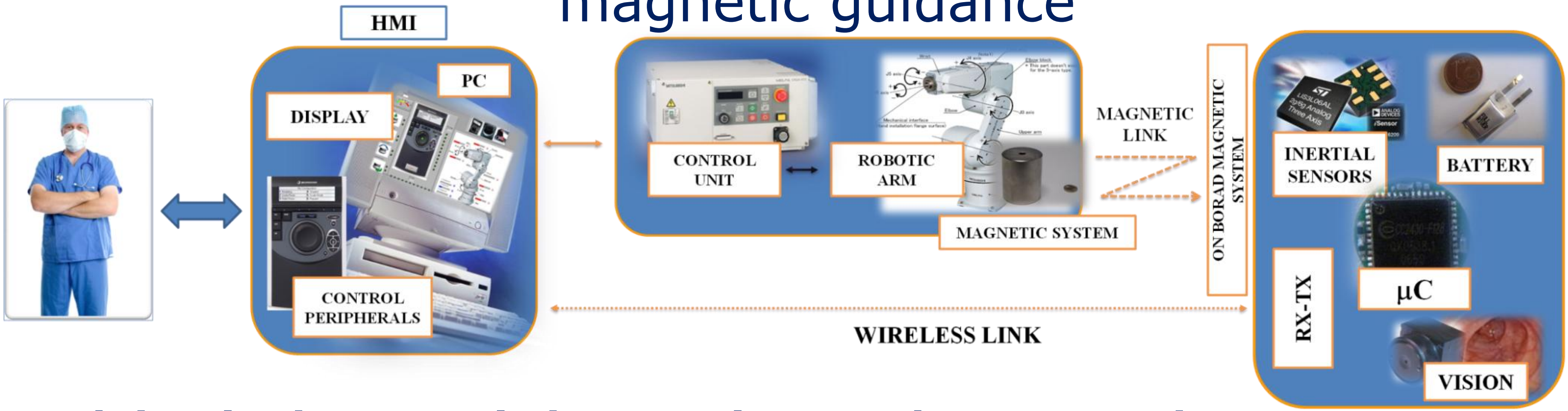




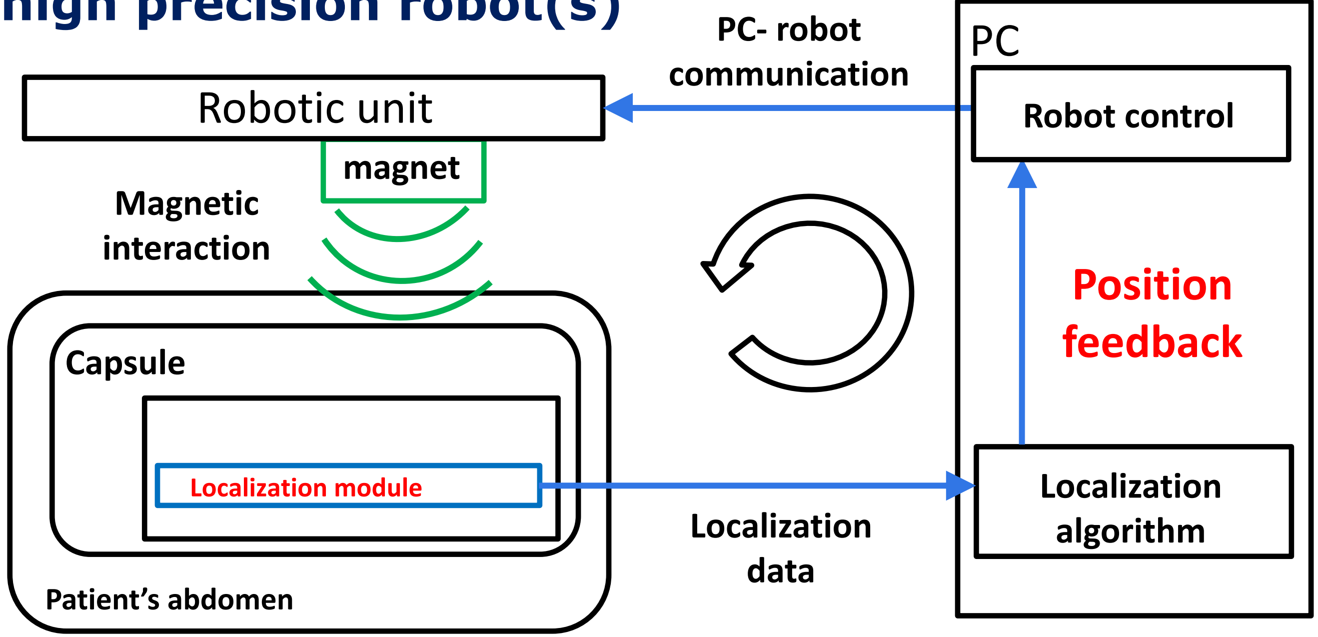




**A legged capsule incorporating state-of-art batteries could only walk for less than 30 minutes along the GI tract**

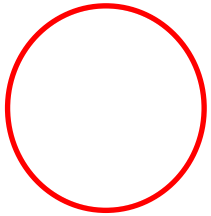
# A possible solution to overcome the energy problem in active capsular endoscopy: robot-assisted wireless magnetic guidance



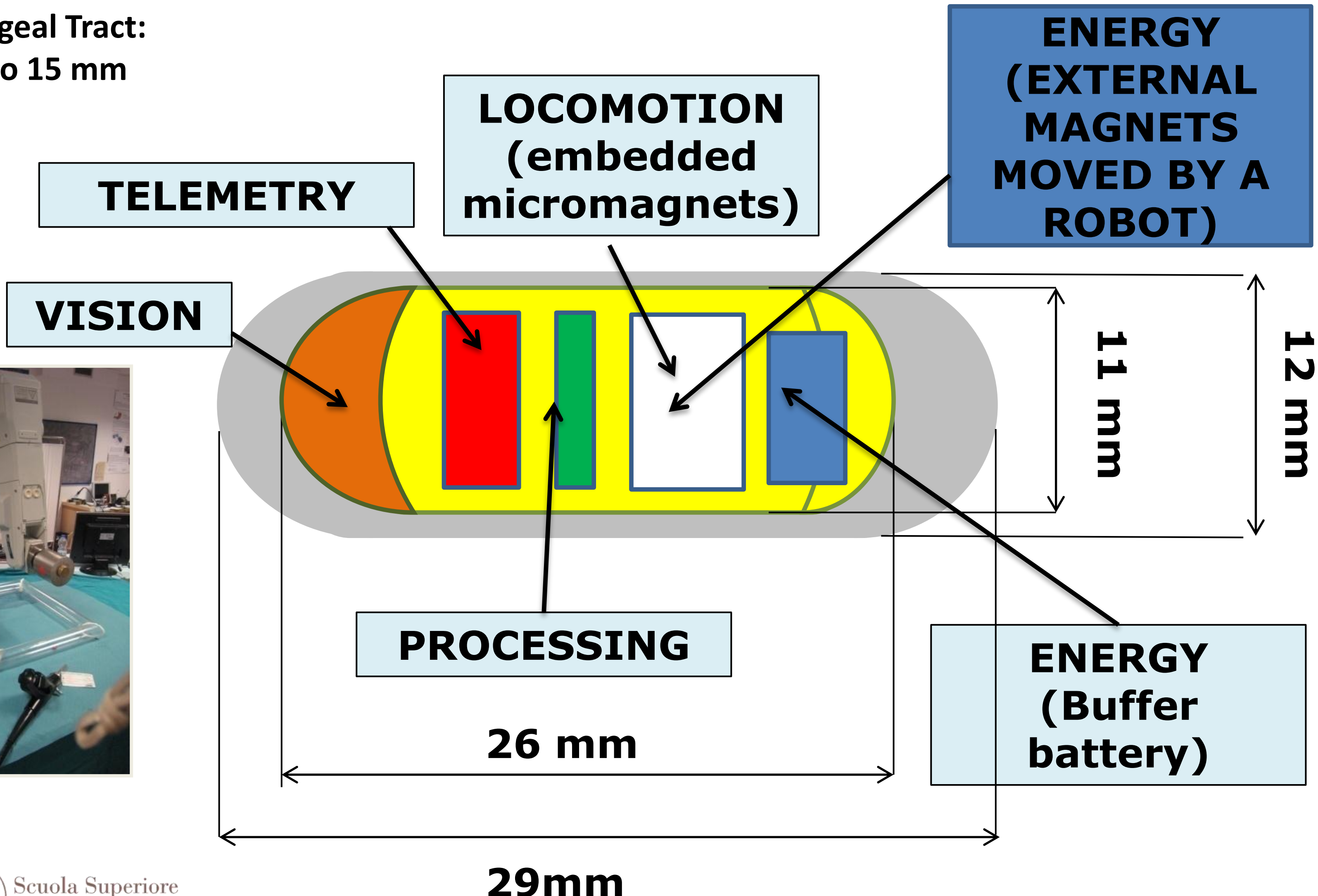

**Endoluminal magnetic locomotion can be extremely precise when the external magnet (s) is/are moved by means of high precision robot(s)**



# Wireless Magnetic Guidance



Oesophageal Tract:
Ø = 10 to 15 mm

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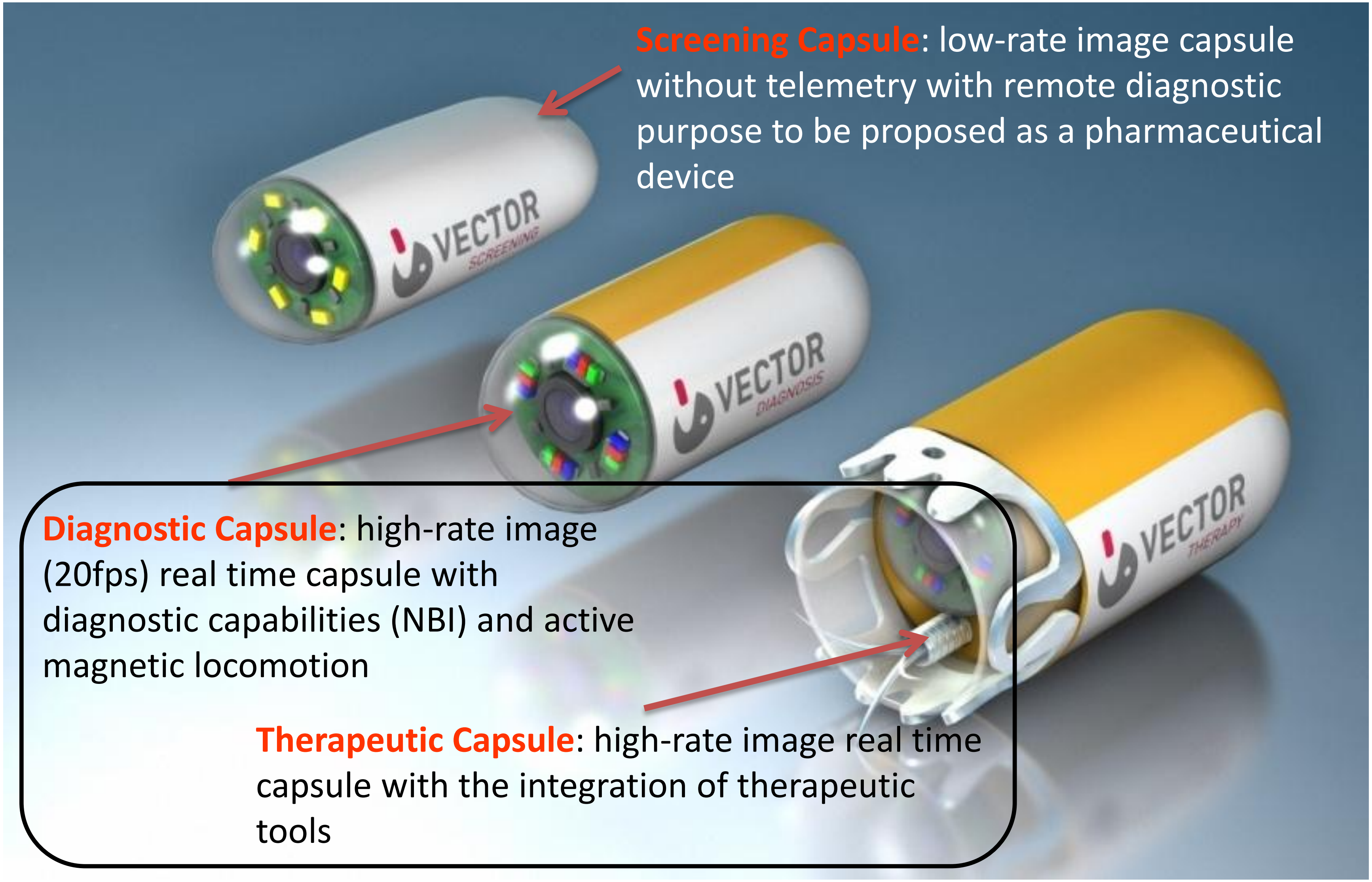
# Swallowable, active endoscopic capsules with additional therapeutic and diagnostic capabilities



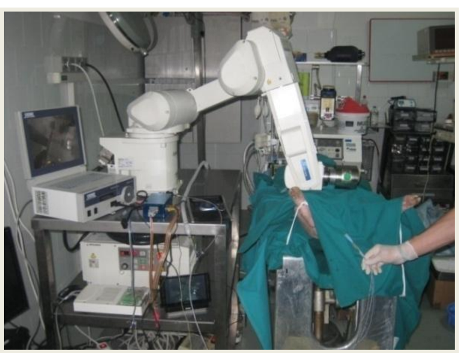

**Screening Capsule**: low-rate image capsule without telemetry with remote diagnostic purpose to be proposed as a pharmaceutical device

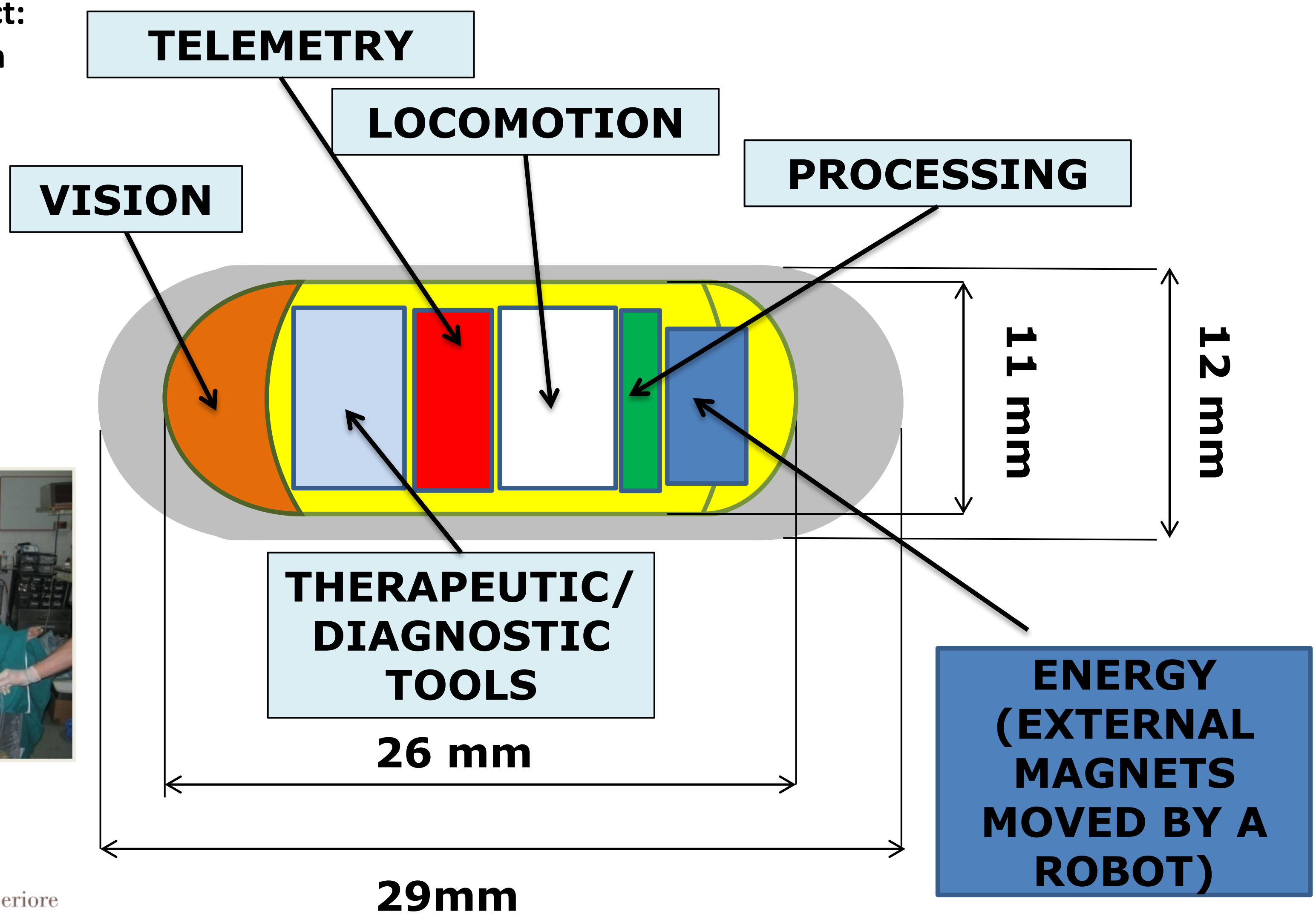
**Diagnostic Capsule**: high-rate image (20fps) real time capsule with diagnostic capabilities (NBI) and active magnetic locomotion

**Therapeutic Capsule**: high-rate image real time capsule with the integration of therapeutic tools

# Swallowable, active endoscopic capsules with additional therapeutic and diagnostic capabilities

**Oesophageal Tract:**
**Ø = 10 to 15 mm**



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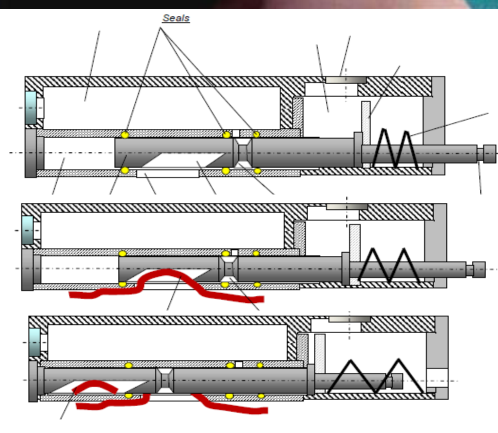
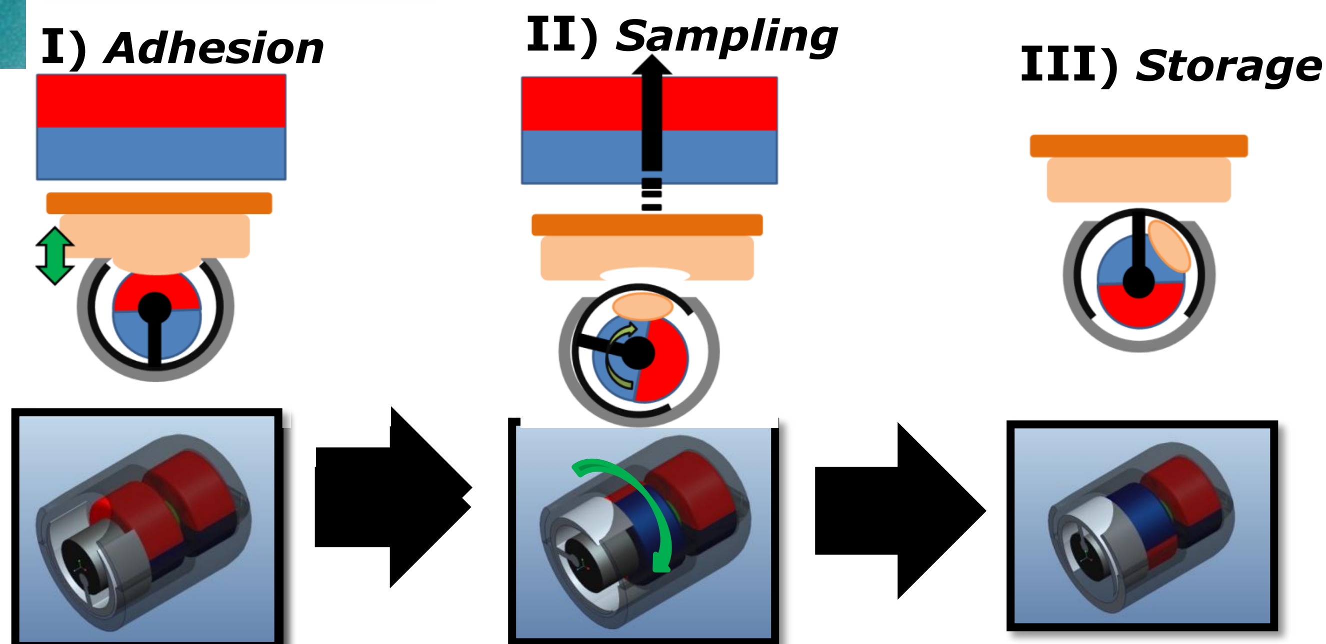
# Capsule for wireless biopsy

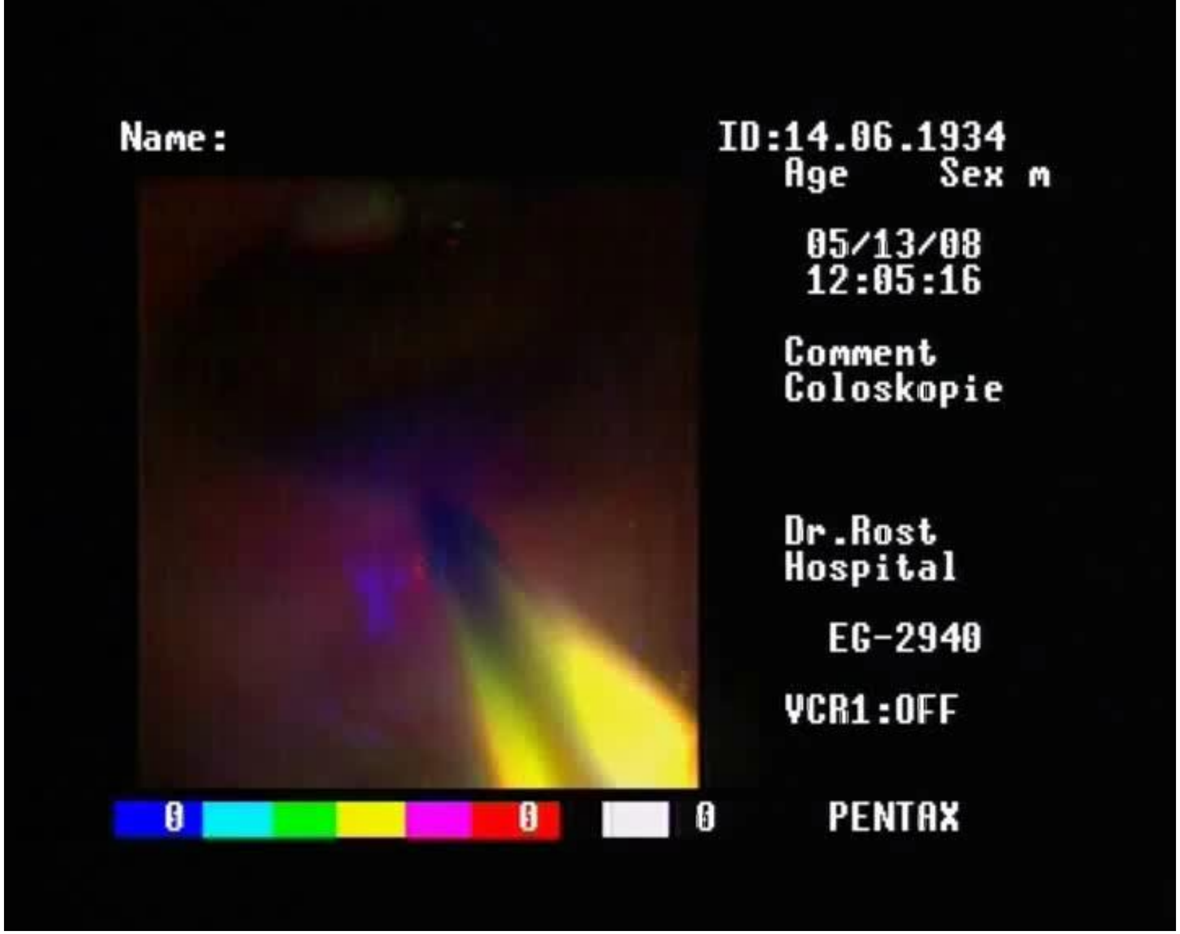

- bistable mechanism
- activation by external magnetic field
- effective adhesion to bowel wall

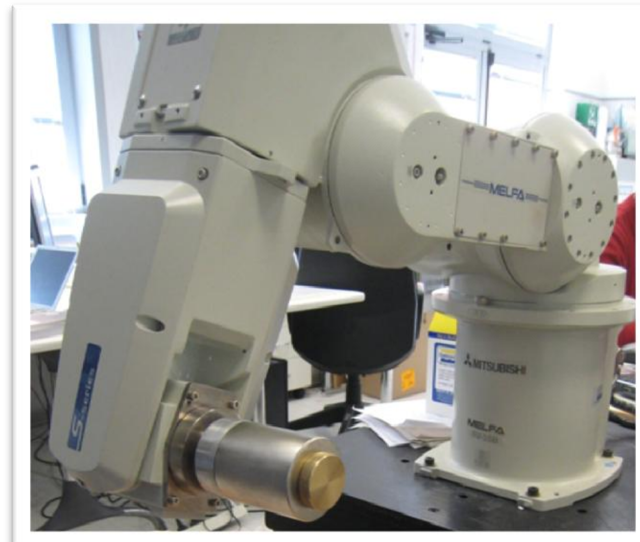


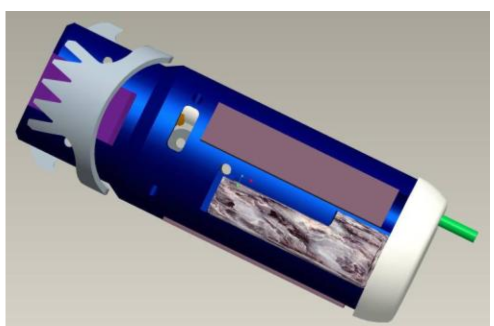

-Capable of 10 biopsies
- 11mm x 25 mm



# Wireless Endoscopic Capsule Releasing a Superelastic Clip



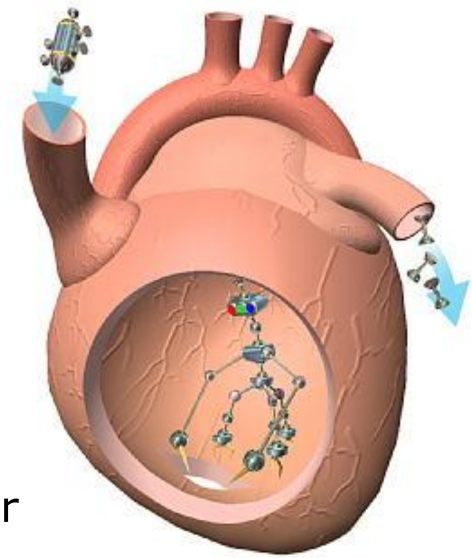



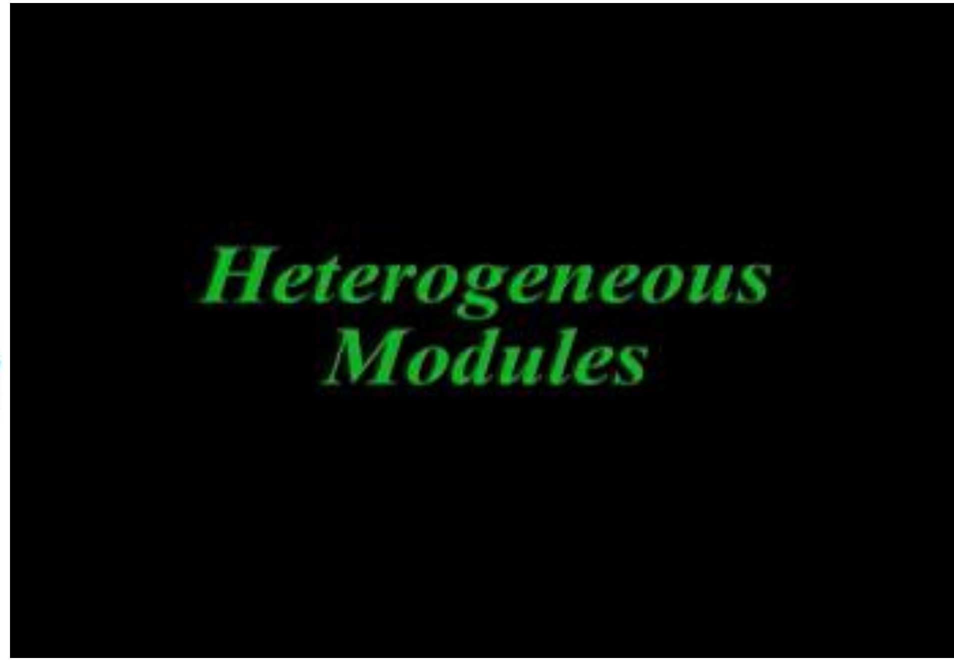


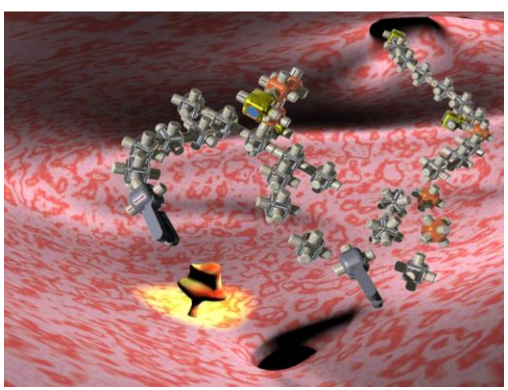
ovesco

# From **Single** Capsules to a **Molteplicity** of Capsules: **Modular** and **Reconfigurable** Surgical Instruments

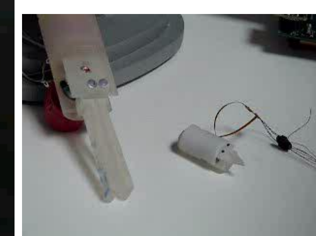
'CEBOT' concept and prototypes, Professor **Toshio Fukuda**, Nagoya, Japan





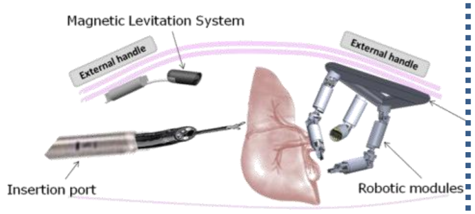



**EU ARES Project**, **P. Dario** (SSSA), **Brad Nelson** (ETH), **Jean-Pierre Merlet** (INRIA) and **Josep Samitier** (UB-CBEN)



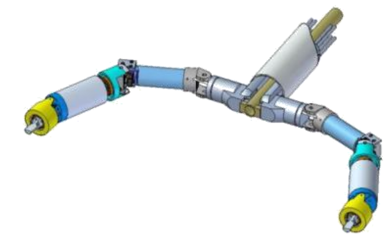
**Kanako Arada**
Waseda University, Scuola Superiore S.Anna and University of Tokyo

# Different Accesses



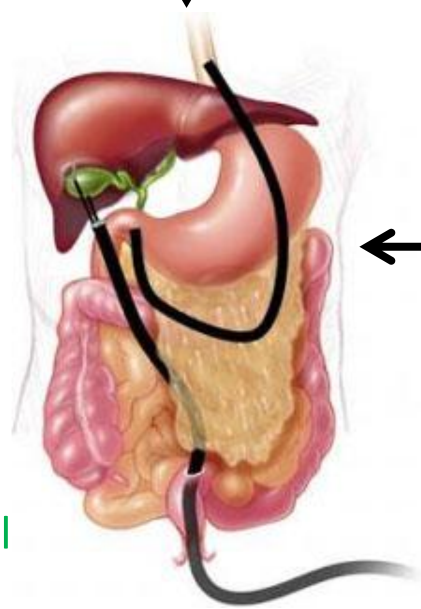

**NOTES (Trans-Oesophageal or Trans-Vaginal**

Abdomen by NOTES/Single Port Access access: Ø = 15 to 32 mm



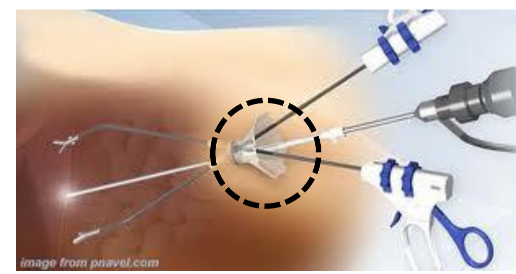
**SINGLE PORT ACCESS (Trans-Umbilical)**

OESOPHAGEAL ACCESS



UMBILICAL ACCESS

TRANSVAGINAL ACCESS




- Small dimension
- Anatomical constraints
- Safety issues

- Totally scarless
- Reduce post-interventional complications

- Fulcrum effect
- Instruments collision
- Triangulation limitation

- Single scarless incision

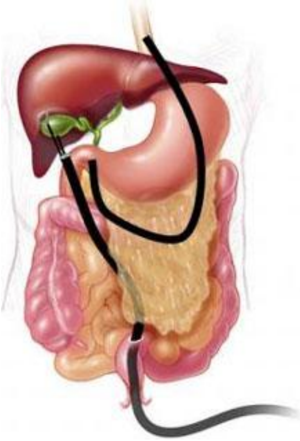
# N.O.T.E.S and **Single Port Laparoscopy**: no visible scars!

**Open** surgery

Abdominal incision **1 year after open surgery**

**Laparoscopic** surgery

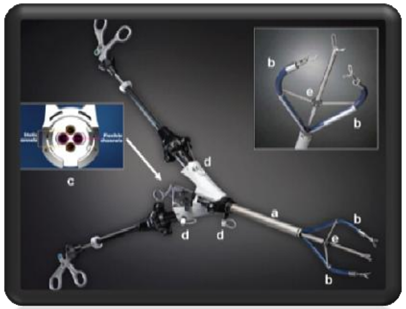
**Laparoscopic scar after 15 days**



Umbilical incision **3 weeks after single-port nephrectomy** (kidney removal) leaves little to no scarring

# Single Port (Incision) Laparoscopy and NOTES require new surgical instruments and robots

**DDE System**
(Boston Scientific, Boston, USA)

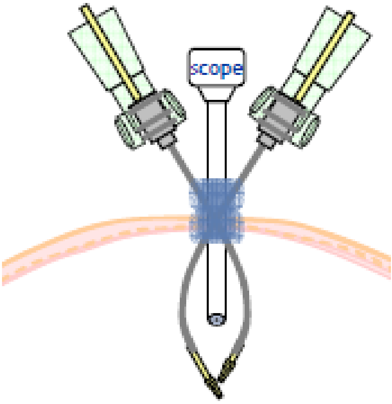


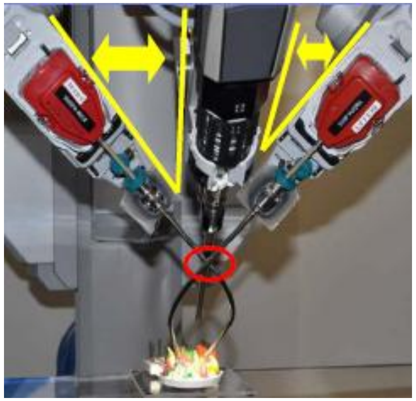
**SPIDER Surgical System**
(TransEnterix, NC, USA)

**Anubis**
(Karl Storz, Tuttlingen, Germany)

**EndoSamurai**
(Olympus, Tokyo, Japan)

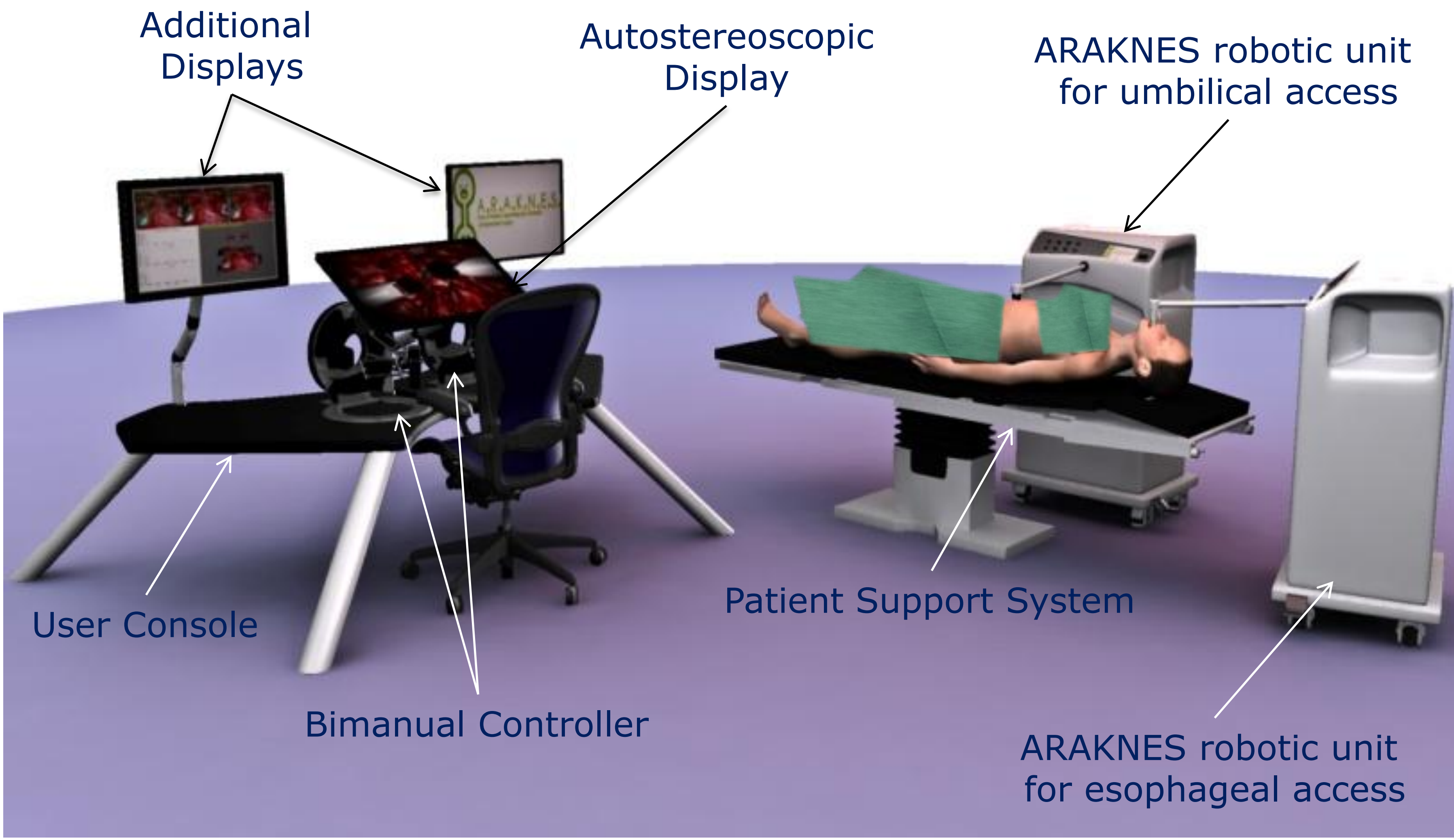
- Using *da Vinci Si* system with 8.5mm 3D HD endoscope.
- Curved Instrument Cannulae.
- 5mm, non-wristed, semi-rigid instruments.



**Research SILS robot: Intuitive Surgical prototype for single port surgery**

# The ARAKNES (Array of Robots Augmenting the KiNematics of Endoluminal Surgery) robotic platform for Single Port and NOTES Surgery

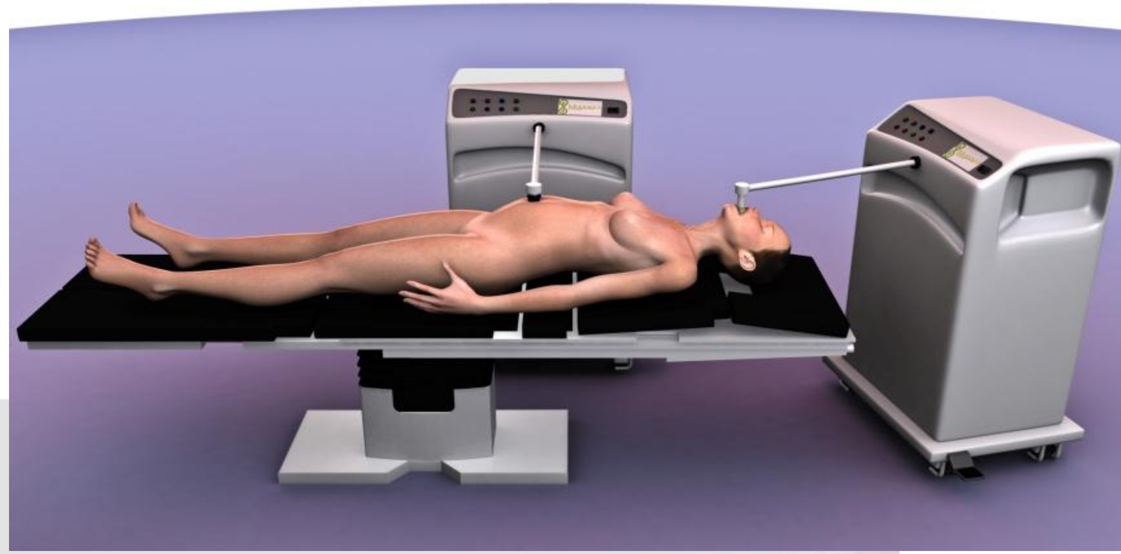


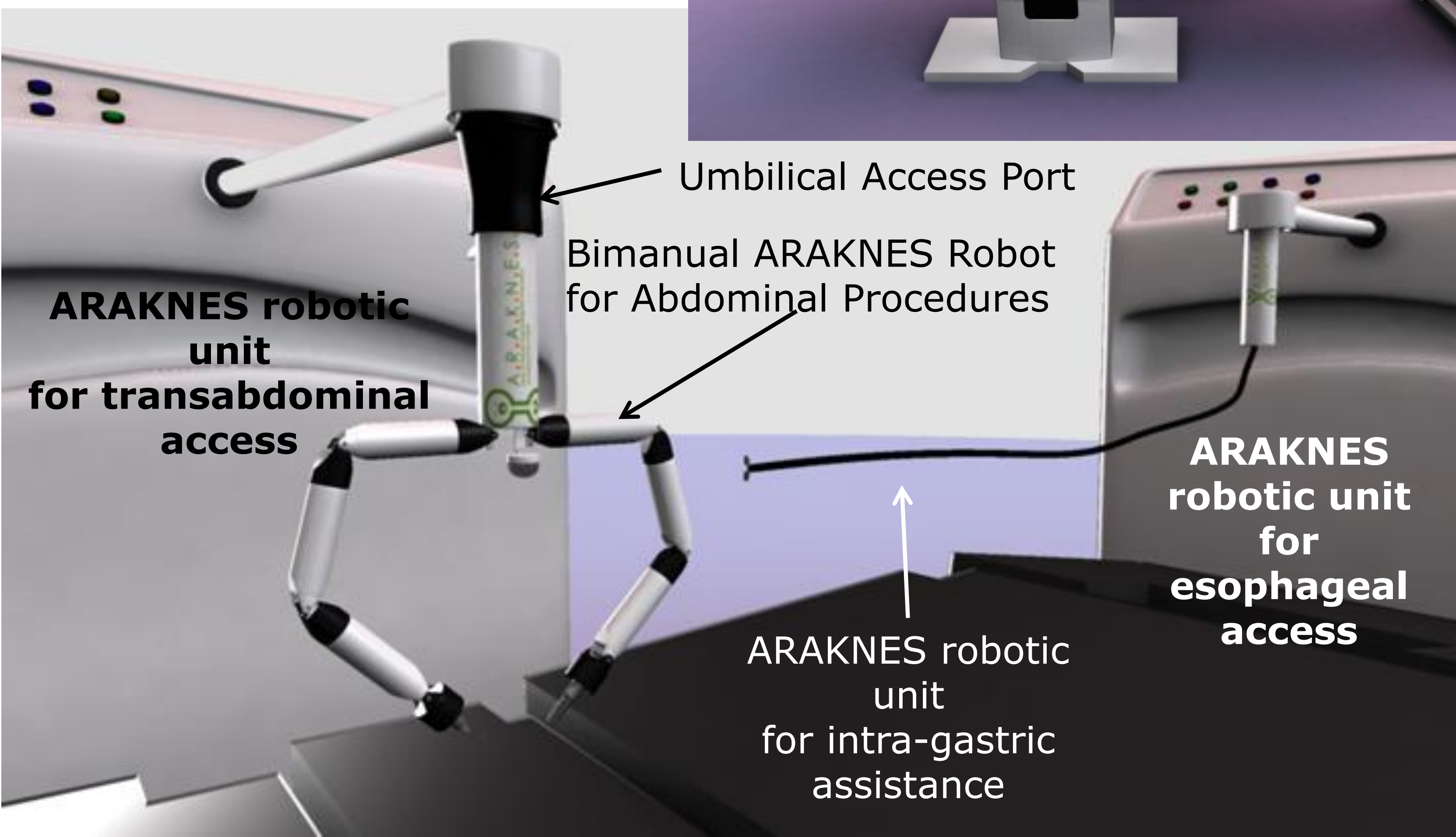

**ARAKNES EU-Project 2008-2012**

**www.araknes.org**

# ARAKNES Hybrid Configuration

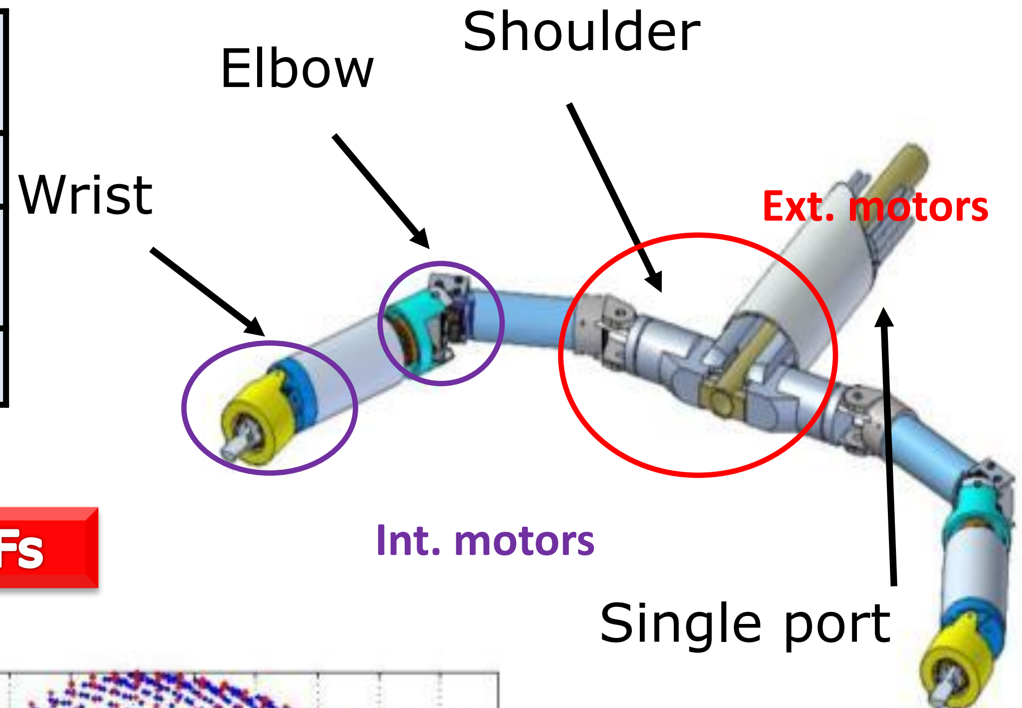
**Double access approach** (the "**HYBRID" APPROACH**), from the oesophagus **and** through the abdomen





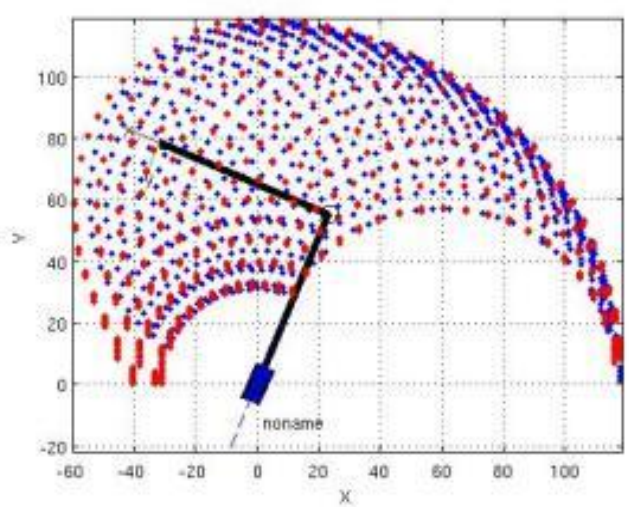
# The ARAKNES Internal Bimanual Manipulator
## SPRINT robot - Single-Port lapaRoscopy bImaNual roboT

| | |
|---|---|
| Arm maximum diameter: | 18 mm |
| Tip force: | 5 N |
| Joint rotational speed: | 360-540 deg/s |
| Total lenght: | 130 mm |




**For each arm:** **14 internal DOFs**

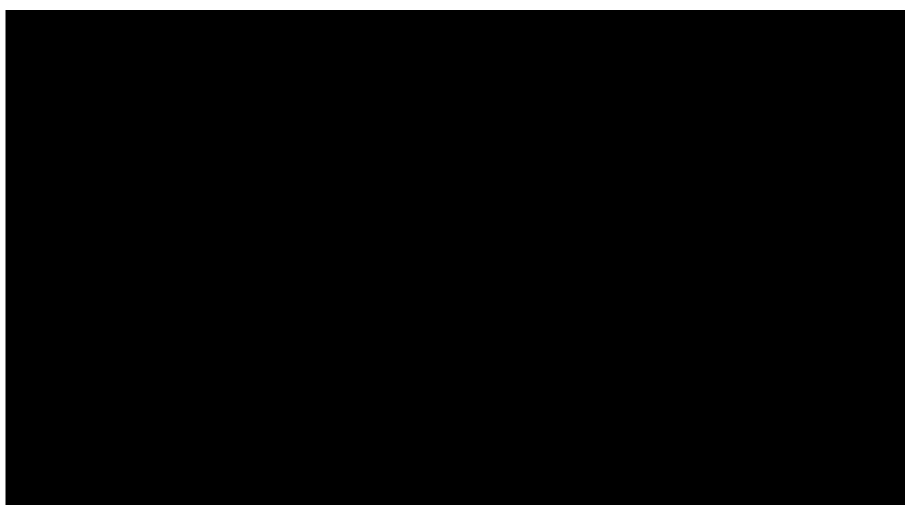
- 2 DOFs actuated by **external** motors
- 4 DOFs actuated by **on-board** motors
- 1 DOF Gripper actuated by an **external** motor

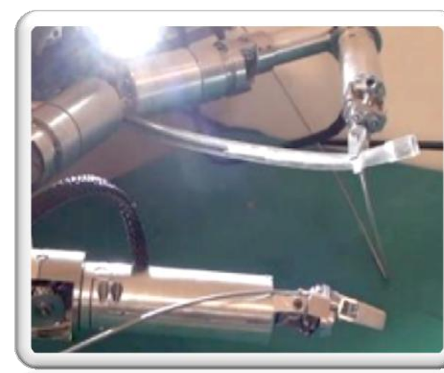


# SPRINT Robot: Mechanisms

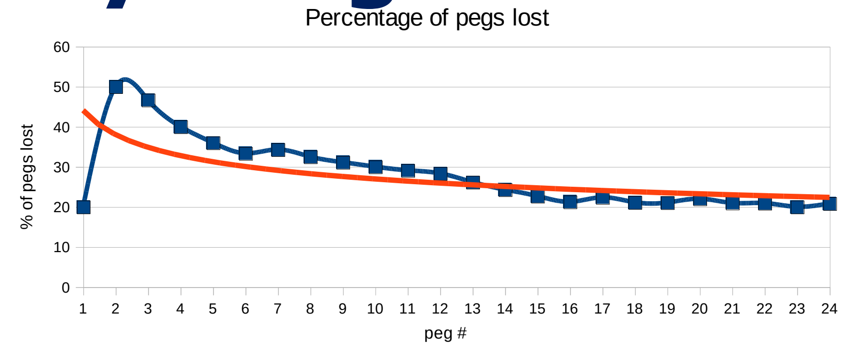
# System Delivery Through the Introducer

**The SPRINT introducer enables simple changes of tools and the insertion of additional sensors**

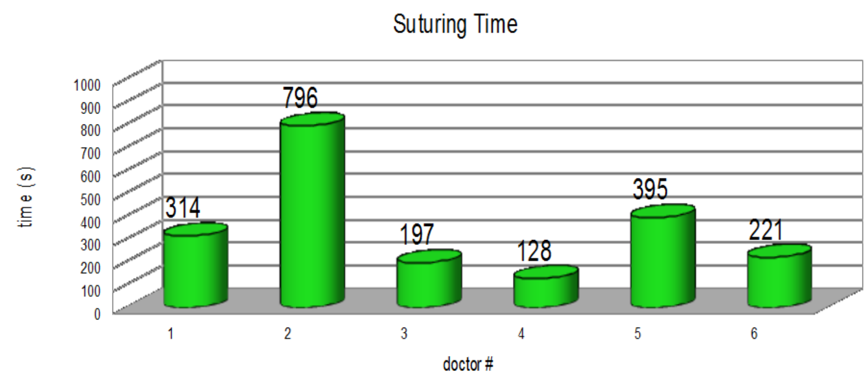




# Characterization by Surgeons




## Peg Transfer Task

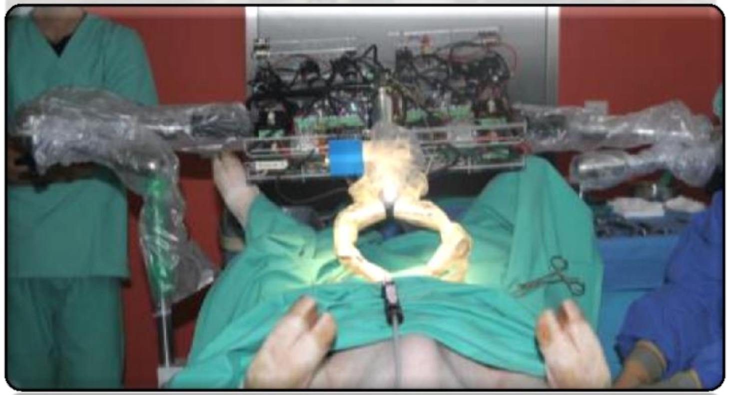



## Suturing Task

| SURGEON Background | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| AGE | 46 | 49 | 37 | 51 | 70 | 47 |
| SPECIALIZATION | General Surgery | Urology | General Surgery | General Surgery | Laparoscopic Surgery | Gynecology |
| # OF YEARS OF EXPERIENCE | 21 | 20 | 12 | 25 | >30 | 20 |
| EXPERIENCE WITH ROBOTIC ASSISTED LAPAROSCOPY | YES | YES | YES | YES | YES | YES |
| EXPERIENCE IN SINGLE PORT LAPAROSCOPY | YES | NO | YES | YES | YES | YES |

G. Petroni, M. Niccolini, A. Menciassi, P. Dario, A. Cuschieri, *A novel intracorporeal assembling robotic system for single-port laparoscopic surgery,* Surgical Endoscopy, 2012

# SPRINT Robot: In-Vivo Tests



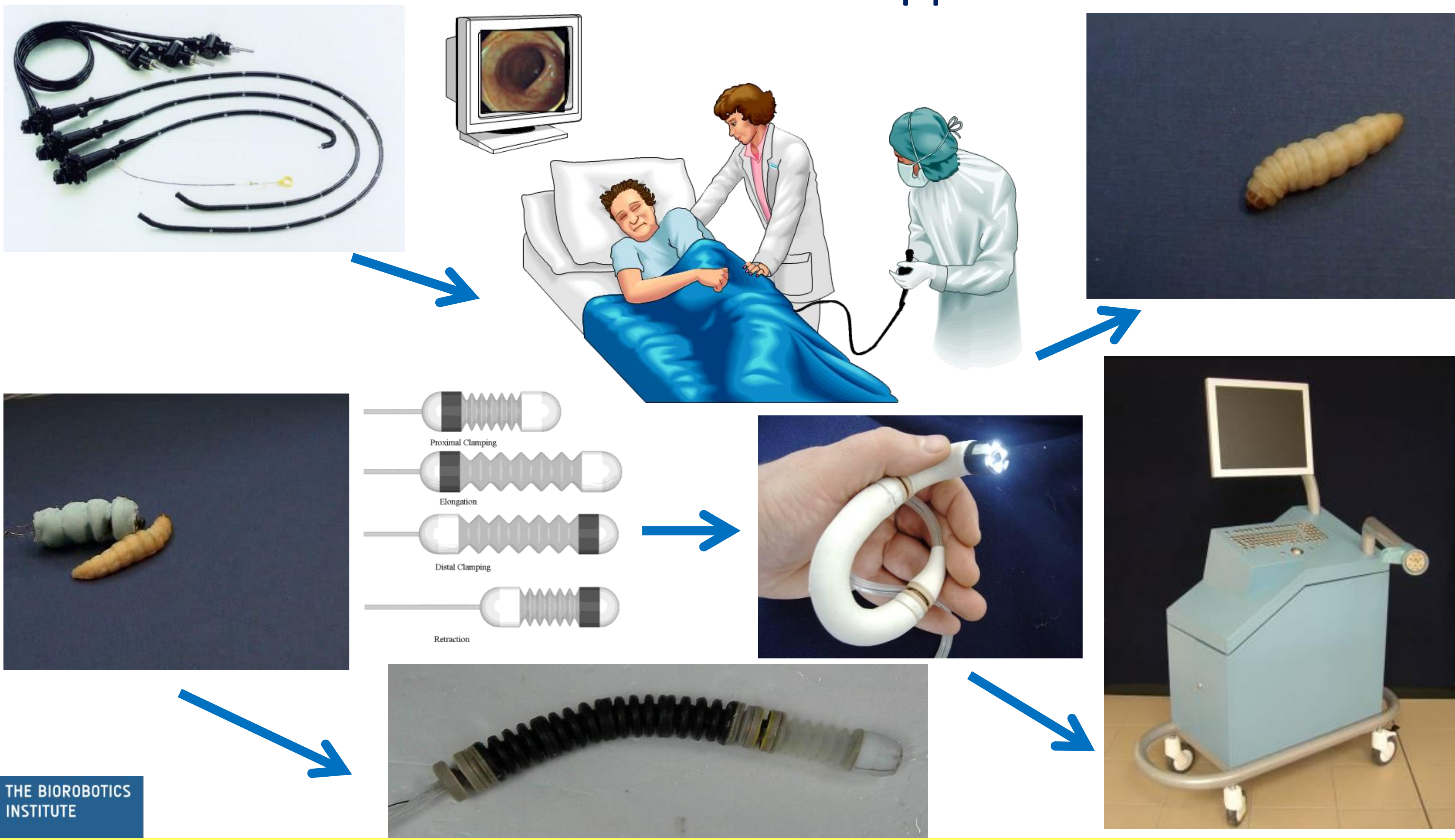
G. Petroni, M. Niccolini, S. Caccavaro, C. Quaglia, A. Menciassi, S. Schostek, G. Basili, O. Goletti, M. Schurr, P. Dario, *A novel robotic system for single-port laparoscopic surgery: preliminary experience,* Surgical Endoscopy, 2012 [Submitted]

# New Approaches to the Design of Mechanisms for Surgical Instrumentation

- **Novel mechanisms needed in the miniature domain (from 20 to 1 mm and smaller) for:**
  - dexterous **locomotion** inside the body
  - precise **manipulation** inside the body
  - device **release** inside the body
  - **non-contact** kinematics
- Current approach, despite being promising, suffers from limitations
- Bio-inspired design may offer useful hints



# Bioinspired design of a PAINLESS colonoscopy system. From scientific investigation to engineering modelling and design, to industrial and clinical application

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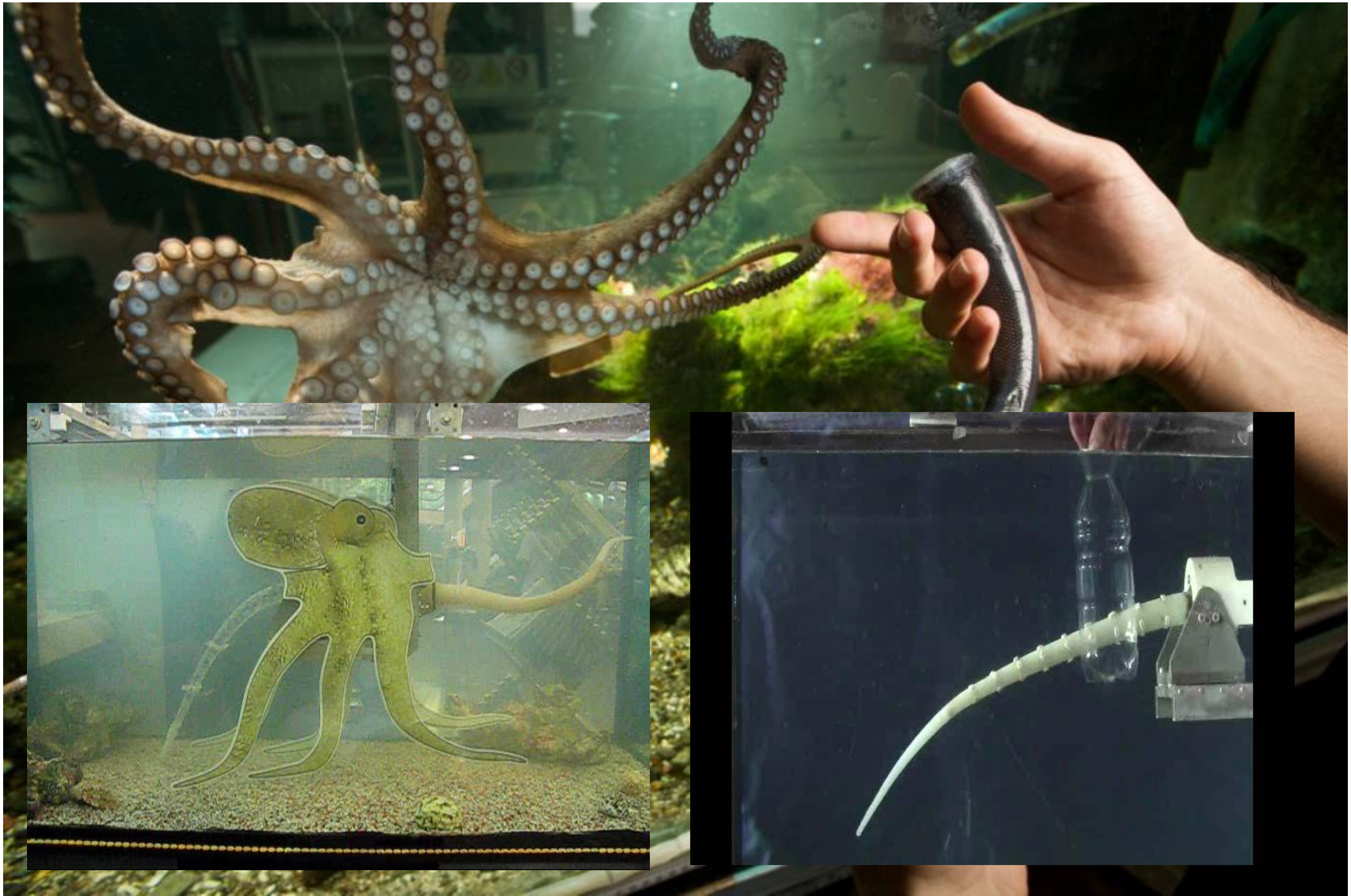
**A. Menciassi, P. Dario: "Bio-inspired solutions for locomotion in the gastrointestinal tract: background and perspectives", Philos. Transact. Roy. Soc. A Math. Phys. Eng. 361(1811), (Oct. 2003), pp. 2287-2298.**

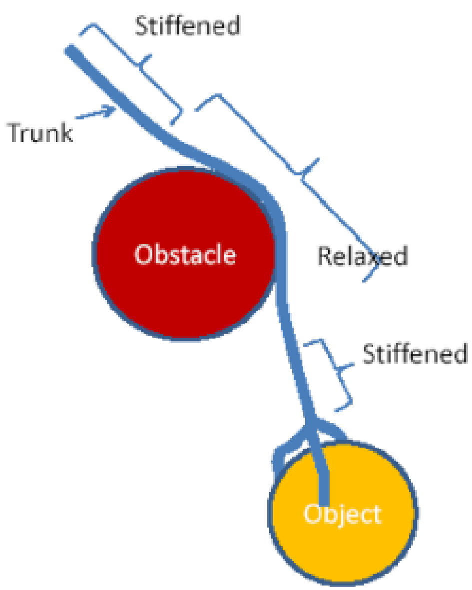
# The biomimetic approach

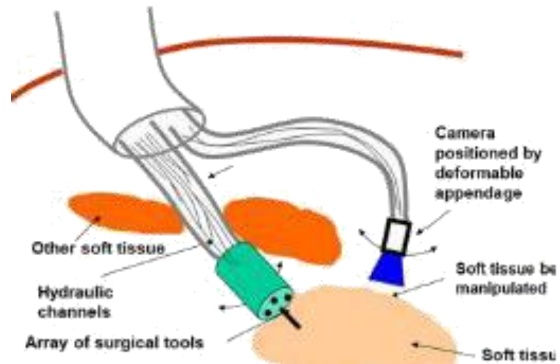


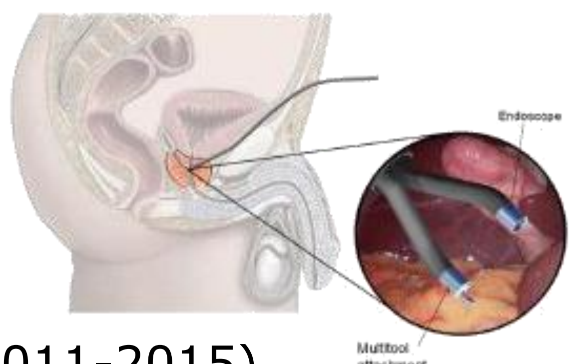
**OCTOPUS project (2008 - 2012)**

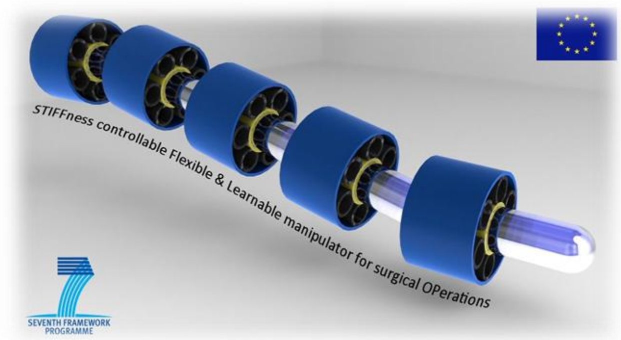
# From Biorobotics Science to BioRobotics Engineering

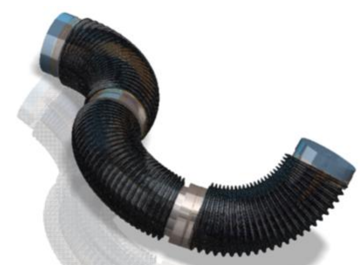
Target: A soft robotic arm that can ***squeeze*** through a standard 12mm diameter Trocar-port, *reconfigure* itself and *stiffen* by hydrostatic actuation to perform compliant force control tasks while facing unexpected situations



STIFF-FLOP Project (2011-2015)

EUROPEAN COMMISSION European Research Area

SEVENTH FRAMEWORK PROGRAMME

**STIFF-FLOP** STIFFness controllable Flexible and Learn-able Manipulator for surgical OPerations

KING'S College LONDON University of London

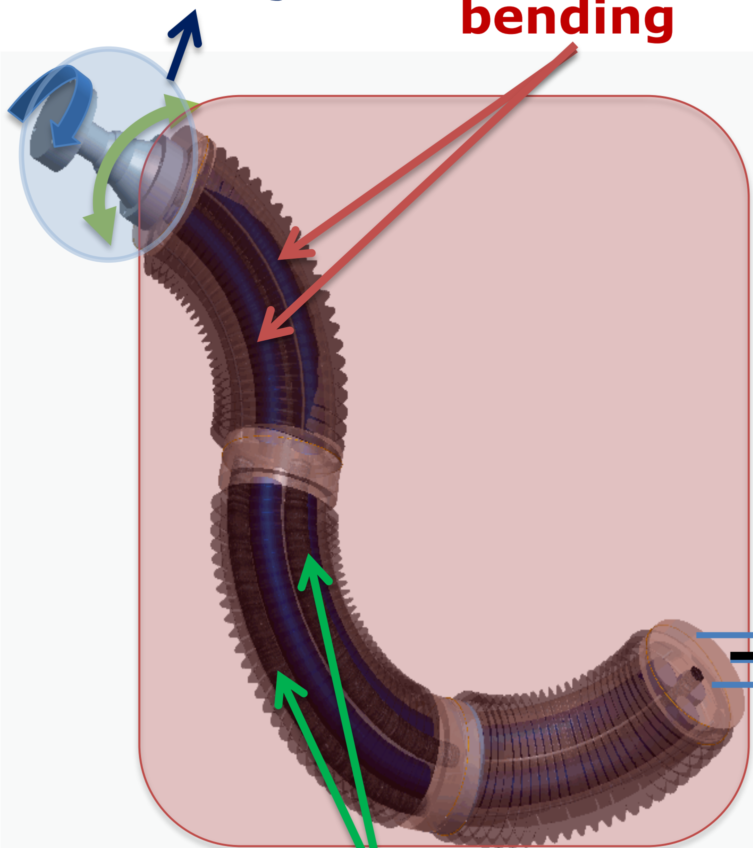

KING'S College LONDON

University of London

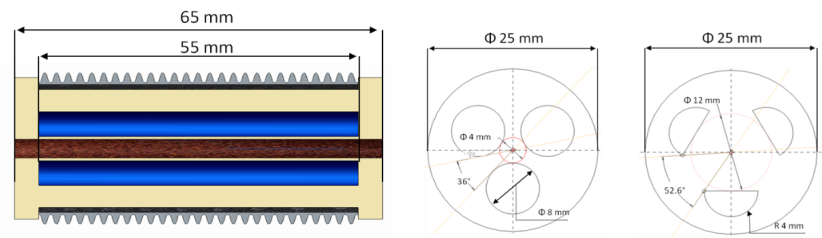
http://www.stiff-flop.eu/index.php/home

STIFF flop

# The STIFF-FLOP Arm: architecture




## - CURRENT DIMENSIONS -

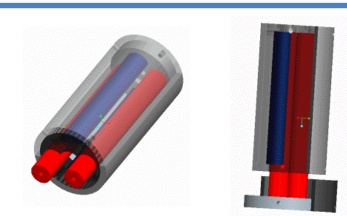



## - MATERIALS -

- Silicone Unit: 0030 EcoFlex
- Sheath: PET
- Stiffening chamber membrane: Latex
- Granular matter: Coarse Coffee

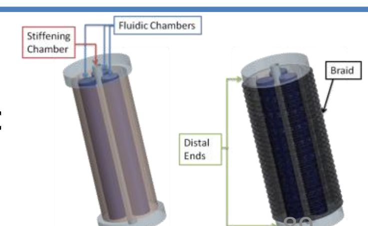
## - FABRICATION PROCESS -

3 phases silicone curing in aluminium mould



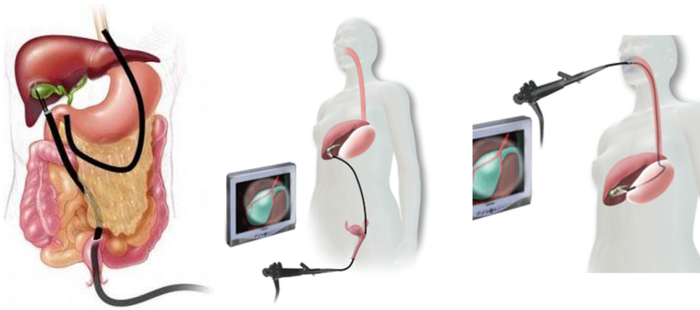
## - OVERALL STRUCTURE -

3 chambers for fluidic Actuation, Stiffening, etc



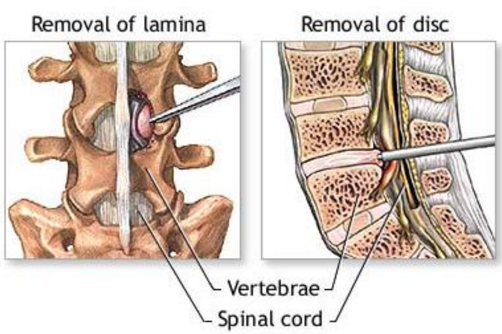
# The Quest for Miniaturization

ABDOMINAL SURGERY



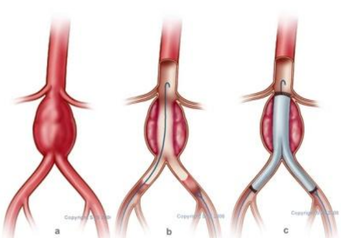
**NOTES (Natural Orifice Translumenal Surgery) SURGERY**
**Reaching** the target (esophagus diameter from **10 to 15 mm**)
**Bringing** actions to the target

NEURO ENDOSCOPY




**Challenges for neuro endoscopy:**
**Reaching** the target (spinal cord diameter: **4 to 1.5 mm**)
**Bringing** actions to the target

VASCULAR SURGERY



**Challenges for vascular therapy:**
**Reaching** the target (Vascular system diameter: **8 to 5 mm**)
**Bringing** therapeutic actions to the target

# ARAKNES Research Platform: an Overview

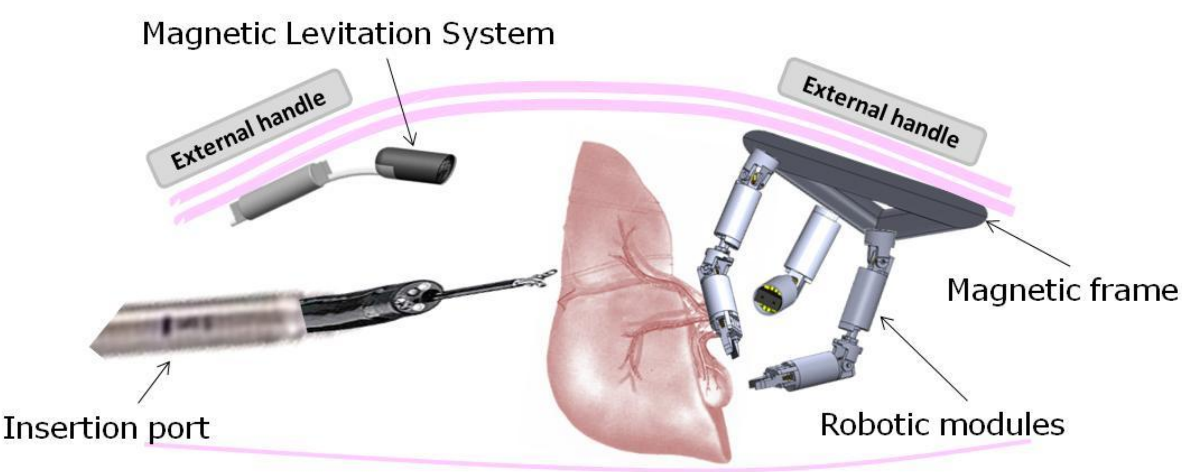
# ARAKNES Research Platform

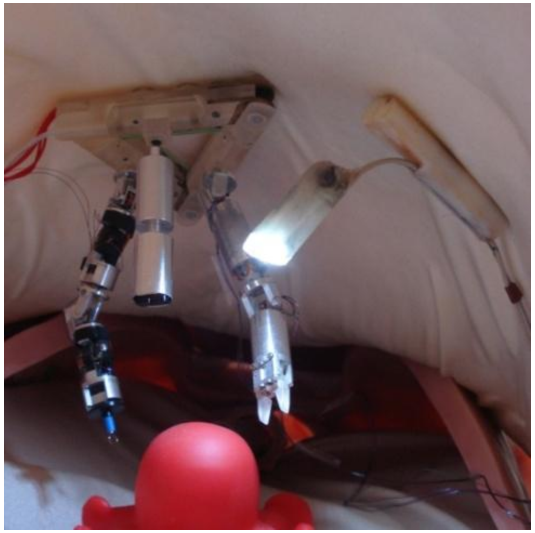
**Intuitive Surgical's heuristic expression of patient value**

$$\text{Patient Value} = \frac{\text{Efficacy}}{\text{Invasiveness}^2}$$

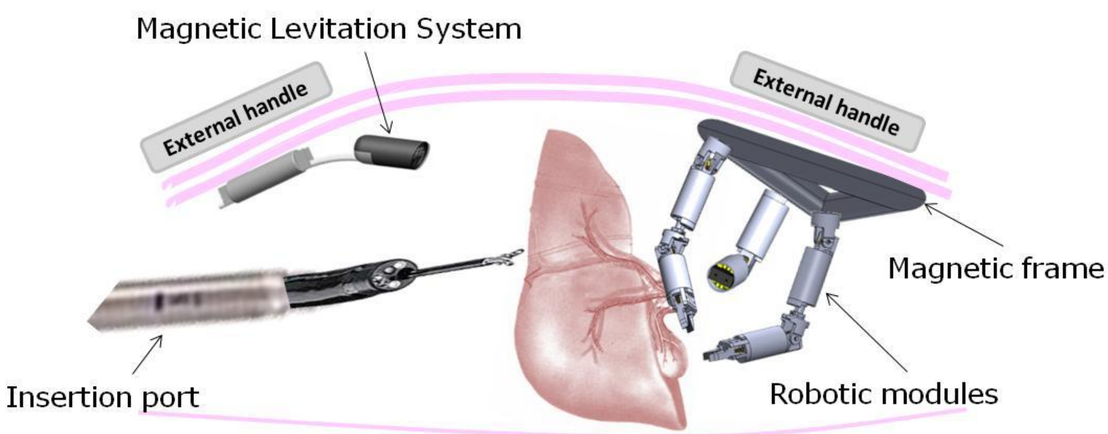
**GOAL for the ARAKNES Research Platform:**
**Robotic Surgery through a single 12-15 mm trocar**

Merging **miniaturized robot design** with **industrial robotic control** by means of a **trans-abdominal magnetic link**



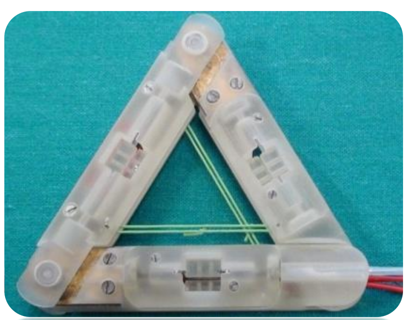



# ARAKNES Research Platform

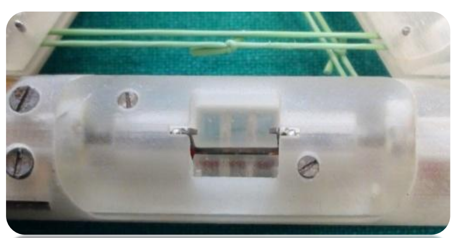



- ***Anchoring frame*** (3 DoFs, length 186 diameter 14)
- ***Docking/Undocking mechanism***
- Modular robotic units
  - **4+EE Dofs Manipulator** (length 80 diameter 12)
  - **2 DoFs Retractor** (length 48 diameter 12)
  - **2 DoFs Stereoscopic Camera** (length 60 diameter 12)
- Magnetic levitation camera ***MLC*** (4 DoFs)

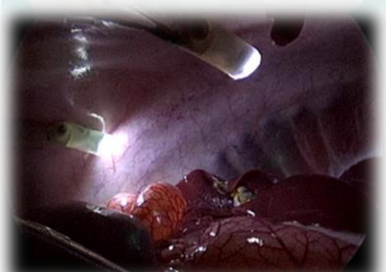
**ANCHORING FRAME**



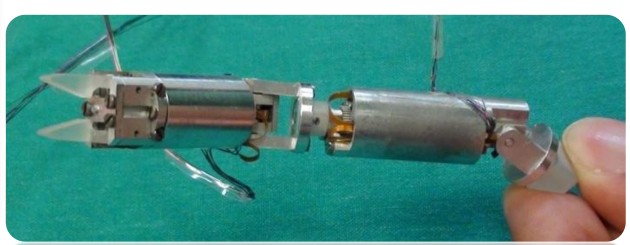
**DOCKING/UN-DOCKING MECHANISM**



**MLC**

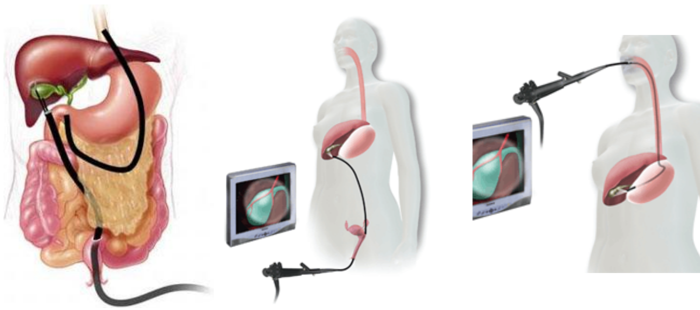


**MODULAR ROBOTIC UNITS**



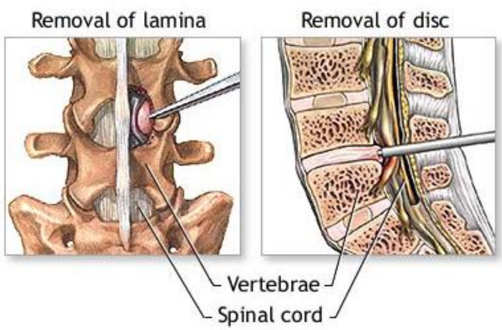
# The Quest for Miniaturization: Integrating Robotics

ABDOMINAL SURGERY



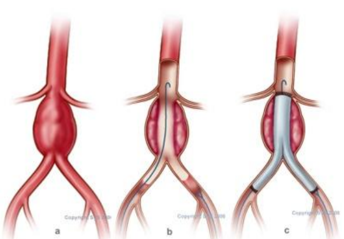
**NOTES (Natural Orifice Translumenal Surgery) SURGERY**
**Reaching** the target (esophagus diameter about 14 mm)
**Bringing** actions to the target

NEURO ENDOSCOPY




**Challenges for neuro endoscopy:**
**Reaching** the target (spinal cord diameter: 4 to 1.5 mm)
**Bringing** actions to the target

VASCULAR SURGERY



**Challenges for vascular therapy:**
**Reaching** the target (Vascular system diameter: 8 to 5 mm)
**Bringing** therapeutic actions to the target

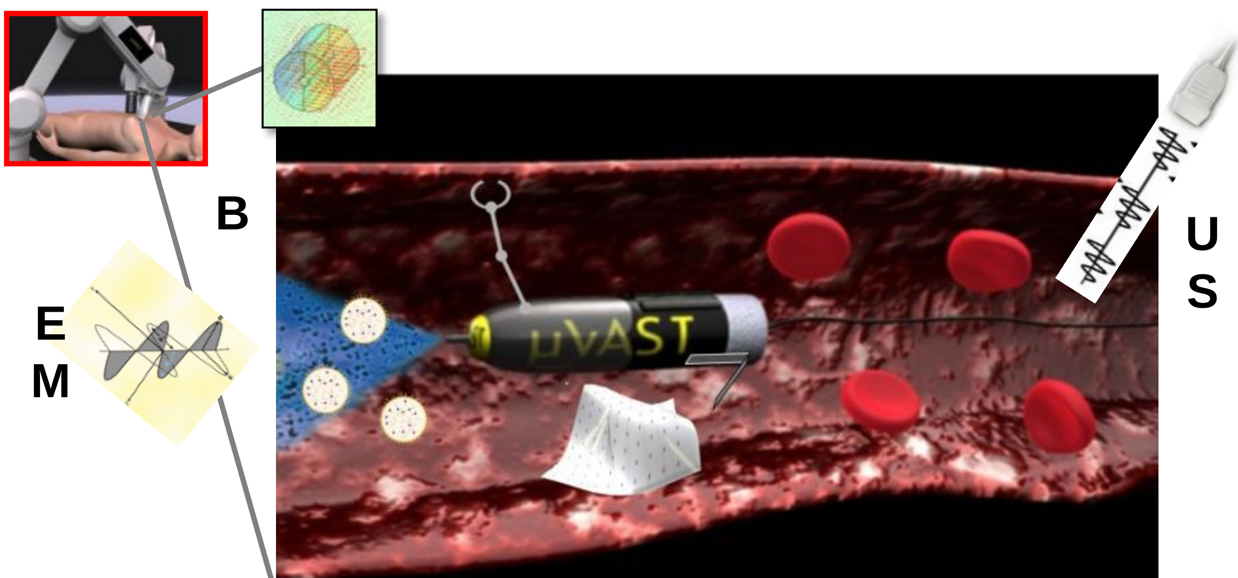
# The problem: finding and destroying the vulnerable plaque in blood vessels

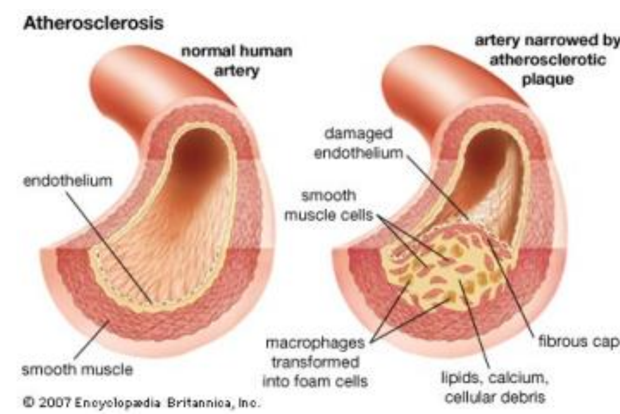
❑ **Cardiovascular disease** is the leading cause of death in industrialized countries (1.9 million deaths in the European Union). Within this group **coronary heart disease (CHD)** is a major cause of death mainly due to **atherosclerotic plaque rupture**, accounts for the largest part

❑ **More than 50% of plaque ruptures occur without significantly observable stenosis**. Identification of relevant anatomical structure and definitive therapy for atherosclerotic lesion is still far from being achieved

| | | |
|---|---|---|
| 1 | Ischaemic heart disease | 6·3 |
| 2 | Cerebrovascular disease | 4·4 |
| 3 | Lower respiratory infections | 4·3 |
| 4 | Diarrhoeal diseases | 2·9 |
| 5 | Perinatal disorders | 2·4 |
| 6 | Chronic obstructive pulmonary disease | 2·2 |
| 7 | Tuberculosis (without HIV infection) | 2·0 |
| 8 | Measles | 1·0 |
| 9 | Road-traffic accidents | 0·99 |
| 10 | Trachea, bronchus, and lung cancer | 0·94 |

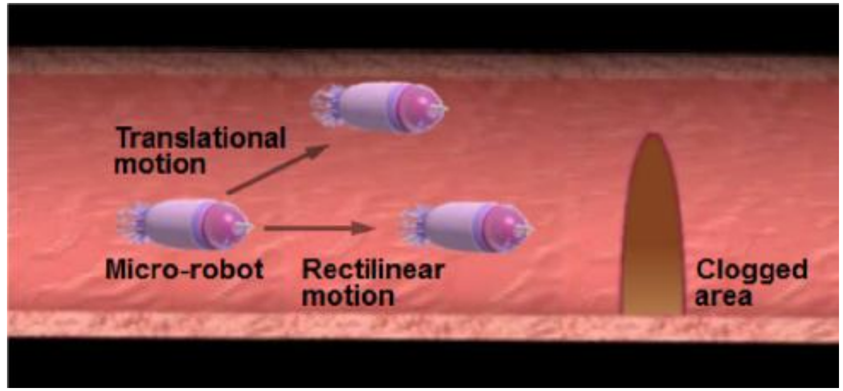
*First ten causes of death worldwide in million of decease (The Lancet, 1997)*



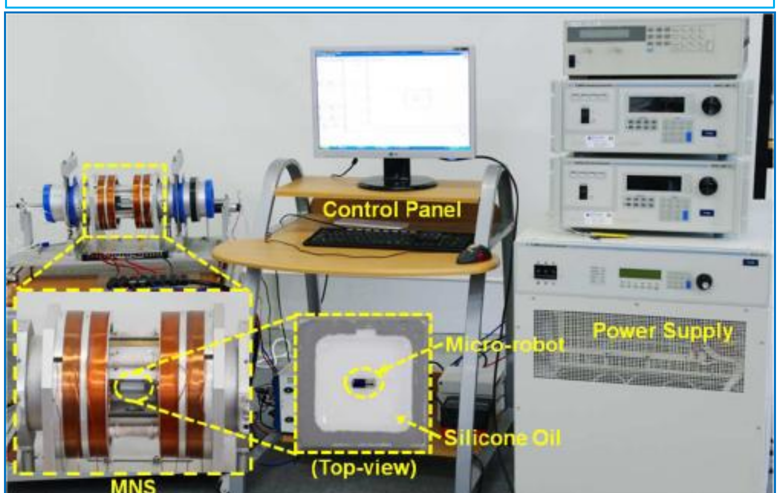
# Magnetic Navigation System for a Micro-Robot in Human Blood Vessels

The magnetic gradients of a custom Magnetic Navigation System are used to generate the **rectilinear and translational motions of micro-robots in human blood vessels**

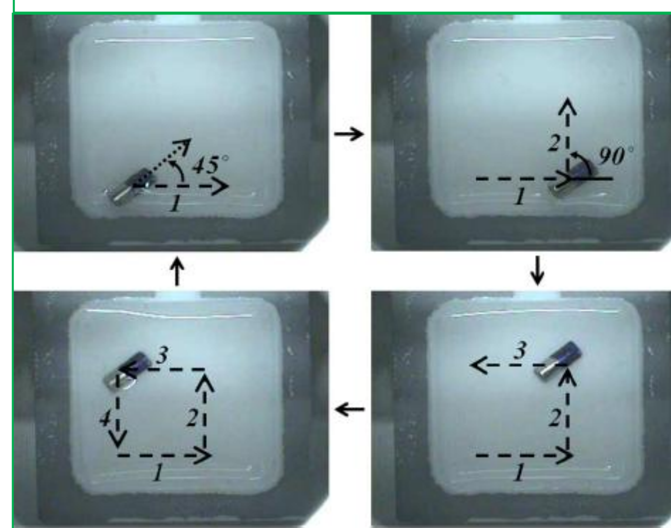



J.O. Park
Chonnam University, Korea

The external electromagnetic system




The results contribute to the effective and therapeutic manipulation of microrobots in human blood vessels




S. M. Jeon et al, IEEE Transactions on Magnetics, vol. 47, no. 10, October 2011

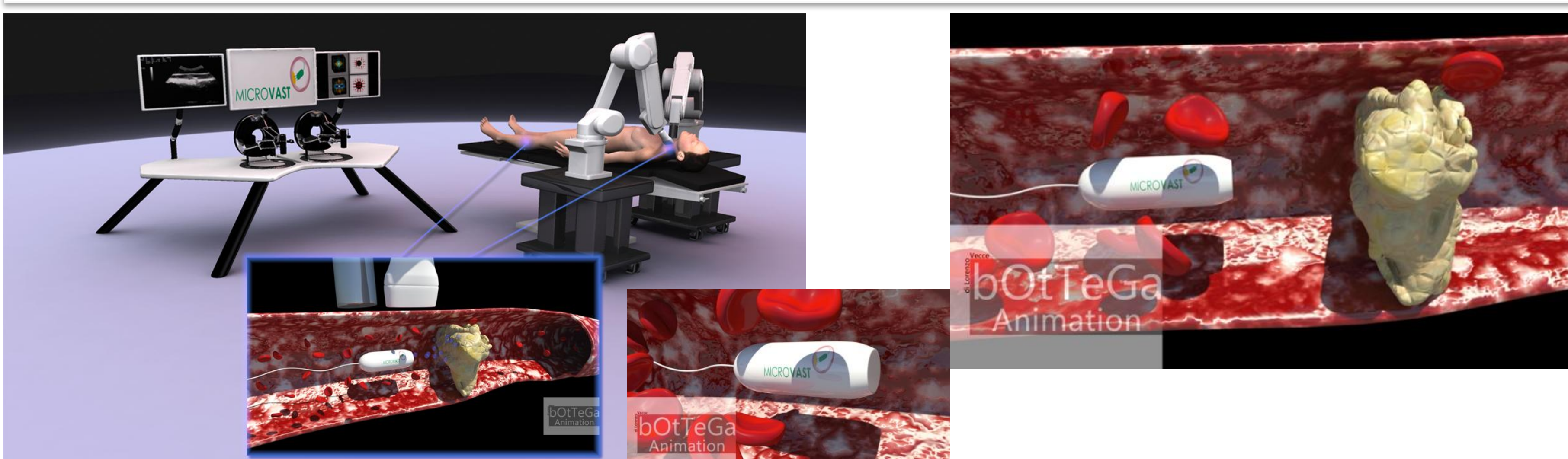
# A Computer Assisted Robotic Platform for Soft-Tail Wired - Wireless Therapy of the Vascular Obstructions

## A TWO-FOLD goal:

- to develop and validate **innovative diagnostic procedures for mapping the vulnerable plaque in arteries** with diameters from 10 mm down to 1 mm
- to develop a set of **innovative solutions for the treatment of artery plaque**, both vulnerable plaque and high-grade stenoses or chronic total occlusions

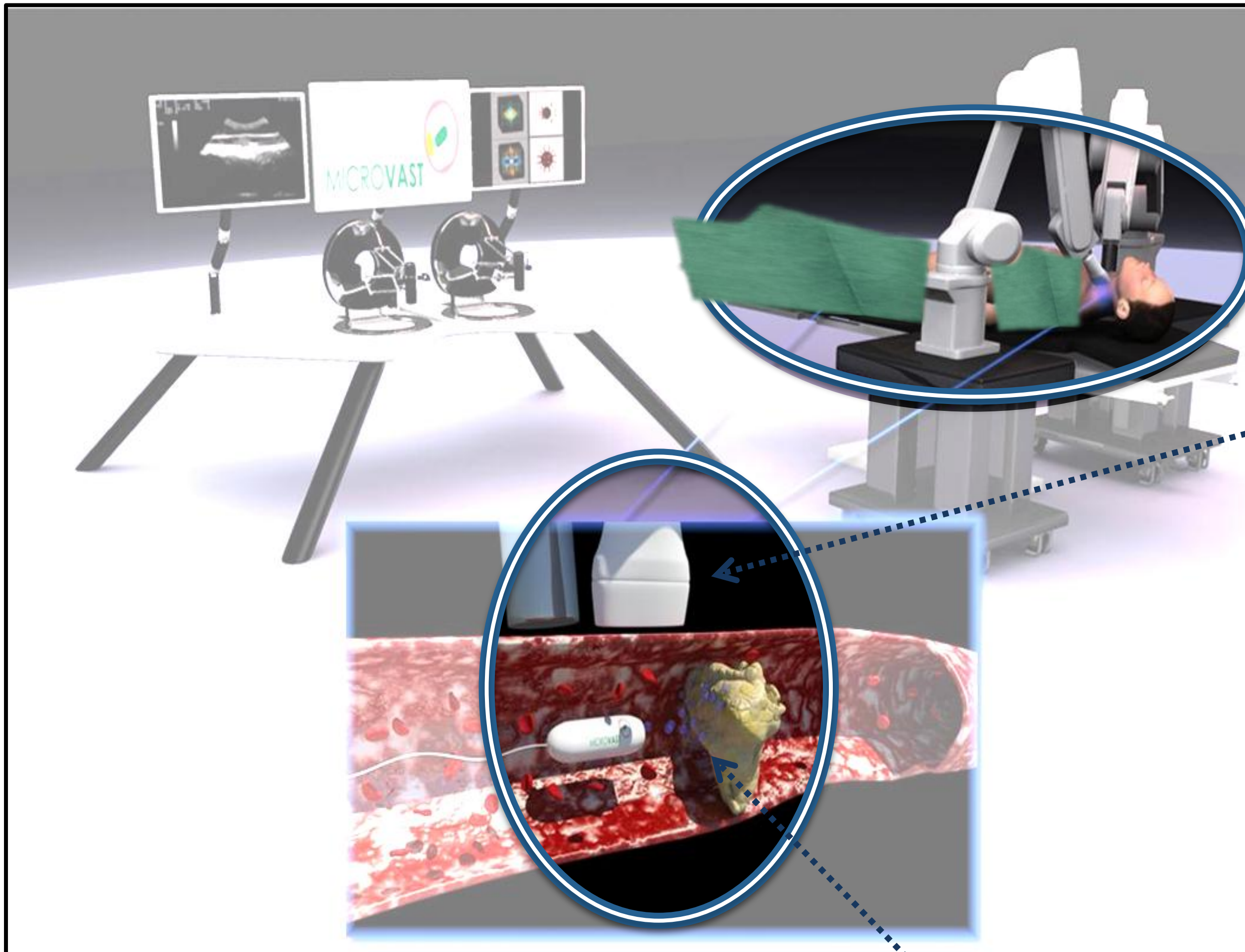
## Four S&T OBJECTIVES:

- **Robotic guidance** for diagnostic and therapeutic micro-systems
- Vulnerable **plaque mapping**
- **Plaque therapy**
- **Plaque debris removal and post-intervention medication**



# The Micro-VAST Platform

**Navigation module**: **External robots** holding a permanent magnet and a diagnostic US probe.

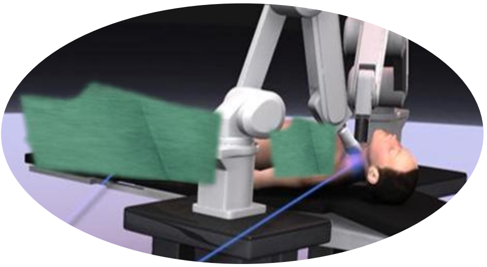


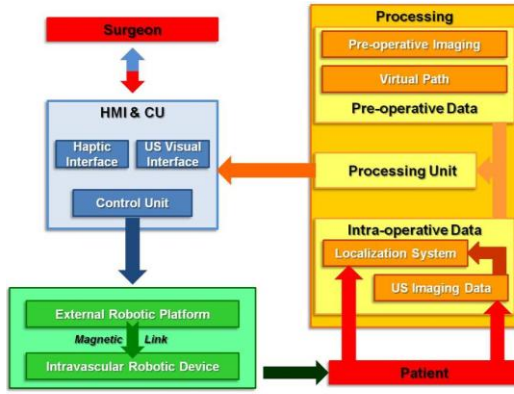

**Therapeutic module: Focused US** thrombolysis enhanced by microbubbles released by means of a magnetic internal mechanism

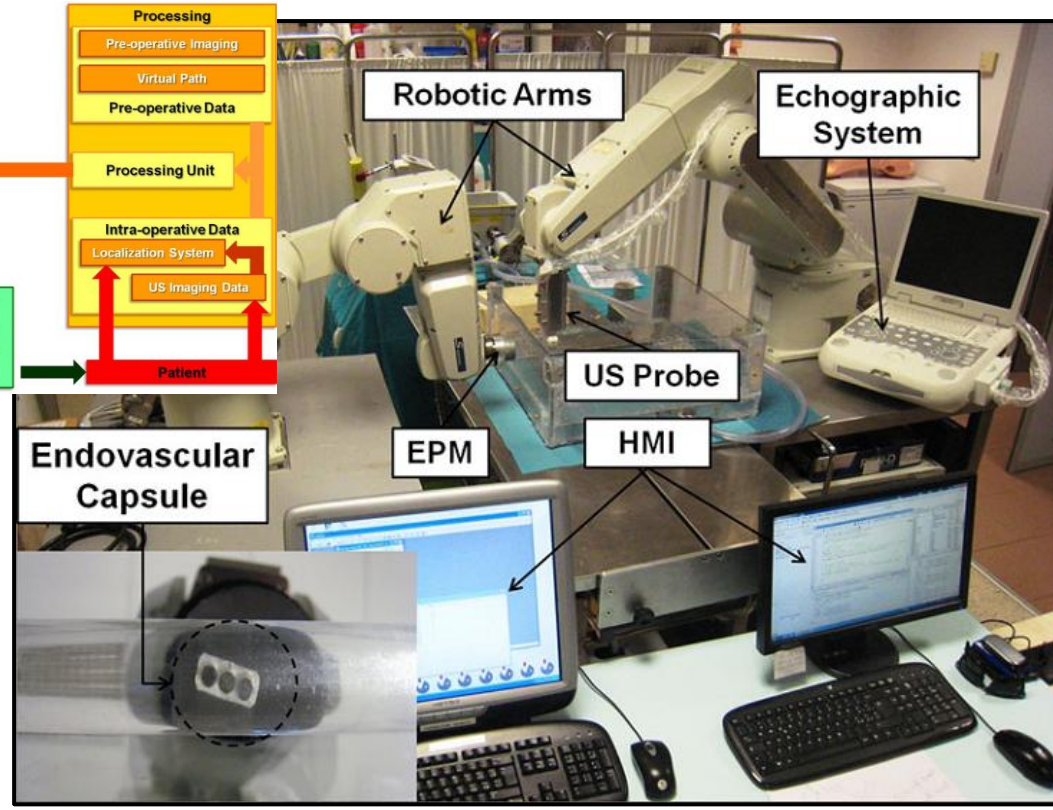
**Debris collection module:** Binding of magnetic particles to thrombus for collection and retrieval of debris.

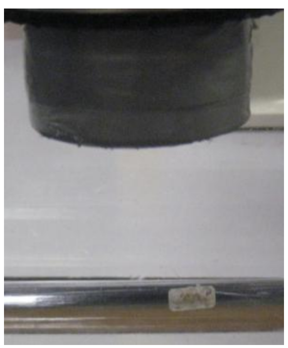
# Navigation Module: Set-up

**Navigation module**: **External robot** holding a permanent magnet and a diagnostic US probe.

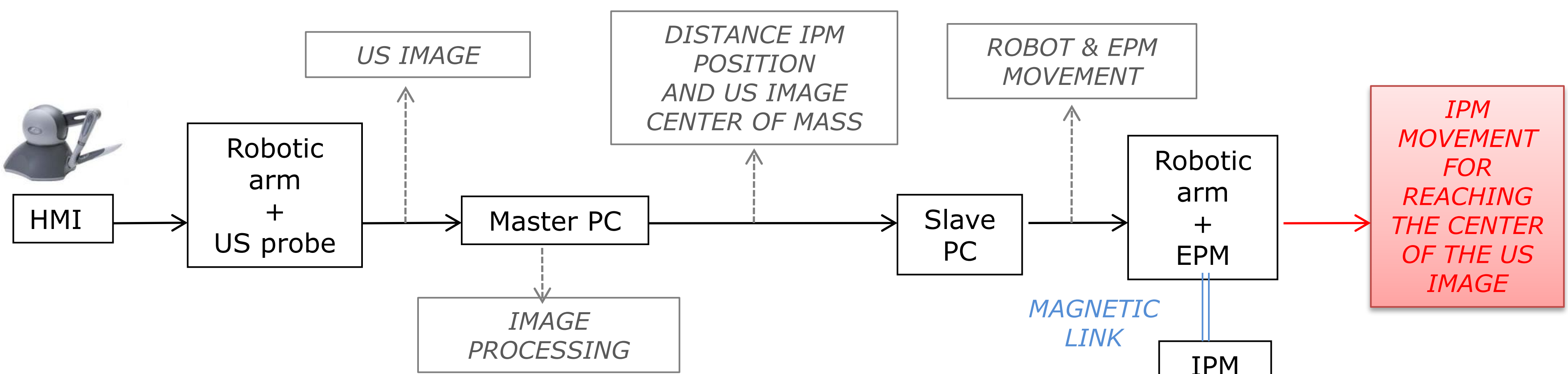




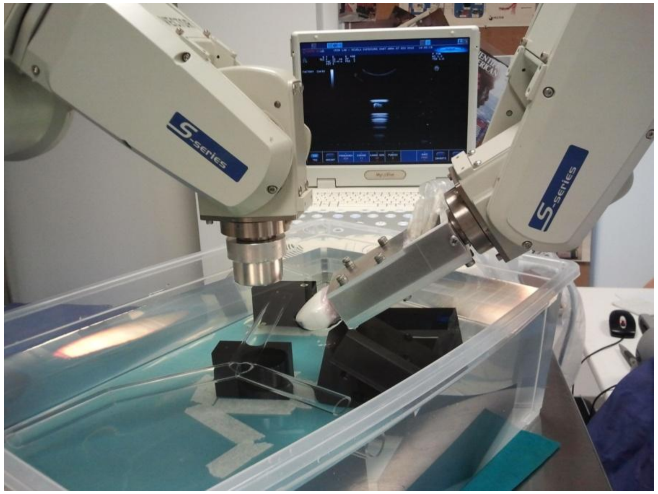



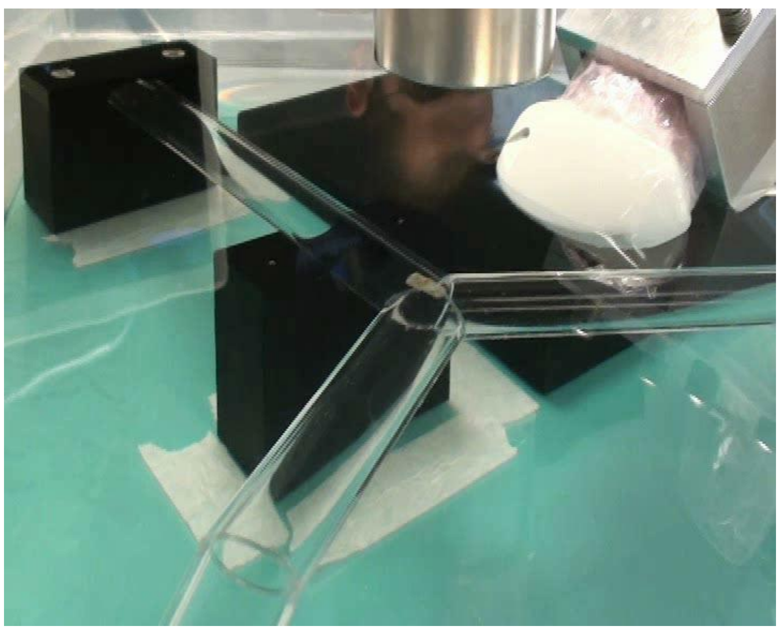
EPM: External Permanent Magnet - HMI: Human Machine Interface

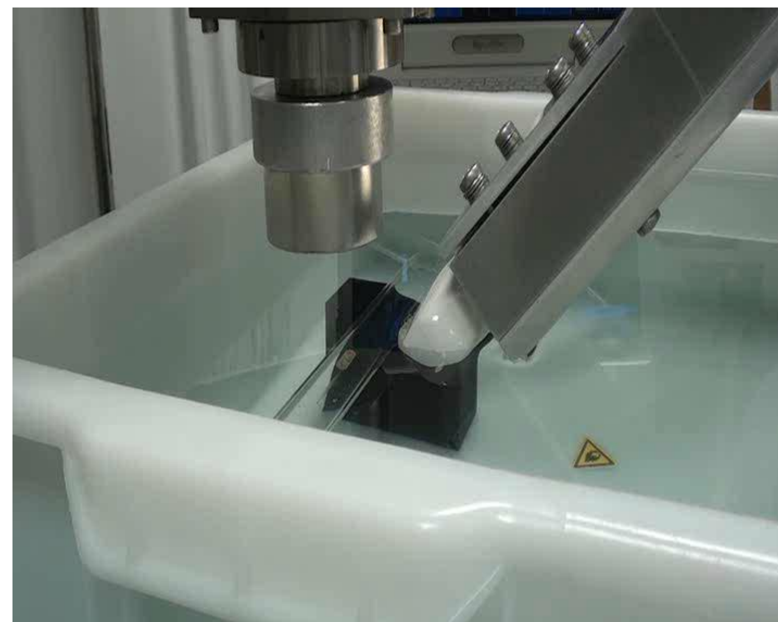


# Navigation module: Robotic guidance



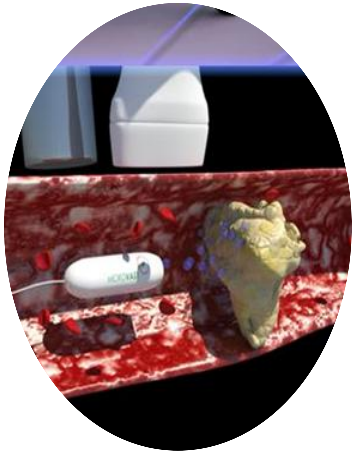

**US-based tracking** of the endoluminal device



**In-vitro 3D tracking algorithm validation –** 3D model based on the combination of the US-based tracking algorithm and the pre-operative path registration.

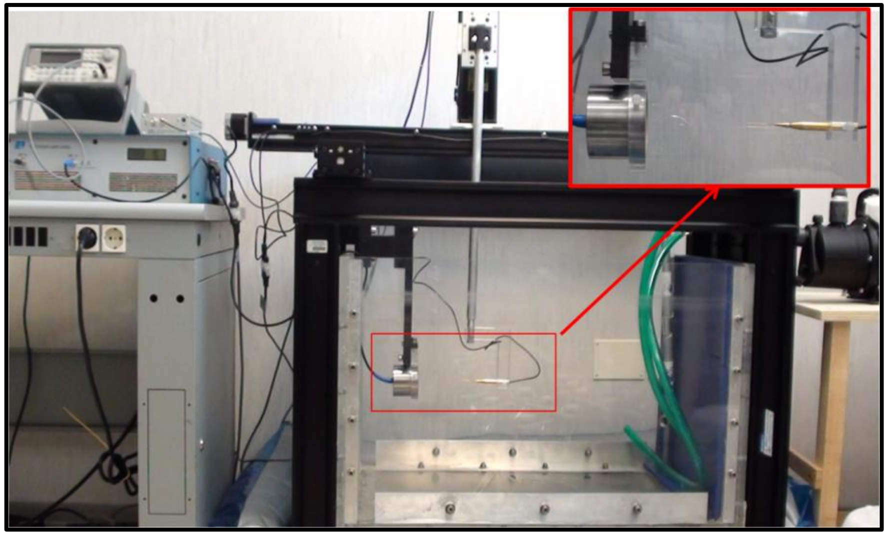
# Therapy Module: Set-up



**Therapeutic module: Focused US**
thrombolysis enhanced by microbubbles released by means of a magnetic internal mechanism

## High Intensity Focused Ultrasound (US) Thrombolysis (dissolution of a blood clot):

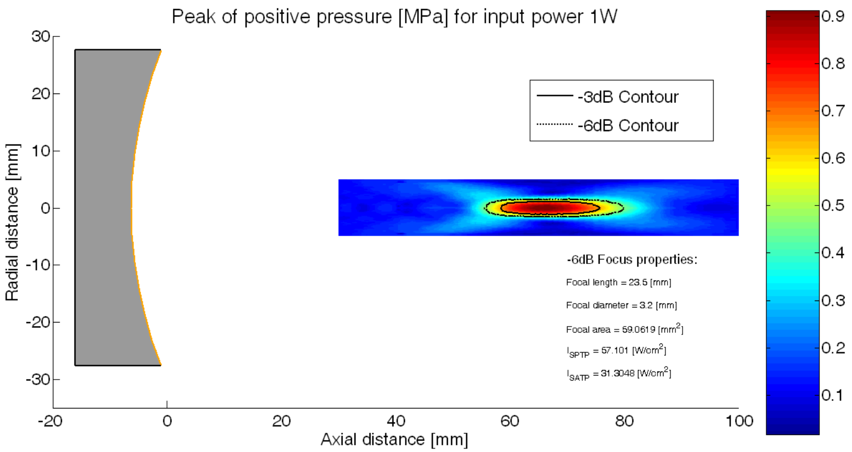
- US can transmit high levels of energy through the body and its effectiveness in attacking thrombi has been demonstrated in several works *.
- However, clinical application is **still** limited mainly because of lack of information on involved phenomena, optimized parameters and safety for healthy tissues.
- Cavitation is credited to play a major role in the dissolution process; addiction of micro-bubbles can augment treatment efficacy.

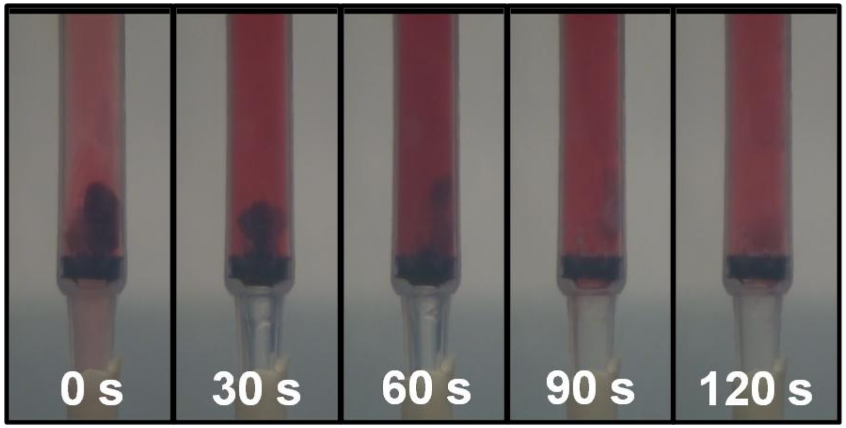


* R. Medel et al., "Sonothrombolysis: an emerging modality for the management of stroke" , Neurosurgery,65(5),2009.

# Therapy module - High Intensity Focused Ultrasound Thrombolysis: Results

## Clots can be dissolved at high power (65W) in approximately 2 minutes.



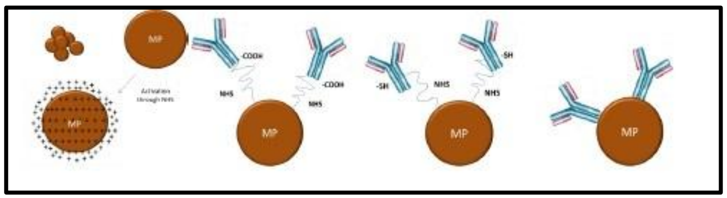


Freq. 1MHz - Power 65W - Pulse Length 450μs - Duty Cycle 1:10 - Flow rate 2ml/min

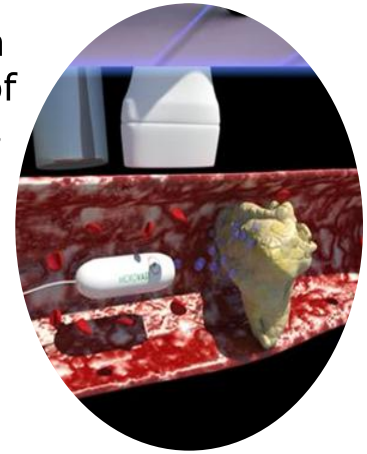
# Debris collection: Set-up & Validation

## ❑ Preparation technique

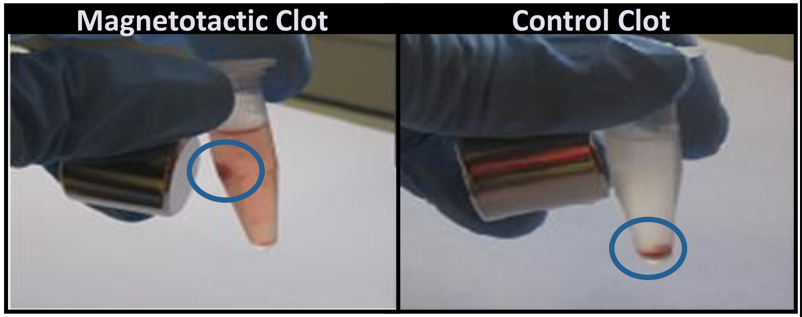
- ✓ Magnetic particles binding to antibody
- ✓ Electrostatic & clot antigen binding to magnetic particles (MPs)

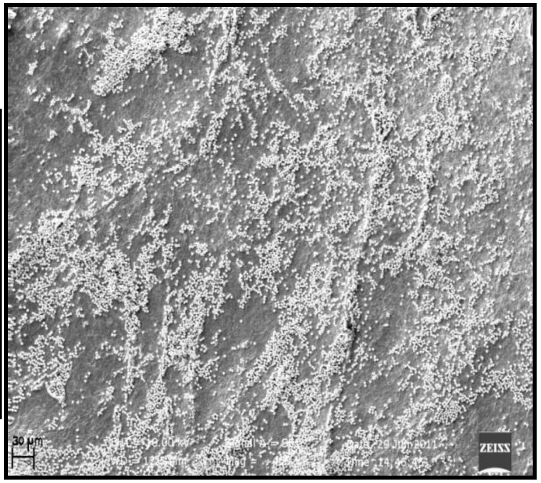


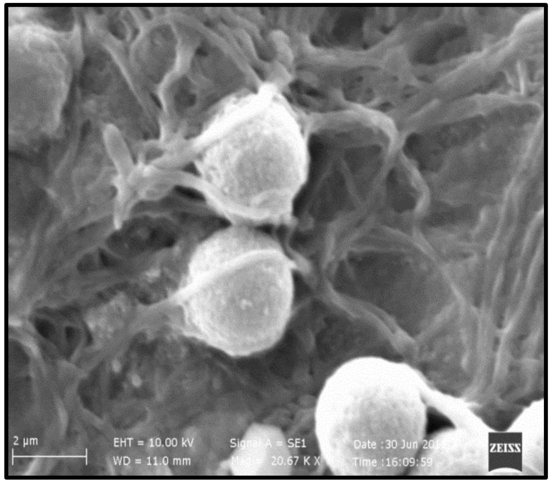

**Debris collection module:** Binding of magnetic particles to thrombus for collection and retrieval of debris.



## ❑ Qualitative assessment of obtained magnetotactic clot.

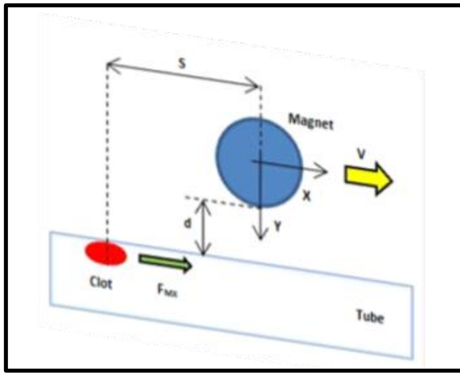


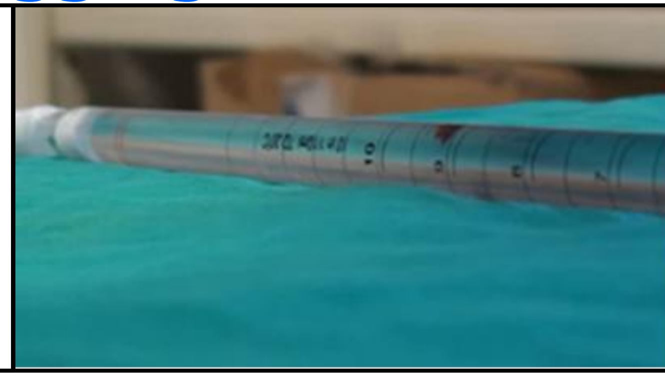



# Debris Collection: Set-up & Results

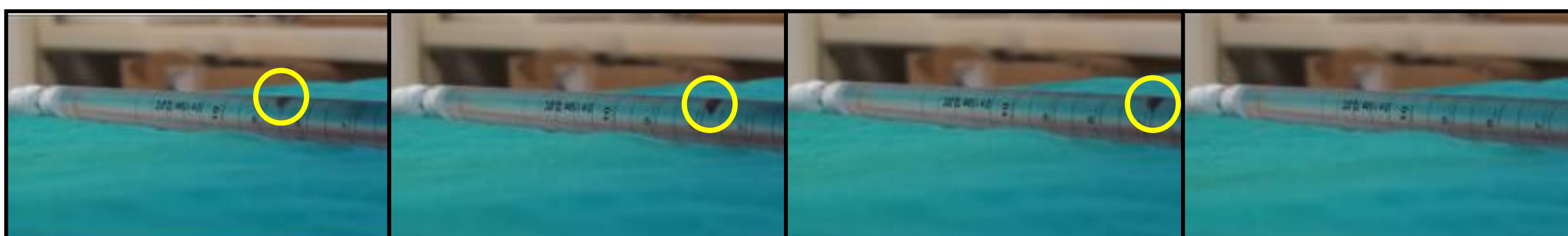
## ❑ Magnetotactic clot dragging



## ❑ Magnetotactic Clot Dragged in a fluidic channel.

Results: Magnetotactic clot dragged inside a fluidic channel by means of External Permanent Magnet



Khorami Llewellyn et.al "Magnetic Dragging of Vascular Obstructions by Means of Electrostatic and Antibody Binding", ICRA 2012

# Next Grand Challenges for Robotics Surgery

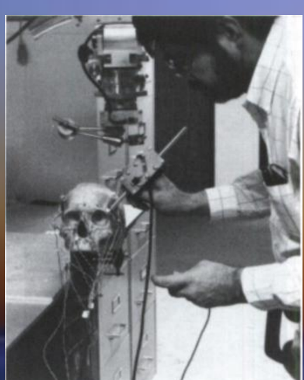
- Transforming (more) dreams into reality

# We had Many Dreams …

# … Now Some of Them are Reality!

1988 (1st IROS!)

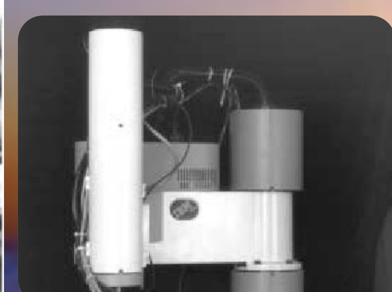




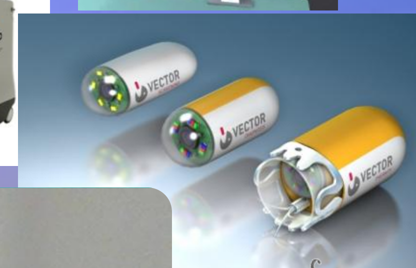
1985

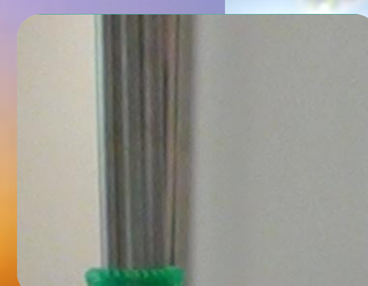
1991

1992





# Medical Robotics may be a real "Dream Job"

## Catherine Mohr at Intuitive Surgical

MEDICAL

# ROBODOC

*She already had her dream job designing electric cars, but sometimes dreams change*

CATHERINE MOHR WANTED to save the world, or at least a piece of it. But she just wasn't sure how to go about it.

At age 27 she had what most engineers would consider a dream job:


her situation. The friend invited her to come to Massachusetts General Hospital to watch some surgeries involving experimental medical devices.

She observed the test of a new device, an aortic stent that could be inserted through the blood vessels like a catheter. The attempt failed, and the surgeons had to revert to traditional open-heart surgery. But that failure was a revelation to Mohr.

...e that if the engineers had been as intimately ...body as the surgeons were, there would have ...ice that the stent would have worked," Mohr ... to the engineers and the surgeons in the oper... ...y just didn't speak each others' languages," ...hat the surgeons would propose fantastical ...olved breaking the laws of physics, and the ...try to bring those solutions into the realm of ...lly understanding the fundamental problem ...ant to solve.

...hat if she wanted to design really revolutionary ...e needed a better understanding of the environ... ...t in which they would be deployed—the human ...y. The best way to get that understanding, she ...ght, would be to go to medical school.

...Oh, my," was her next thought. "Am I really ...g to do *that*?"

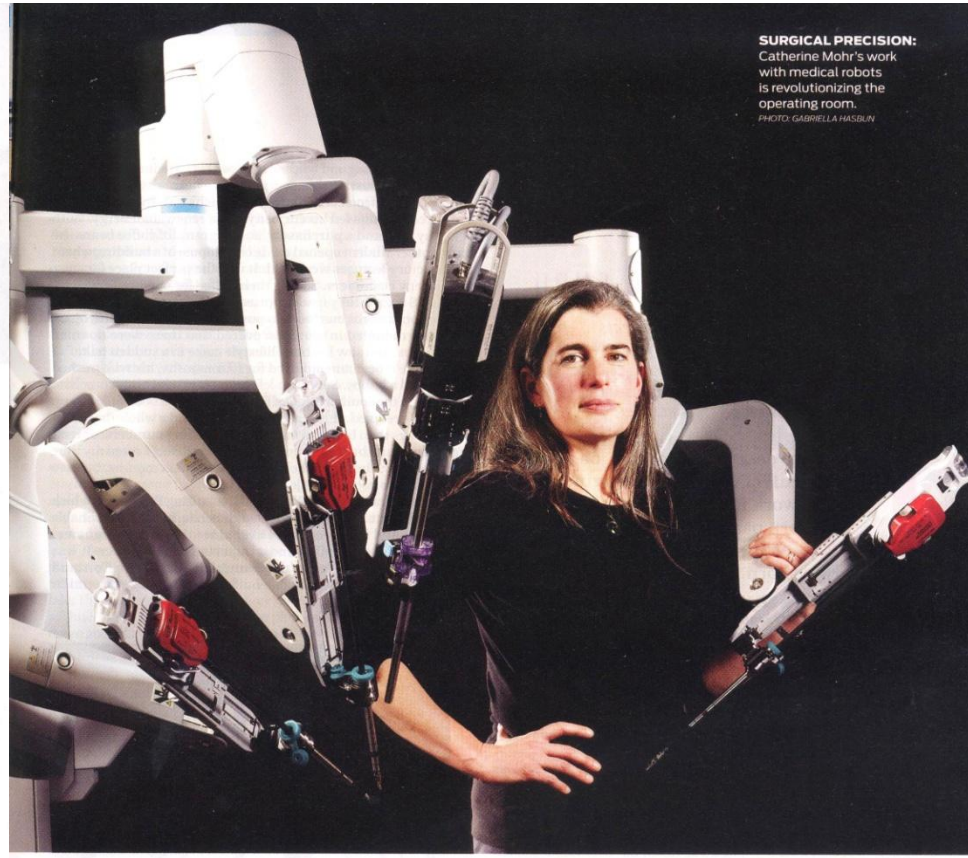
...Mohr looked into academic alternatives— ...thing but medical school," as she puts it. But ...became convinced that attending a medical ...ool with a surgical program that let her par... ...ate in operations was the only way she could ...the deep understanding of the human body ...she sought.

...veryone she knew thought she was nuts. The ...cal reaction went like this: "You're throwing ...y a good income in a high position in a world... ...ous company that makes great things—to go to ...ical school?"

...ut Mohr never saw her choice as throw... ...anything away. "I always looked at it as add... ...on. I fully intended to take what I enjoyed at ...Vironment, which is the engineering, and ...ok at device design from the point of view of ...eone who's both an engineer and a doctor."

...he entered Stanford School of Medicine as ...e-year medical student (the extra year is ...ted to a research project). While studying to ...doctor she had a child, served on the board ...e Association of Women Surgeons, worked





**SURGICAL PRECISION:** Catherine Mohr's work with medical robots is revolutionizing the operating room.
PHOTO: GABRIELLA HASBUN

with the Association of Surgical Education, and spent every free moment trolling the hospital for surgeons who would let her scrub in on operations. She became a regular surgical assistant to two surgeons who specialized in laparoscopies, which are surgical procedures performed through a small incision with the help of a camera. She also developed a tool that makes it safer to inflate the abdomen before laparoscopic surgery and then started a medical device company to market the tool.

And then it came time to sign up for "the match," the annual process by which medical students around the country are assigned to hospitals for internships and residencies.

Mohr didn't register. She loved the intellectual challenge of medicine and the connection with patients. But she loved the design projects she'd been doing on the side just as much. And she had a 2-year-old daughter she needed time for as well. She realized she couldn't do it all.

So she joined Intuitive Surgical, a company located just kilometers from Stanford. Intuitive makes a surgical robot called the da Vinci. She started out by studying the forces generated during surgery by cutting and suturing and is now applying lower-force alternatives to surgery, such as lasers. As director of medical research, she's also investigating applications for other new surgical technologies. One is focal therapy, which involves inserting a catheter into a tumor and then destroying the tumor from the inside out by applying RF, microwave, or other forms of energy. She considers how to integrate such novel techniques into the da Vinci and future surgical robots.

And Mohr gives advice to other engineers who are thinking about going to medical school. "I say it's a long, hard path, and it's fraught with lots of really hard decisions to make along the way about whether you're going to go all the way through residency, if you're going to practice, if you're not. I also tell them that you're probably not going to make a lot of money designing biomedical devices. But it has the potential for being very, very rewarding.

"The job is technical, clinical, and creative, and constantly on the steep part of the learning curve," she says. "It has all the satisfaction of being a researcher in academia, but because I'm in industry, when I find things that will make a very big difference in patients' lives, there's a very short path to getting them into patients."

—TEKLA S. PERRY

HÖGSKOLAN I GÄVLE

# Current international robot standardization activities: Background

- Prior to 2004 most robot standardization activities focussed on industrial environments. ISO and IEC are main international organisations with responsibilities for the standardization
- EC funded Network of Excellence on Climbing and Walking Robots (CLAWAR: 1998-2005) ⇒ primary aim to widen the application base for robotics. Initiatives in robot modularity and standardisation for mobile service robots
- Formal contacts made to many national standards bodies to activate work required
  - BSI (Univ Leeds, UK), AFNOR (Cybernetix, France), SIS (Orebro, Sweden), ONH (Univ Vienna, Austria), IBN, (RMA, Belgium), BIS (BAS, Bulgaria), FSA (HUT, Finland), DIN (F-IFF, Germany), MSZT (Univ Budapest, Hungary), ENIU (UNICT, Italy), NNI (TNO, The Netherlands), PKN (Poznan, Poland), IPQ (ISQ, Portugal), AENOR (CSIC, Spain)
- New robot standardization work under with SC2: Robots and robotic systems proposed. ISO Resolution to setup an ISO Advisory Group on "Standards for mobile service robots", with GS Virk as Chairman.
  - Advisory Group setup in June 2005 with GS Virk as Chair with ≈30 nominated experts + Observers for maximising input
  - Advisory Group reported results at ISO TC184/ SC2 Plenary meeting in Paris on 15-16 June 2006
- 2006: Creation of WG1 on Robot Vocabulary (Prof Soon-Geul Lee, Korea as chair)
- 2006: Creation of WG7 on Personal care robot safety (Prof GS Virk, UK as chair)
- 2006: Creation of WG8 on Service robots (Prof Seungbin Moon, Korea as chair)
- 2011: Creation of IEC/ISO JWG9 on Medical electrical equipment and systems utilising robotic technology (Prof GS Virk, UK as chair)

HÖGSKOLAN I GÄVLE

# JWG9 Medical robot standardization

- IEC SC62A / ISO TC184/SC2 JWG: Medical electrical equipment and systems using robotic technology
  - JWG9 set up in April 2011 under IEC admin lead; 3 meetings to date
- Chairman: GS Virk, CLAWAR Association Ltd, UK
- 14 participating countries: ≈50 experts from Brazil, Canada, China, France, Germany, Hungary, Italy, Japan, Korea, The Netherlands, Romania, Switzerland, UK, USA
- Medical robot will be medical device rather than a machine
- Aim
  - Develop general requirements and guidance related to the safety of medical electrical equipment and systems that utilize robotic technology. (i.e., medical robots)
  - The work would encompass medical applications (including aids for the disabled) covering invasive and non-invasive procedures such as surgery, rehabilitation therapy, imaging and other robots for medical diagnosis and treatment

# A "Financial" Perspective …

**SEPTEMBER 28, 2012**

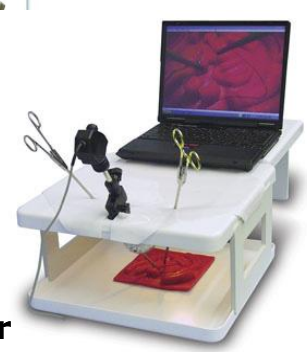
## Robotics are a 'game changer'

Other technologies and navigation procedures are also enhancing the precision with which surgeons can remove tumours. This means they can eliminate more cancer cells, lowering the chance of recurrence, while also protecting normal tissue surrounding the tumour.

the medical community is also anxious to find new ways of bringing cancer treatments to a larger number of people to combat the rising incidence of cancer in a global population that is ageing rapidly.

$37bn

**Amount needed to correct the shortfall of surgeons**



**Training simulator**

**37bn $ saved** thanks to surgical simulation training

# What's Next for Robotics Research in Surgery?

Working hard on strengthening and increasing our knowledge and capabilities by addressing and solving many open issues, such as:

energy-efficient actuators (variable impedance, smart materials)

novel design principles and mechanisms

haptics (enhanced usability?)

multi-robot systems (integration)

multi-modal imaging integration

MRI-compatible robots (cost-effective?)

distal actuation

non-rigid registration

adaptive planning for dynamic environments

safe human-robot interaction

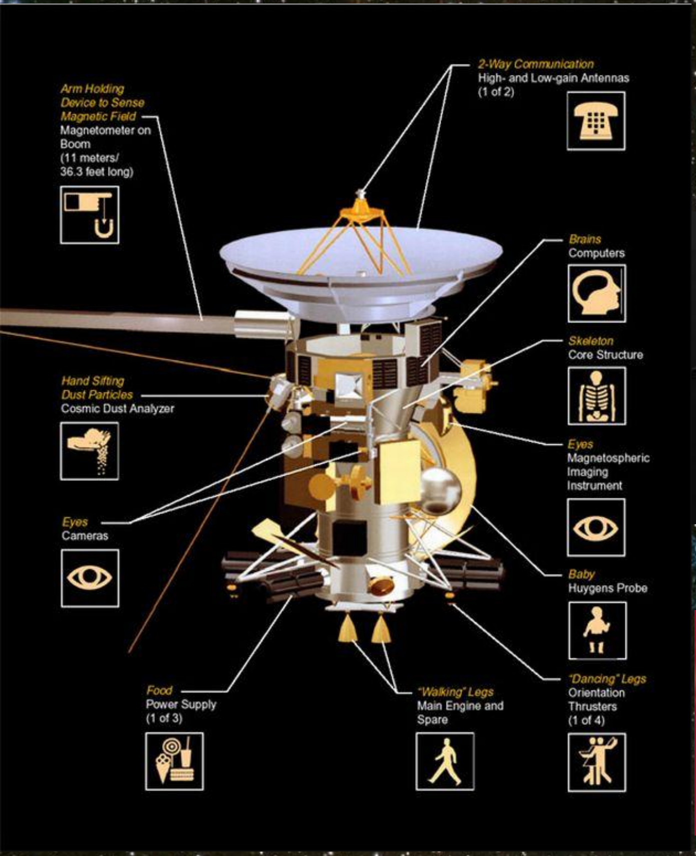
New simulators

# Next Grand Challenges for Robotics Surgery

- Transforming (more) dreams into reality

- **Dreaming new dreams**

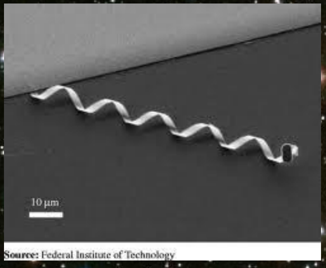
… from wired to wireless



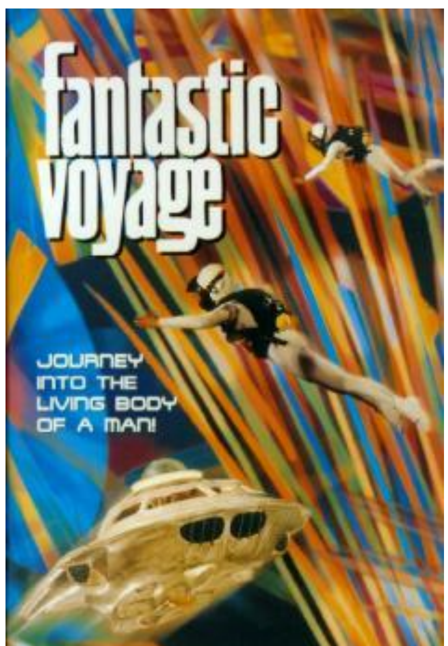

… from external (e.g. magnetic) powering to harnessing internal actuation and environmental energy

…

… up to the hyper-integration of micro-/meso-/nano-components



# Is it the time to revisit science fiction?



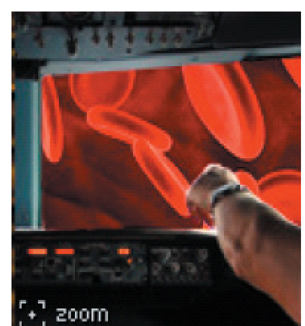

Isaac Asimov, ***Fantastic Voyage***, **Bantam Books, Inc., 1966.**

FANTASTIC VOYAGE—FROM FICTION TO REALITY

ÉCOLE POLYTECHNIQUE DE MONTRÉAL RESEARCHERS MAKE NEW INROADS FOR CANCER TREATMENT BY USING MRI TO TRACK AND PROPEL DEVICES THROUGH THE BLOODSTREAM.

**By Véronique Barker**

ISSUE #29 // JULY-AUGUST 2007




**PROJECT**

In the same vein as the 1960s classic movie, Fantastic Voyage, where a crew of scientists are miniaturized and injected into the bloodstream, Sylvain Martel [1], director of the NanoRobotics Laboratory at École Polytechnique de Montréal, has successfully made travel through a living animal's bloodstream possible. "This is really what we are doing, except that we

S. Martel, CANADA

# … Current research may not be lagging too behind

❑ **Functions of different modules:**

pilot→ navigation

surgeon→ operation

nurse→ assistance tasks

1966 science fiction movie (Dir. R. Fleischer)


❑ **Tasks:**

1. Locomotion
2. Cooperation and Manipulation
3. Therapy

*S. Martel (2009)*, Ecole Polytechnique de Montreal, Canada

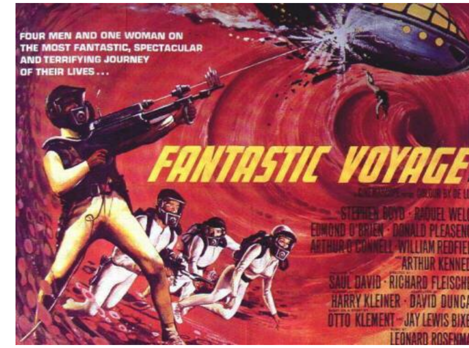
Cinematography

Reality

# ... Current research may not be lagging too behind

- **Tasks:**

1. Locomotion
2. Cooperation and Manipulation
3. Therapy

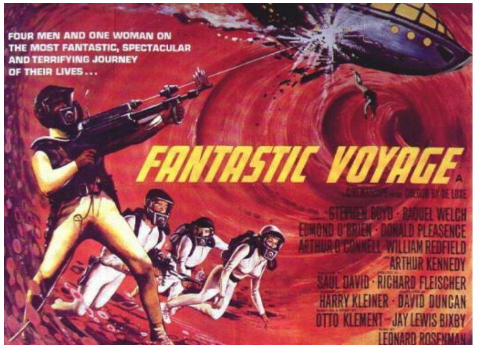



Cinematography

Reality


*S. Martel (2009)*, Ecole Polytechnique de Montreal, Canada

# … Current research may not be lagging too behind




❑ **Tasks:**

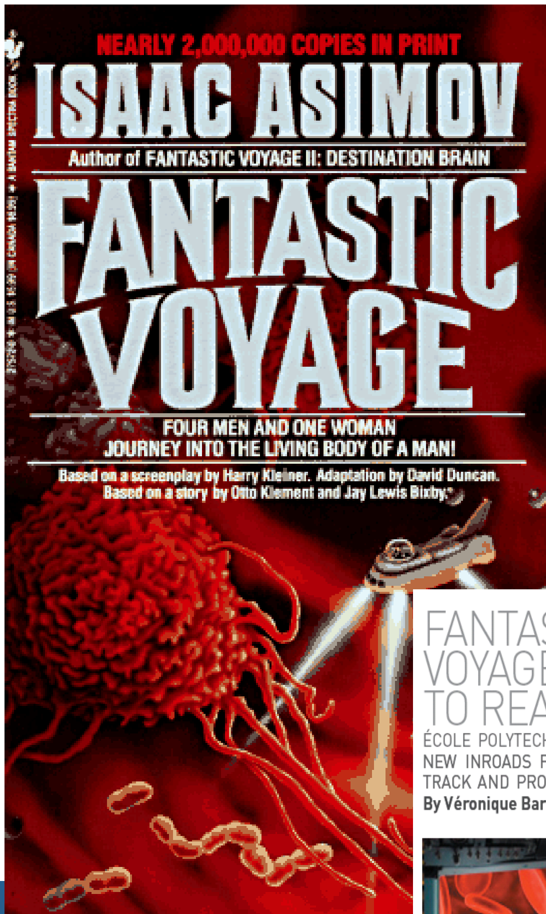
1. Locomotion
2. Cooperation and Manipulation
3. Therapy

Cinematography

Reality (targeted drug delivery )

# Science Fiction Becoming Reality

## SCIENCE fiction




### FANTASTIC VOYAGE—FROM FICTION TO REALITY

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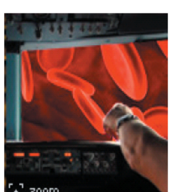


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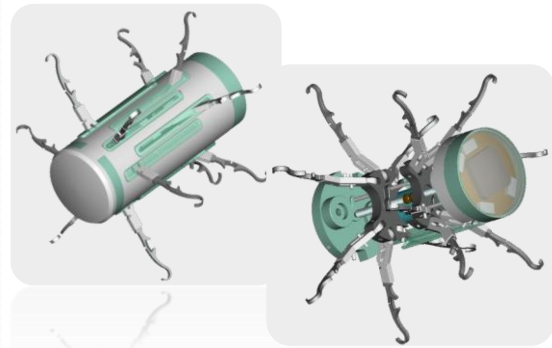
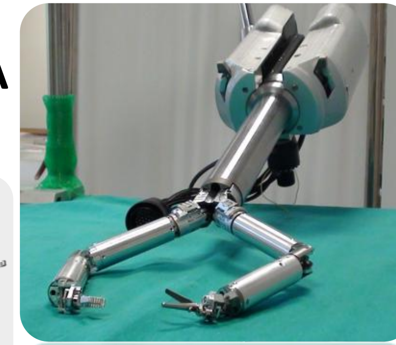
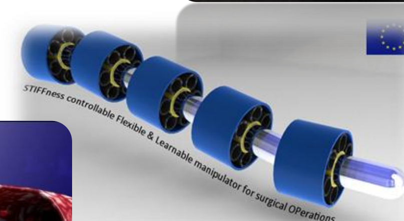
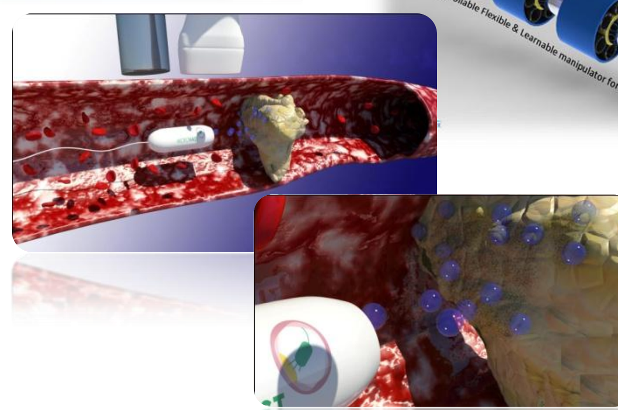
## REALITY @ SSSSA



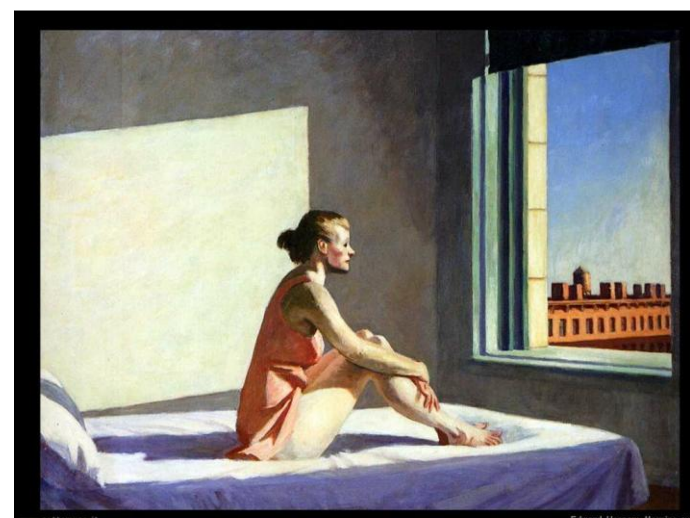




# Outline

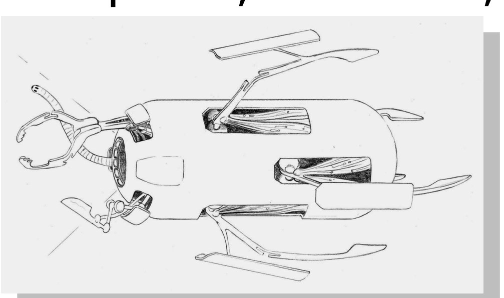
- The onset of modern surgery
- The onset of robotic surgery
- Current Scientific and Technological Challenges
- Conclusions



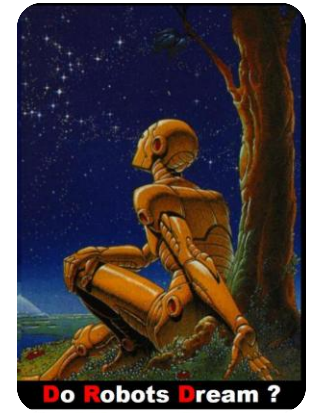

E. Hopper, Morning sun, 1952

# Concluding Remarks

- Robotics technologies just begin to show their tremendous **potential** in Surgery
- Robots have a place in the modern operating room, because of their established ability – in a growing number of different fields – to exploit the **increasing power of planning, imaging and diagnostics techniques to improve surgical outcomes**
- The advantages of robotics (accuracy, repeatability, motion control, image-based planning, “intelligence”, learning and cognition, etc.) has effective potential for **filling the gap between academic research and real clinical applications**
- An extraordinary opportunity to explore and implement new and even **visionary ideas** (just as happened **25 years ago, when the robots now in clinical use were conceived and preliminarily tested**)
- The grand challenges for robotics: the performance of **therapeutic** technologies should match the progress of current **diagnostic** technologies, and including as many functions/capabilities (mechanical, optical, chemical, powering, electronic …) into a miniaturized shell



# A small tribute




**To those (robotics researchers, surgeons, entrepreneurs) who envisioned Robotics Surgery and brought it to reality, thus benefiting the health and quality of life of a huge and increasing number of patients (and creating new opportunities and jobs)**

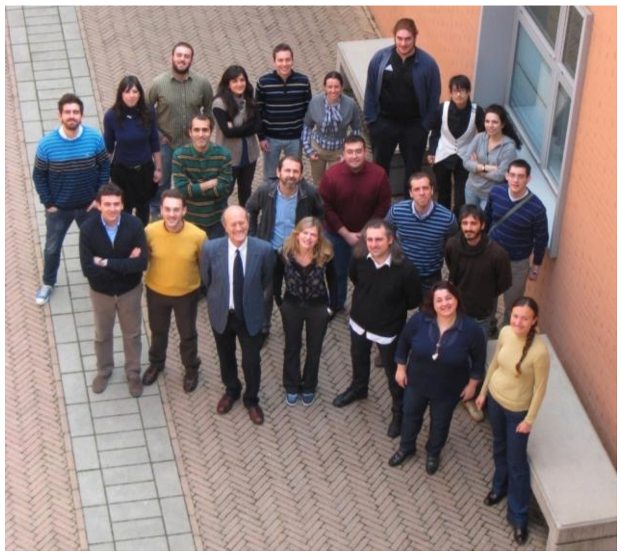
The only thing more dangerous than trying too hard and failing… is not trying hard enough and succeeding!

***- Michelangelo -***

# Acknowledgments

**Many colleagues, many PhD students, many funding agencies (*European Commission, IMC, IIT, Cassa di Risparmio di Pisa*)**

**Arianna Menciassi**
**Edoardo Sinibaldi**
**Selene Tognarelli**
**Virginia Castelli**
**Gioia Lucarini**

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*Celebrating 25 Years of IROS*