THE BIOROBOTICS INSTITUTE

Scuola Superiore Sant'Anna

## 6th Summer School in Surgical Robotics

Montpellier, France
September 4-11, 2013

# Trends in Surgical Robotics


## Prof. Paolo Dario

### with many contributors as outlined on closing slide

The BioRobotics Institute, Scuola Superiore Sant'Anna
Pisa, Italy


September 11, 2013

SURGICAL ROBOTICS
MONTPELLIER/FRANCE/2013
6th Summer School

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

CAMI
COMPUTER ASSISTED MEDICAL INTERVENTIONS

cnrs

um2 UNIVERSITÉ MONTPELLIER 2

I2S ECOLE DOCTORALE

UM1 Université Montpellier 1

# Paolo Dario’s Profile

THE BIOROBOTICS INSTITUTE

Scuola Superiore Sant’Anna

- Full Professor of Biomedical Engineering, Scuola Superiore Sant’Anna, Pisa
- Director, The BioRobotics Institute (190+ staff members, 88 PhD students)
- Founding Director, IIT Center for Micro-BioRobotics@SSSA
- Senior Scientist (2012 – 2013), Italian Institute of Technology
- Visiting Professor, College de France, Waseda University, Japan, Tianjin University, China
- Fellow, School of Engineering, University of Tokyo
- Author of 300+ ISI journal papers
- H-index: 48 (in the list of Top Italian Scientists)
- Coordinator of 50+ European Projects (in the past 20 years)
- Co-founder of 5 start-up companies
- Member of the Technology Council, STMicroelectronics
- IEEE Fellow
- President IEEE Robotics and Automation Society (2002-2003)
- Member (2 terms) of the ISTAG (IST Advisory Group) of EU
- Member of the Global Agenda Council on Robotics and Smart Devices of the World Economic Forum
- Member of the International Scientific Committee of the Institute for Bioengineering of Catalunya (IBEC), Barcelona, Spain
- Honorary Advisor, The Jockey Club Minimally Invasive Surgical Skills Centre, The Chinese University of Hong Kong
- Recipient of the Joseph Engelberger Award for Pioneer Research in Biomedical Robotics

# Italy, Tuscany and Pisa in Europe

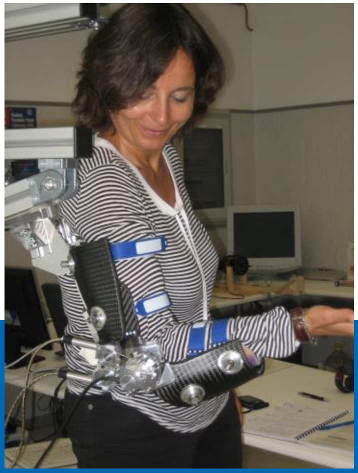

**_Pisa_**

**_Firenze_**

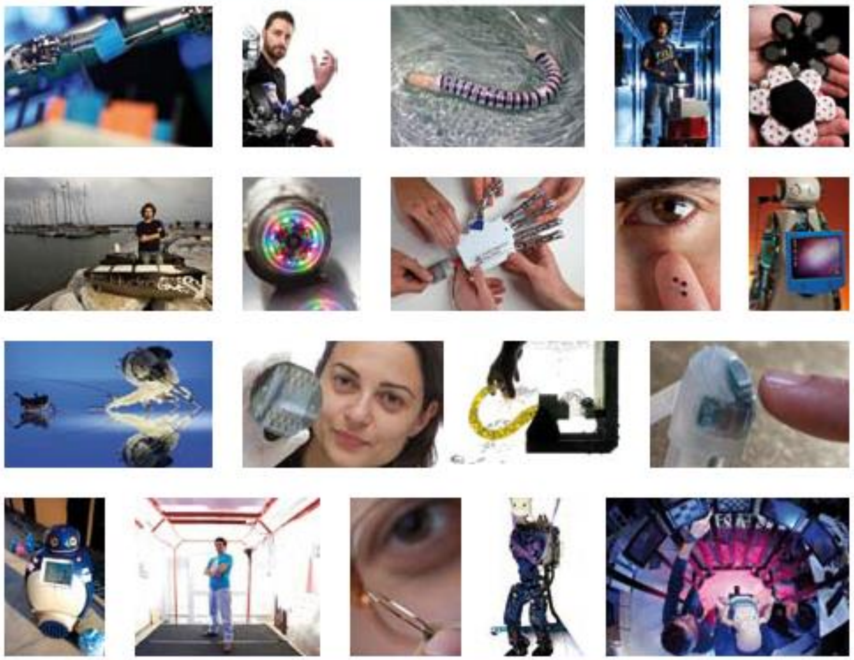
# Tuscany, Italy

A country and a region with an extraordinary wealth of artistic and cultural heritage, deep attention to preserving the **environment** and **social relations**, excellent climate, good **food**, excellent and sustainable **healthcare**, and a relaxed, friendly atmosphere favoring long (**highest life expectancy in the world for males**: 79.6 years; second highest for women: 84.7 years) and active life

# Tuscany: the Land of Robots

# the BioRobotics Institute



12 Faculty

75 PostDocs

88 PhD Students

Scuola Superiore Sant'Anna

di Studi Universitari e Perfezionamento


www.bioroboticsinstitute.eu

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

**2008**

52. Medical Robotics and Computer-Integrated Surgery

Springer Handbook of Robotics

Siciliano Khatib Editors

Russell Taylor,
Arianna Menciassi,
Paolo Dario

**2007**

IEEE/ASME TRANSACTIONS ON MECHATRONICS

Guest Editorial
Introduction to the Focused Section on …

*P. Dario and A. Menciassi*

**2003**

Special issue on **Medical Robotics**

IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION

RUSSELL H. TAYLOR, *Guest Editor*
PAOLO DARIO, *Guest Editor*
JOCELYNE TROCCAZ, *Guest Editor*

**1989**

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

**1988**

IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING

Special issue on **Biomedical Mechatronics**

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

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  1st laparoscopic cholecystectomy
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**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

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An Advanced Robot System for Automated Diagnostic Tasks Through Palpation

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**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

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*Abstract*—In this paper, we describe how a U
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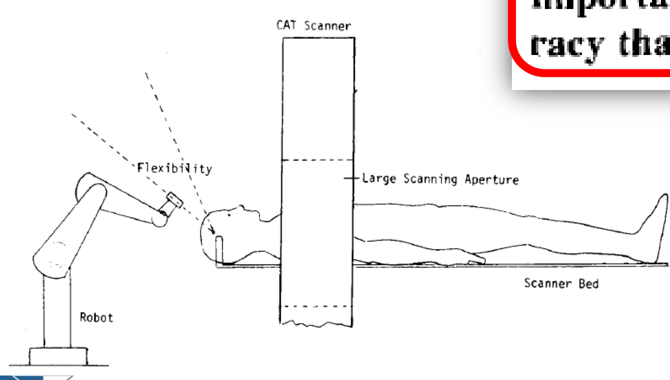
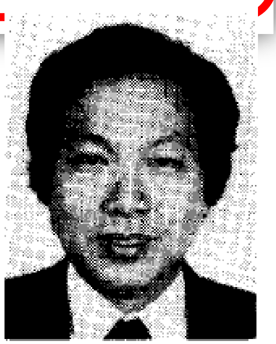
than one with a manually adjustable frame. I
important advantage, as we show in this paper
racy that can be reached by proper calibration

*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

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

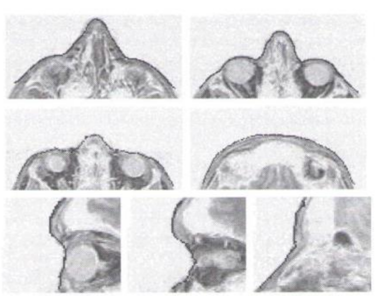


FIGURE 4.2 Here we represent the surface once we have reached a minimum of the energy *E*. Some vertical and horizontal cross-sections of the surface are given. They show an accurate localization of the surface at the edge points.

Philippe Cinquin, Grenoble, France

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 thrc 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.)

Stephane Lavallè, Grenoble, France


Jocelyne Troccaz, Grenoble, France

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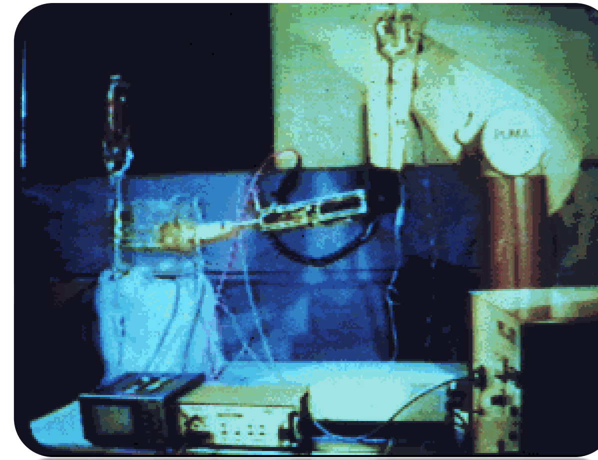
  1st patient in neurosurgery (Neuromate)
- **1991: Davies et al.**
  **1st patient for prostate surgery (Puma 560)**

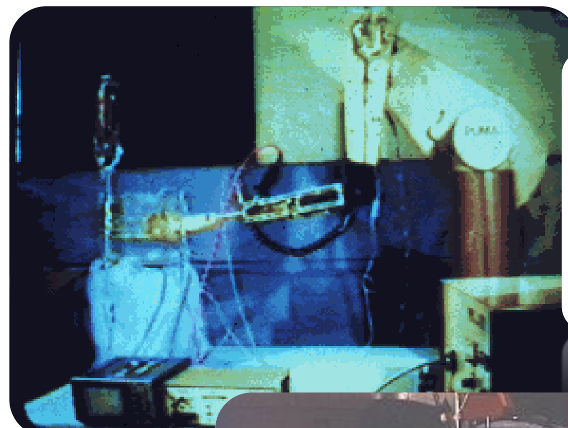


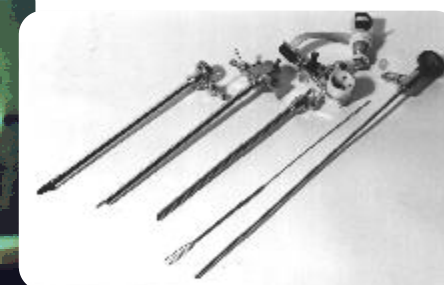
# Surgeon Assistant Robot for Prostatectomy (SARP)

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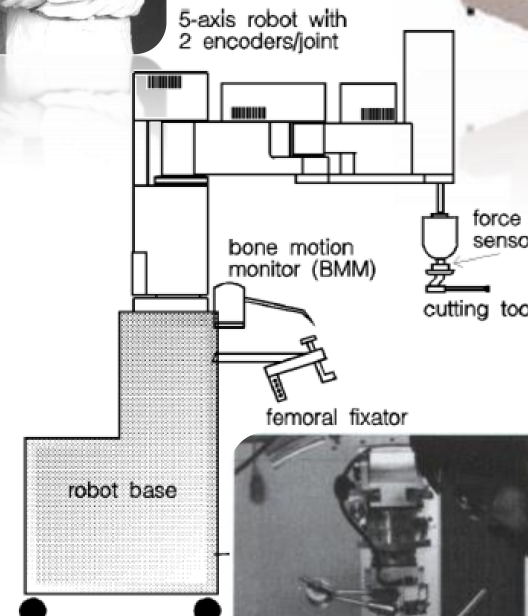
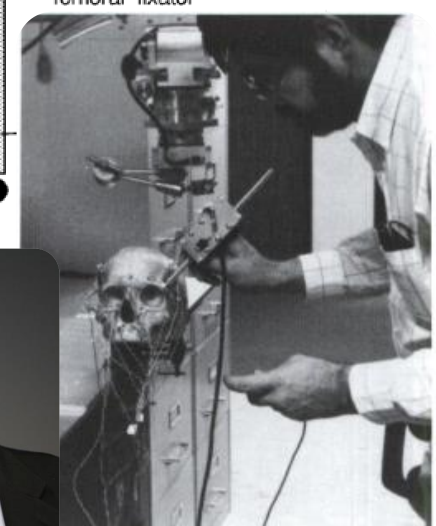
- 1989: Benabid, Lavallée, Cinquin et al.
  1st patient in neurosurgery (Neuromate)
- 1991: Davies et al.
  1st patient for TURP (Puma 560)
- **1992: Taylor et al. Integrated surgical systems 1st <u>hip</u> surgery with ROBODOC**



# 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**

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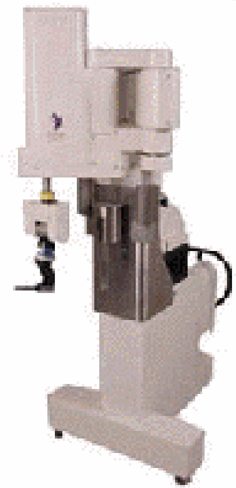
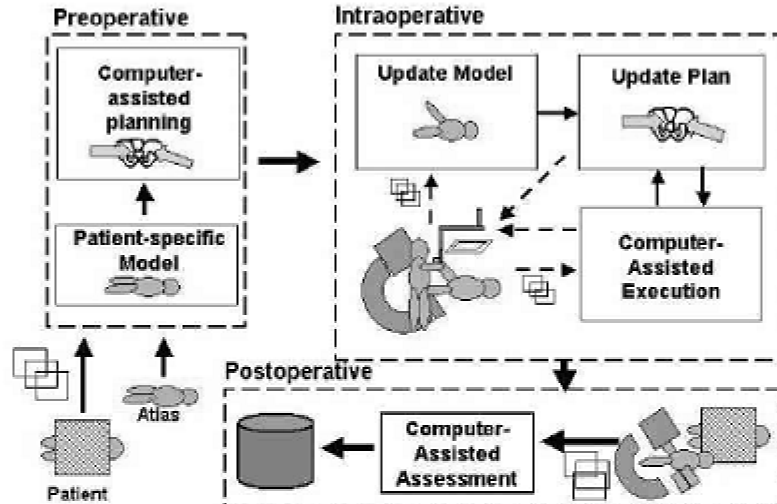
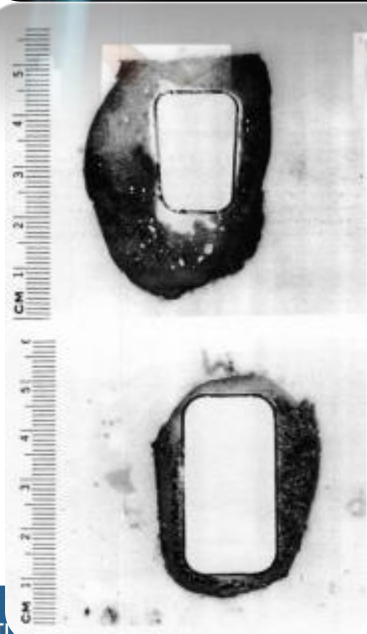
Scuola Superiore Sant'Anna

# The ROBODOC Integrated Surgical Systems, Inc.





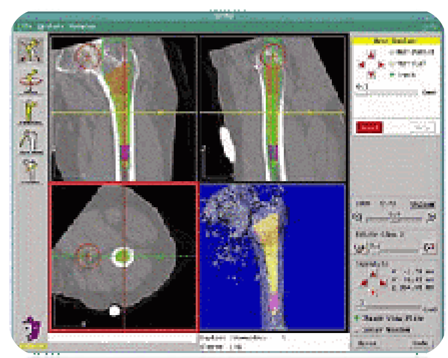



**Bone implant comparison**

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



Scuola Superiore Sant'Anna

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

# ROBODOC: from riches…
# ROBODOC: …to rags…

INTEGRATED SURGICAL SYSTEMS

*Redefining Surgery...*

**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

# Micro-active Endoscopes and Needle Steering

IEEE ICRA 2012 Needle Steering Workshop

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

Prof. Koji Ikuta

Prof. Jaydev Desai

Prof. Rajni Patel

Prof. Moshe Shoham

Prof. Mamoru Mitsuishi

Lecture Notes in Computer Scienc
Volume 2878 2003

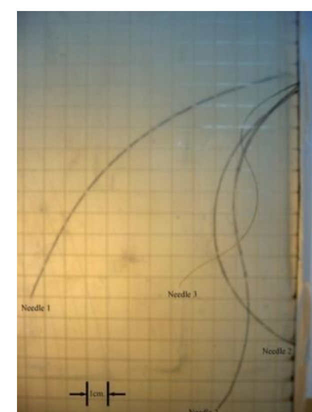
Medical Image Computing and Computer-Assisted Intervention - MICCAI 2003

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

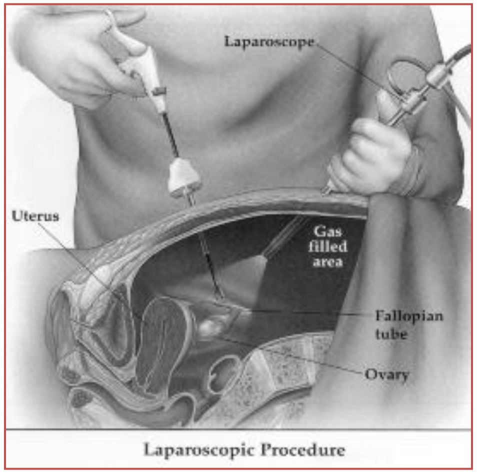
Prof.Tim Salcudean

P. Pierre Dupont


Prof. Allison Okamura



# Modern Surgery results from the "convergence" and integration of many scientific discoveries and technological advancements




- Anesthetics
- Antiseptics
- Anticoagulants
- Antibiotics
- Analgesics

→ **Modern surgery**

- Endoscopic instruments

Modern surgery + Endoscopic instruments → **Minimally invasive surgery**

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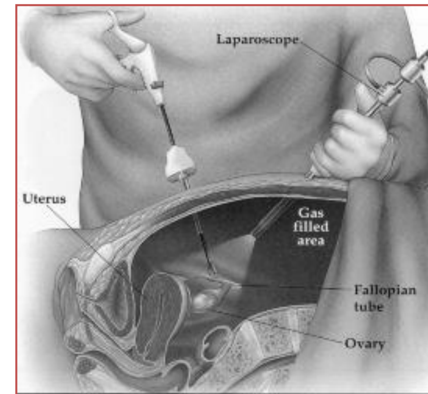
- Anesthetics
- Antiseptics
- Anticoagulants
- Antibiotics
- Analgesics

→ Modern surgery

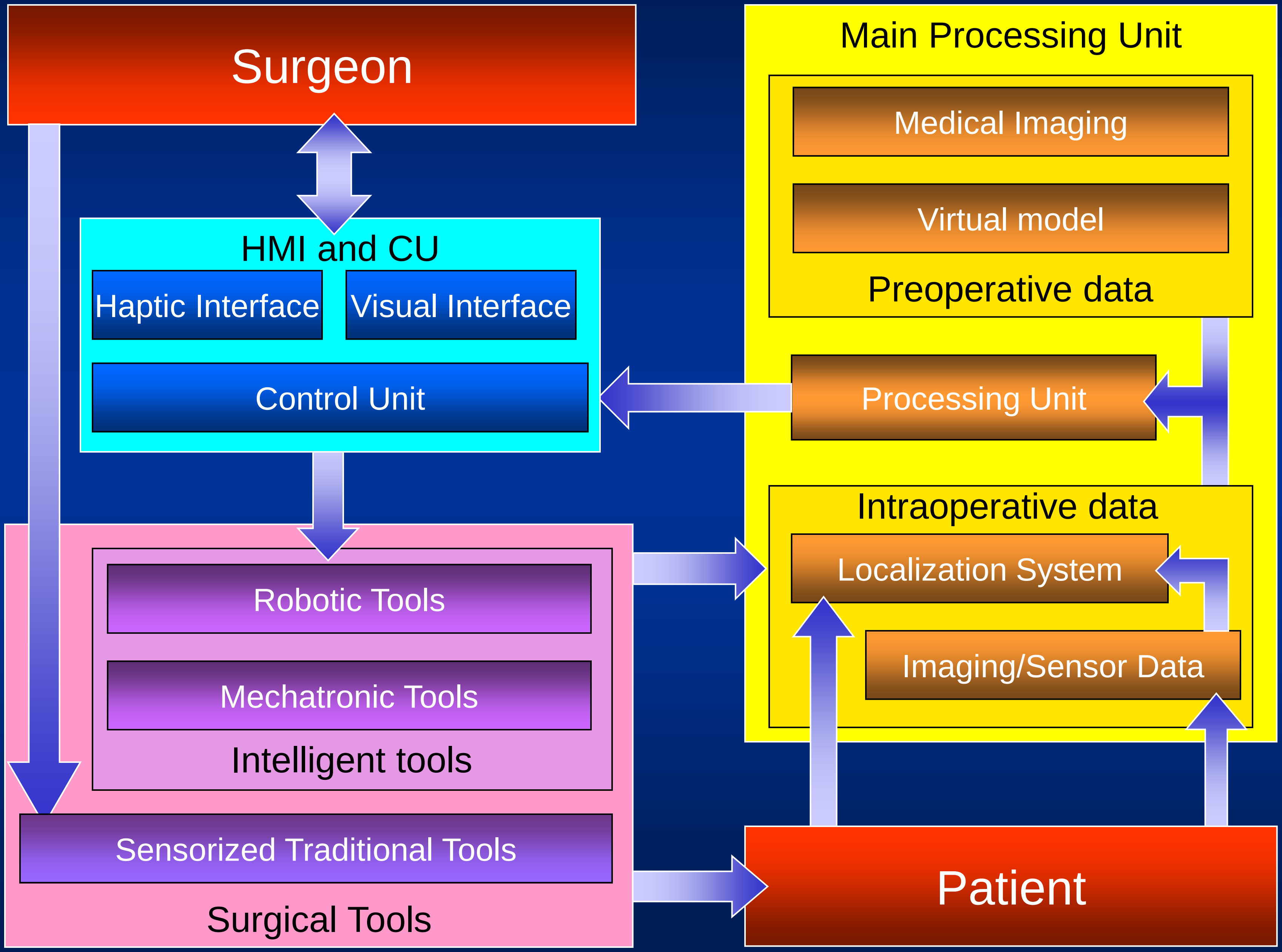
Endoscopic instruments → Minimally invasive surgery (from Modern surgery)



Laparoscopic Procedure

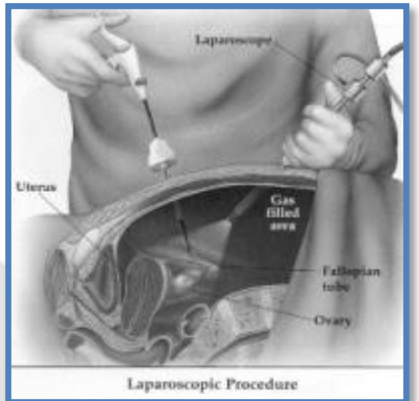
Imaging and robotics → Computer-assisted surgery (from Minimally invasive surgery)

# Computer Assisted Surgery: Functional Scheme



# The Evolution of Surgery

**TRADITIONAL TECHNIQUES**




**LAPAROSCOPIC SURGERY**


Access Trauma Reduction &
Increased Internal Dexterity


**ROBOTICS SURGERY**

- \+ Accuracy
- \+ Predictability
- \+ Repeatability

= Quality

# Robotics Surgery: Lessons Learned in 25 years

- **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**

52. Medical Robotics and Computer-Integrated Surgery

**2008 and 2013**


Russ Taylor, Arianna Menciassi, Paolo Dario,

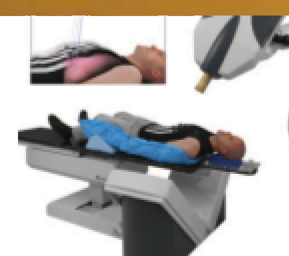
The two most successful surgical robots so far:

- DaVinci (teleoperated)
- CyberKnife (autonomous)

**adopt solutions based on the above lessons**

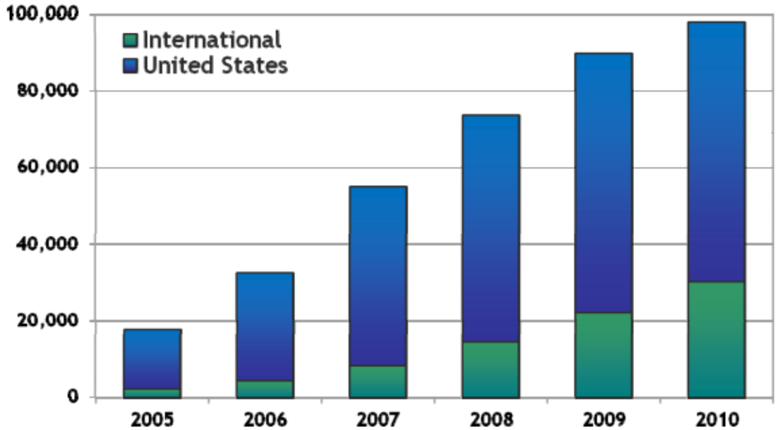


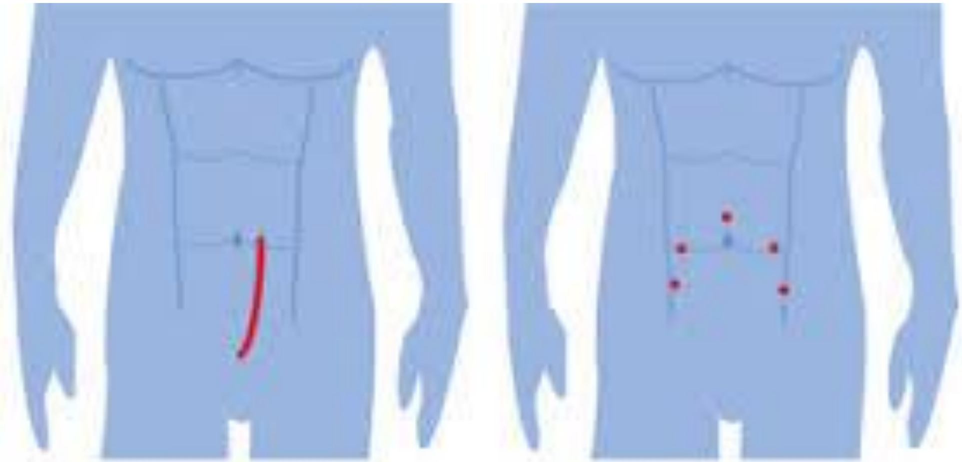





# Successful daVinci applications in surgery

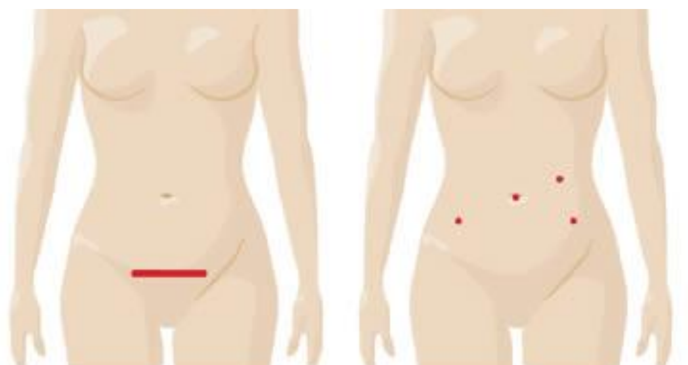
## *da Vinci®* Prostatectomy Procedure Growth



Open Prostatectomy Incision

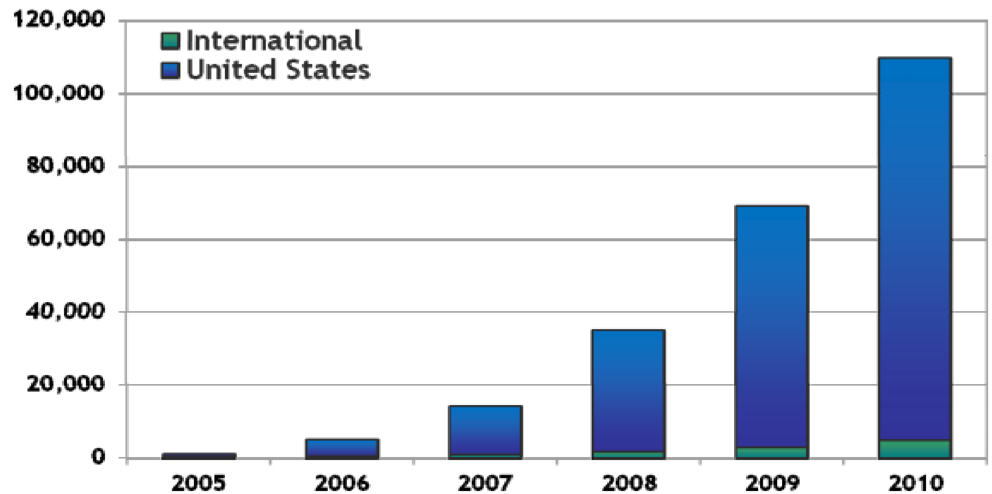
*da Vinci* Prostatectomy Incisions



Open Hysterectomy Incision

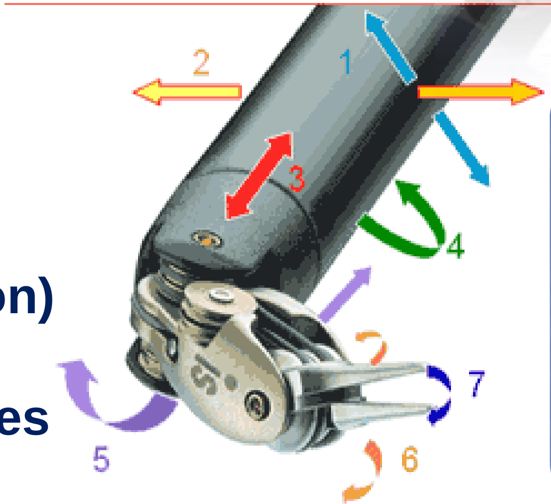
*da Vinci* Hysterectomy Incisions

## *da Vinci®* Hysterectomy Procedure Growth

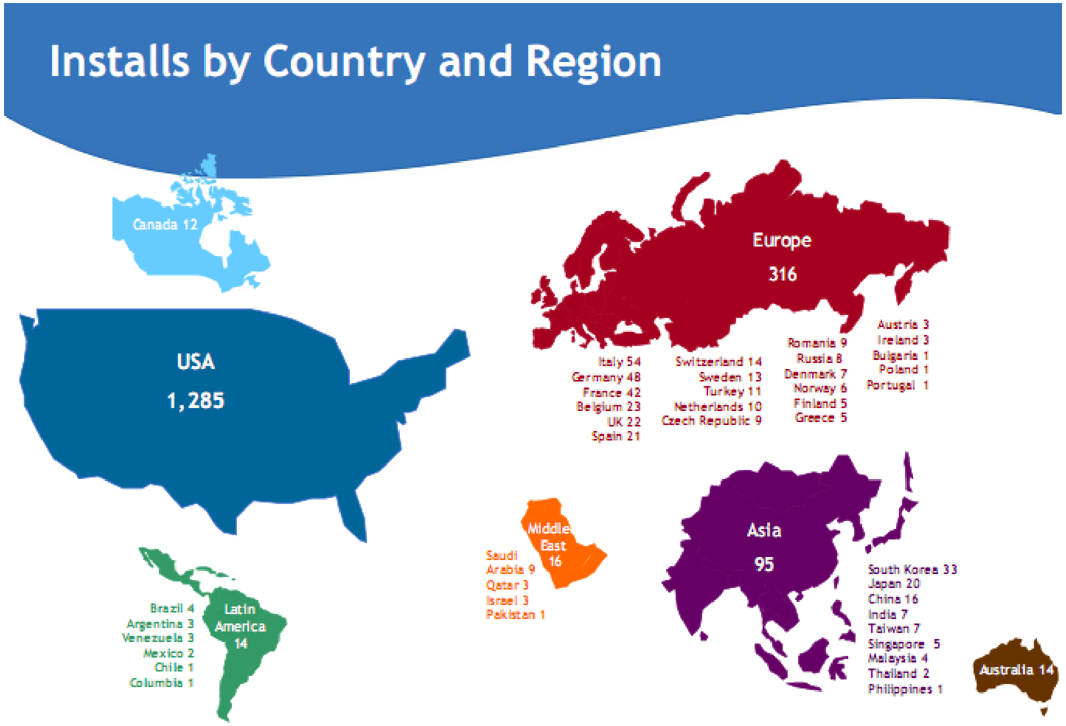


# The “Secrets” of the DaVinci Robot Success: Accuracy, Dexterity, Intuitiveness


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




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




**DaVinci Worldwide Installations**

**2.700+ systems installed in 30 Countries and in 1800+ 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 |

**In 2012, 450.000 surgical procedures** were performed with the da Vinci Surgical System. **1.500.000 procedures in total so far**.

SOURCE: www.intuitivesurgical.com

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

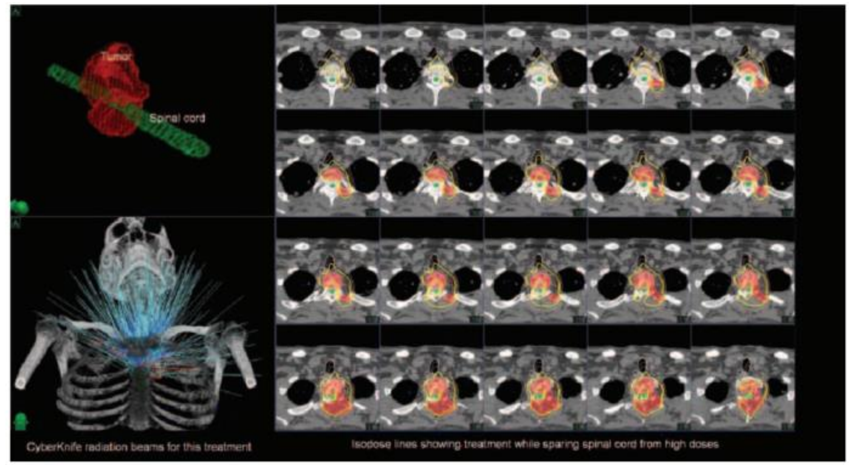
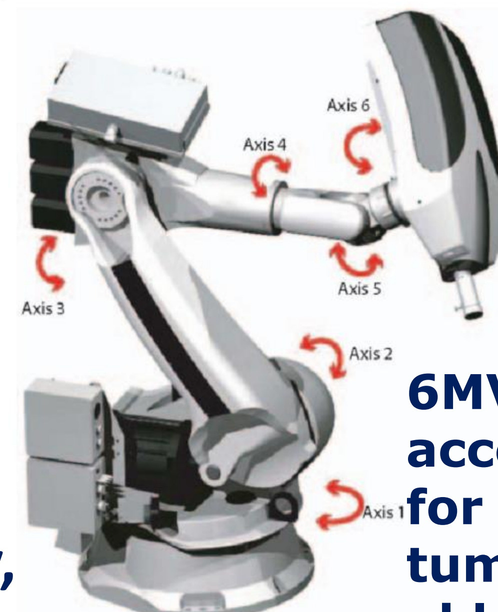




**Figure 4** Top left image: the patient model with the tumour to be targeted and the spinal cord radiosensitive area. Bottom left: CyberKnife radiation beams for treatment. Right: Isodose lines for treatment.

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)**

# The Synchrony Tracking System


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

**Overall precision of treatment**

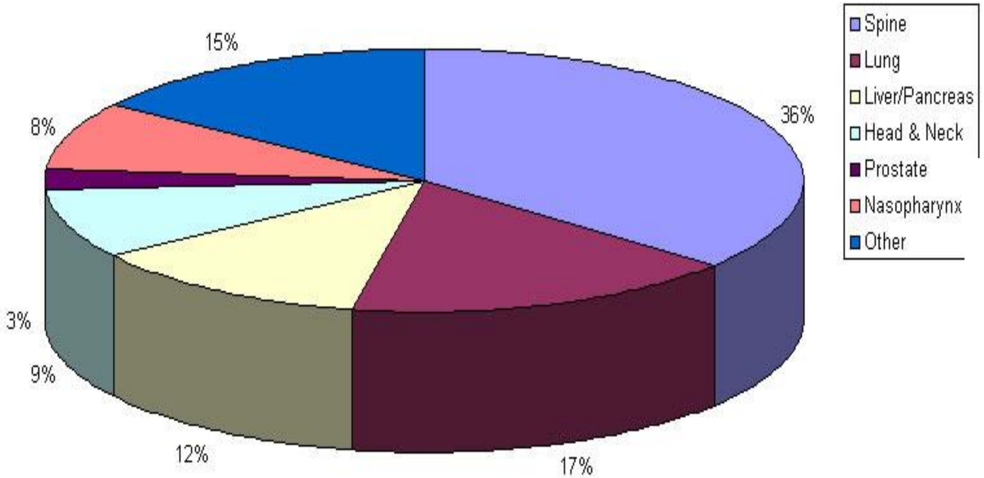
- **<0.95mm for cranial and spinal lesions**
- **1.5mm for moving targets with respiratory tracking**

# 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.

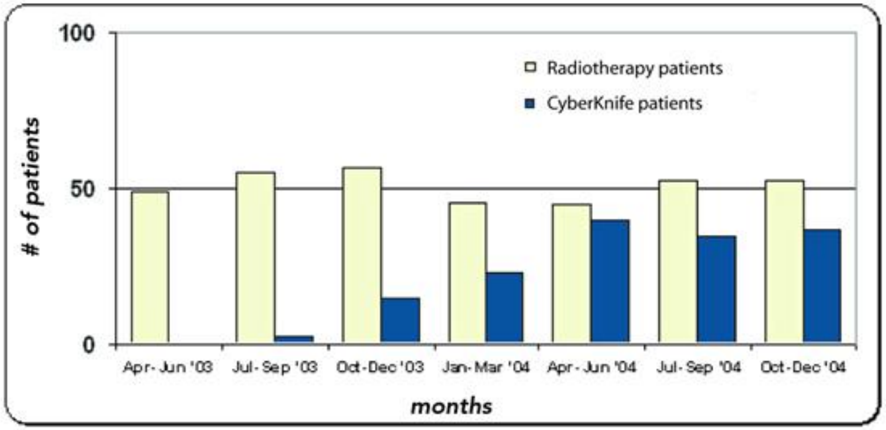
2011 AccuRay Data

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




Total CyberKnife System Treatments by Tumor Location

Source: www.accuray.com




Patient Population

# 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: 450.000+ surgical interventions worldwide in 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

# 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?)

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# Why a Change of Paradigm is INEVITABLE

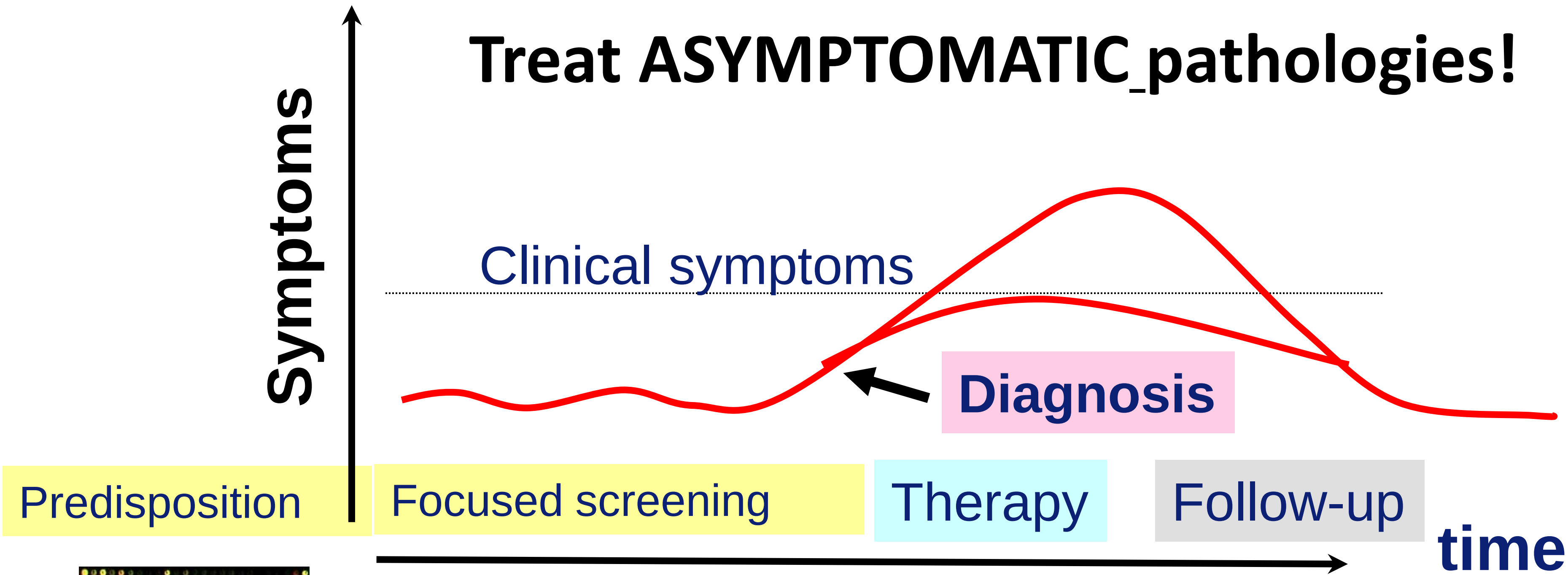
**Professor Sir Alfred Cuschieri, MD**
Director of the Institute of Medical Science and Technology in Dundee and St Andrew's Universities. Pioneer of endoscopic surgery

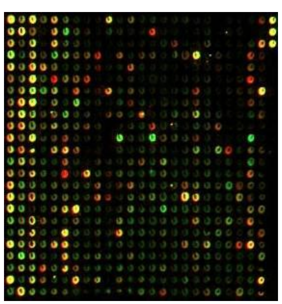
***The operating room of the year 2030 will be a totally different environment than today***

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

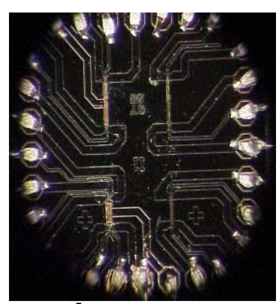
**The combination of micro/nano/bio technologies, molecular biology, chemistry, physics, robotics/microrobotics, etc. will be key technologies enabling future high quality (accurate and repeatable), early and minimal invasive surgery**

# Prevention: the challenge of modern medicine

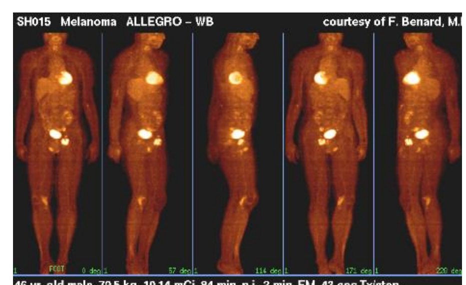


Gene Chip



Biosensor




PET-CT
Molecular Imaging

Molecular Diagnostics

***Courtesy by Philips***

# Trends in Surgical Robotics Research

## Ultra-low access and endoluminal robotics surgery

Da Vinci-like robots

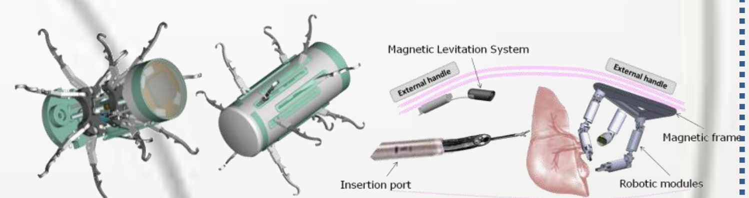
### Ultra-low access surgery


OUTSIDE: large robot

INSIDE: very small access and tools inside the body

Capsule-like robots

### Endoluminal surgery




OUTSIDE: no robots or small control platform

INSIDE: small or modular robots

# Ultra-low access robotics surgery

Ultra-low access and endoluminal surgery

Da Vinci-like robot

Ultra-low access surgery

OUTSIDE: large robot

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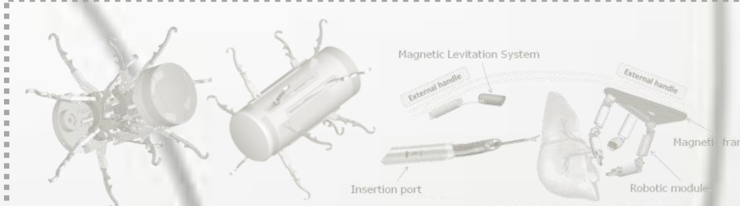
Endoluminal surgery




OUTSIDE: no robots or small control platform

INSIDE: small or modular robots

# Surgical Robots

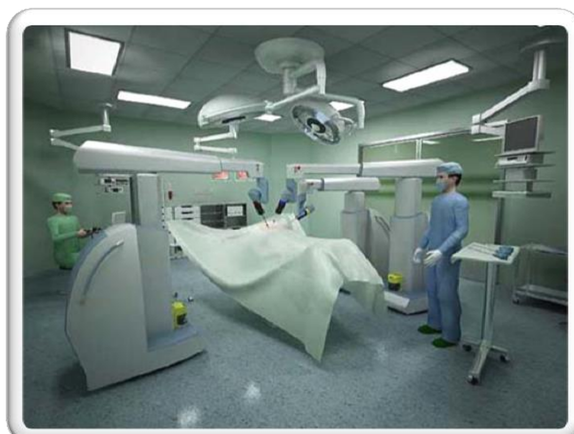
**daVinci Surgical System**
(Intuitive Surgical Inc., CA, USA)

In 2010 approximately **276,200** procedures were performed worldwide with a **40%** increase over 2009

**THE PRESENT: ONE SUPPLIER**

**daVinci Surgical System**
(Intuitive Surgical Inc., CA, USA)

**Amadeus Maestro**
(Titan Medical Inc., Canada)



**Alf_X**
(Sofar S.p.A., Italy)

**Approved for Human Clinical Trials**

**THE NEAR FUTURE: MORE SUPPLIERS**

# Titan Medical & KUKA LWR

**April 19, 2010**
Titan Medical Inc. (Canadian public company (TSX VENTURE:TMD) http://www.titanmedicalinc.com/ ) is pleased to announce that **it has selected KUKA Robotics Corporation to supply its Lightweight Robot (LWR) to be integrated with Amadeus*** , a next generation robotic surgical system currently under development by the Company.

Dr. **Reiza Rayman**, President of Titan Medical Inc., commented as follows:
"**KUKA's Light Weight Robot represents a significant advancement in medically designed robotic technology**. The intelligence, speed, and accuracy of the LWR are currently unprecedented. We feel confident that this technology will add further advanced capability to Titan's Amadeus platform."

* Amadeus® Robotic Surgical System is the next generation 4-armed robotic surgical platform. The goal is to bring surgery to a completely new level, because technology will give surgeons extraordinary capability.

The ARAKNES Project has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement num. 224565.

# Hyundai Heavy Opens New Surgical Robot Lab

2012.02.20

**Photo**
(from left): Mr. Park seong-wook, President of Asan Medical Center, Mr. Cho Sung-jang, Secretary General of Asan Foundation and Mr. Lee Choong-dong, Senior Executive Vice President of Hyundai Heavy with a 5-axis surgical robot.

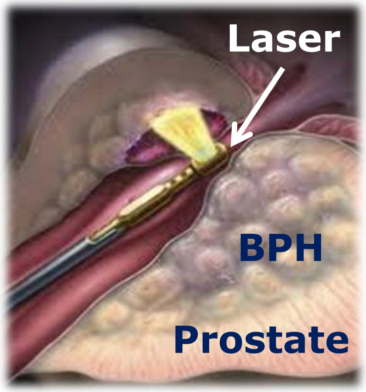
Hyundai Heavy Industries, the world's biggest shipbuilder and Korea's largest industrial robot manufacturer, announced today the opening of a laboratory with Asan Medical Center in an effort to step up the development of surgical robots at Asan Institute for Life Science on February 17.

The opening ceremony was followed by the Symposium for Surgical Robots at Asan Medical Center. At the Korea's largest robot symposium, the Company unveiled projects developing a 6-axis surgical robot system for joint repair, ligament reconstruction robot, and interventional robots.

Hyundai Heavy won US FDA approval for main bodies and controllers of the surgical robot ROBODOC with the local robot venture CUREXO last year. Asan Medical Center completed 2,800 clinical tests using surgical robots.

Surgical robots are one of the future growth engines Hyundai Heavy pursue developing. According to Frost & Sullivan, a consultancy, the global surgical robot market is projected to grow to USD 6.6 billion by 2014.

# Laser assisted robotic surgery in UROLOGY

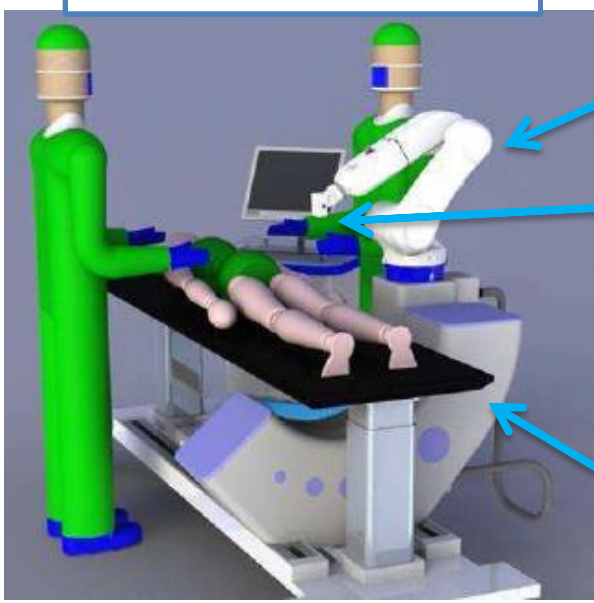



**PROBLEM**:

- To perform the **laser treatment of benign prostatic hypertrophy** (BPH), by reconstructing the channel of the prostatic urethra in a homogeneous way
- To increase the accuracy of the treatment
- To ensure the contact between the laser fiber and the tissue, thus avoiding thermal damage (carbonization) as much as possible

**SOLUTION: a guidance system to provide the surgeon with a 3D visualization and sensor feedback**

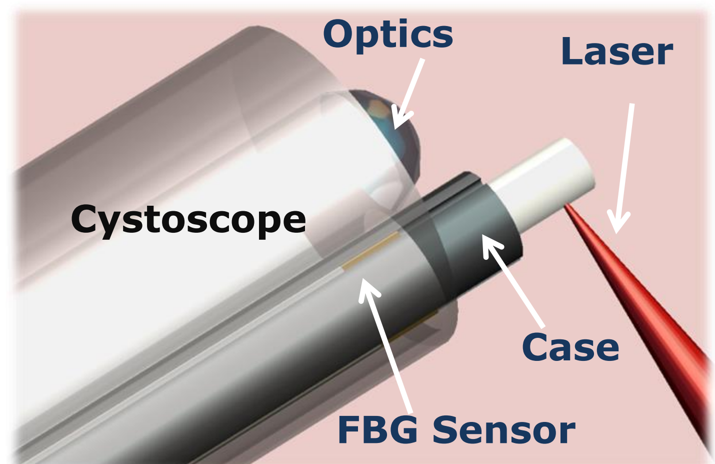
**ROBOTIC PLATFORM**



6 DOF ADEPT Robot

Shared control:
Cystoscope is mounted on the robot's end effector and moved by surgeon

Imaging system (3D RX)




Strain sensor for detecting contact with tissue

A new EU Project
Coordinator: Prof. Arianna Menciassi, SSSA

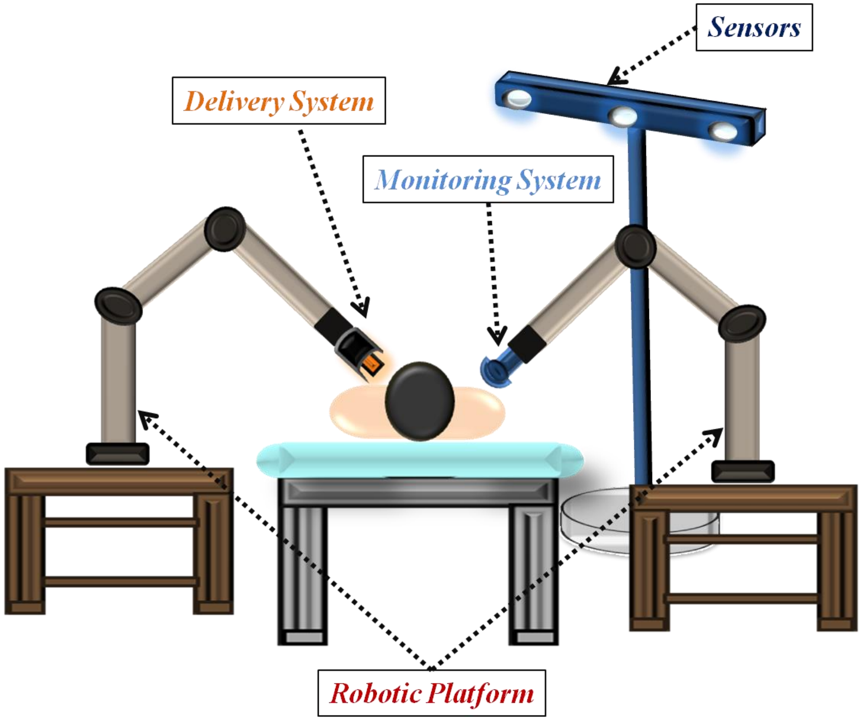
# FUTURA

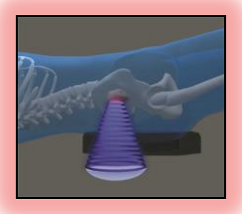
**F**ocused **U**ltrasound **T**herapy **U**sing **R**obotic **A**pproach

SEVENTH FRAMEWORK PROGRAMME

**Merging surgical robotics, non-invasive therapy (e.g. focused ultrasounds) and machine learning for medical imaging**

- ***Robotic platform:*** two serial commercial manipulators
- ***Monitoring system:*** 2D US confocal probe + 3D US probe
- ***Delivery system:*** custom made HIFU transducer
- ***Sensors:*** Smart environmental sensors + Human-Robot Interaction (HRI) monitoring



**UNDER NEGOTIATION WITH EU COMMISSION**

# Ultra-low access robotics surgery

## Ultra-low access and endoluminal surgery

Da Vinci-like robot

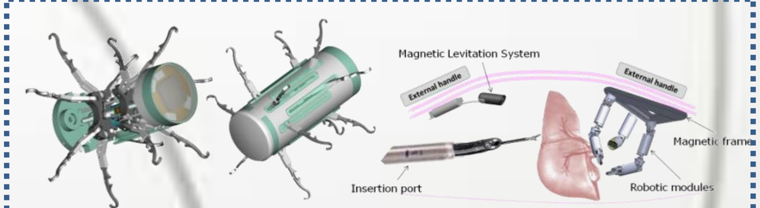
Ultra-low access surgery

OUTSIDE: large robot

INSIDE: very small access and tools inside the body

Capsule-like robot

Endoluminal surgery



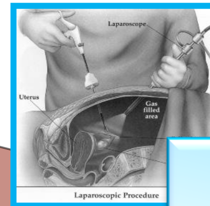

OUTSIDE: no robots or small control platform

INSIDE: small or modular robots

# The Evolution of Surgery

**TRADITIONAL TECHNIQUES**

**Access Trauma Reduction in Surgery**



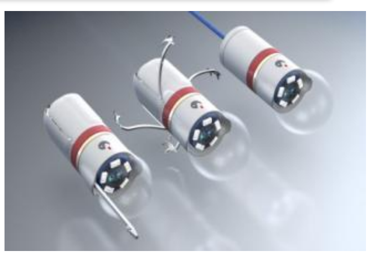

**LAPAROSCOPIC SURGERY**

**SURGICAL ROBOTICS**

**Size: in the ≤ 1 mm range**

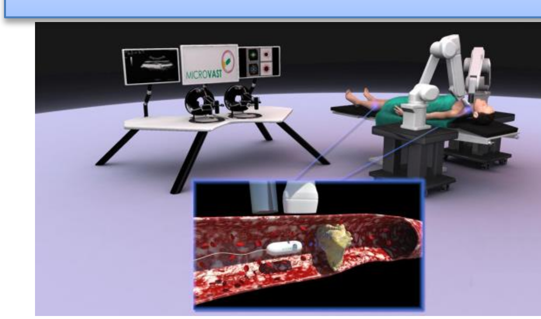
**Interventional platforms in the meso scale**

**ACTIVE (ROBOTIC) ENDOSCOPIC DEVICES AND CAPSULES**



**SCARLESS ROBOTIC SURGERY**

**VASCULAR ROBOTIC SURGERY**



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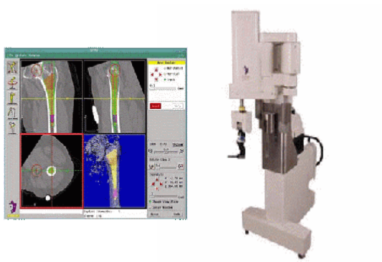
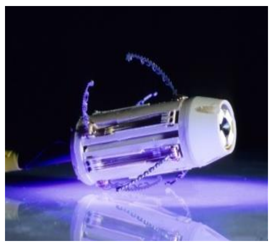
# Robotics Surgery: Our Vision & Our Roadmap

$1=10^{0}$ [m] $10^{-1}$ $10^{-2}$ $10^{-3}$

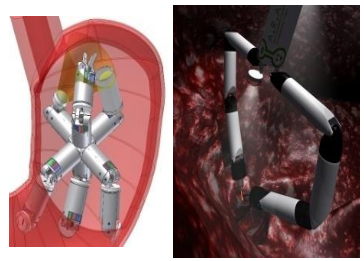
**Surgical Robotics**



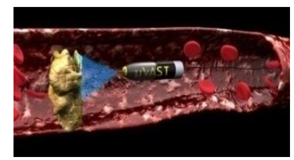
**Capsular Endoscopy**



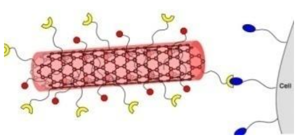
**Reconfigurable endoluminal platforms**



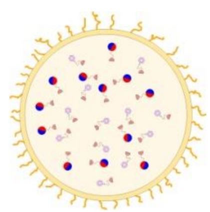
**Intravascular robotics**



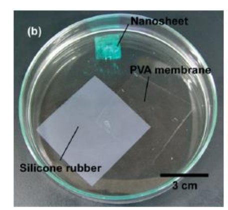
**Interventional platforms in the meso scale**



**Nano-particles, nano-tubes, nano-shells**



**Functionalized nano-carriers, advanced drugs**

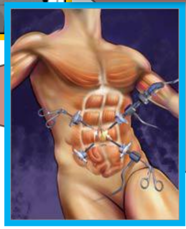



**Smart structures**

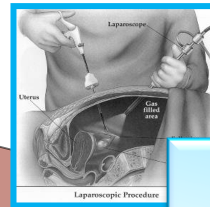
$10^{-9}$ [m] $10^{-6}$ $10^{-3}$

**Advanced Photonics**

**TRADITIONAL TECHNIQUES**



**Access Trauma Reduction in Surgery**



**LAPAROSCOPIC SURGERY**

**SURGICAL ROBOTICS**

**Size: in the ≤ 1 mm range**

**Interventional platforms in the meso scale**

Combining **robotic technologies**, "wireless" actuation and biotech **for** transforming **systemic** therapeutic approaches into **targeted, local and precise** therapeutic approaches

**An endoluminal robot could also be seen as a carrier of micro/nano therapy agents (i.e. a SHUTTLE)**

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# Passive and Active Endoscopic Devices

ess Reduction in GI Endoscop

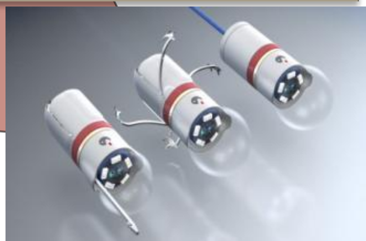
**TRADITIONAL TECHNIQUES**

**FLEXIBLE ENDOSCOPY**

**PASSIVE ENDOSCOPIC CAPSULES**



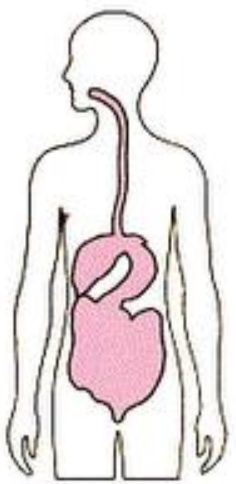
**ACTIVE (ROBOTIC) ENDOSCOPIC DEVICES AND CAPSULES**



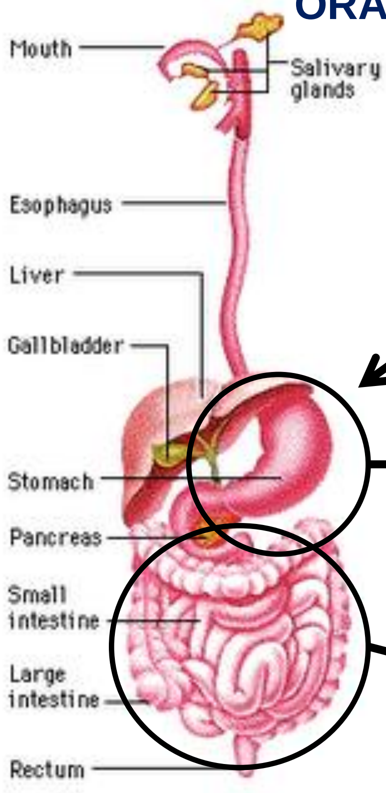
# Endoluminal endoscopy and therapy in the gastrointestinal tract: different possible accesses

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

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

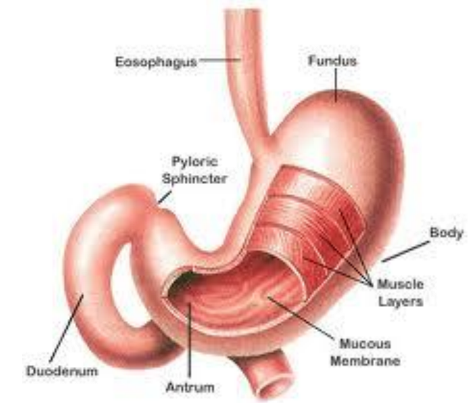


**ORAL ACCESS**




**ABDOMINAL AND UMBILICAL ACCESS**

**Stomach**




**RECTAL ACCESS**

**Colon**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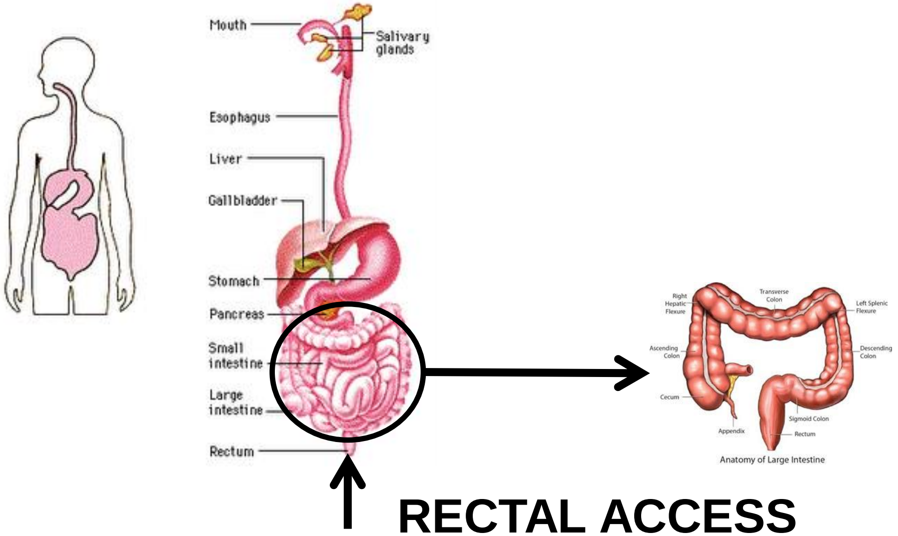


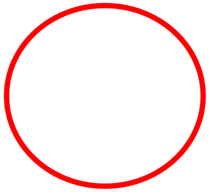

**Gastrointestinal Tract: Ø = 20-30 mm**

# Case Study #1

# Developing a system for **painless** gastrointestinal endoscopy

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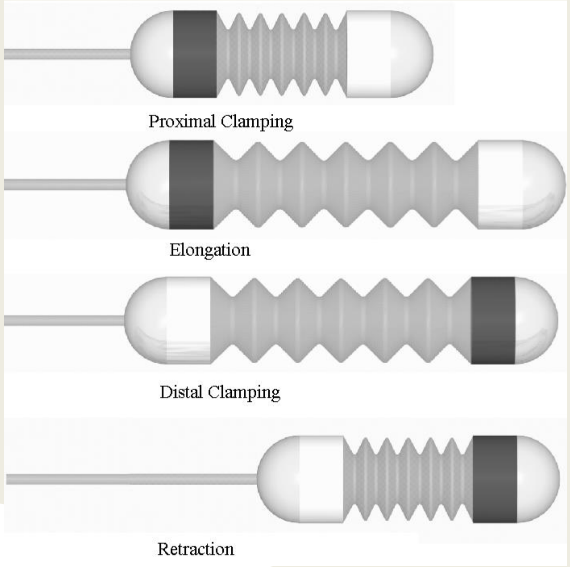
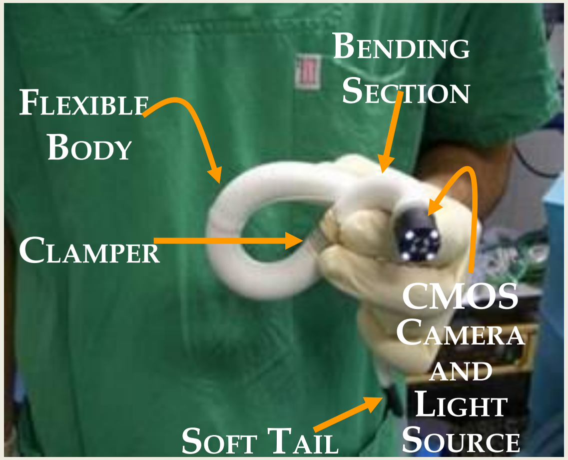
# From **bio-inspiration** to **bio-application**
## (the EU FET BIOLOCH and the EMIL IMC Projects)




**Problems in colonoscopy: pain, difficult maneuverability…**

**Semi-autonomous inchworm-like locomotion**

**…like a worm in the gut…**




# The E-WORM Painless Colonoscopy System

# From bio-inspired design to industrial design and clinical application (≈ 10 years)

Bio-inspiration

Engineering design

In vitro and in-vivo (animal) validation

Research (IMC EMIL Project@ SSSA)

Industrial design

Clinical application

Industrial and Clinical application (Endotics®) (more than 600 patients)

**Self propelling, inchworm-like painless colonoscopy system**

# In-Vitro Tests

## Conventional Colonoscopy Vs worm-like colonoscopy

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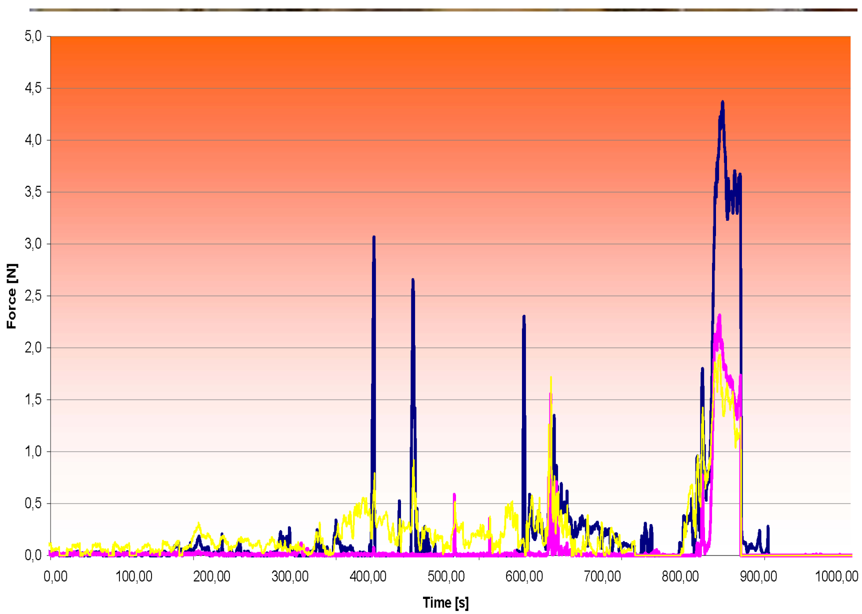
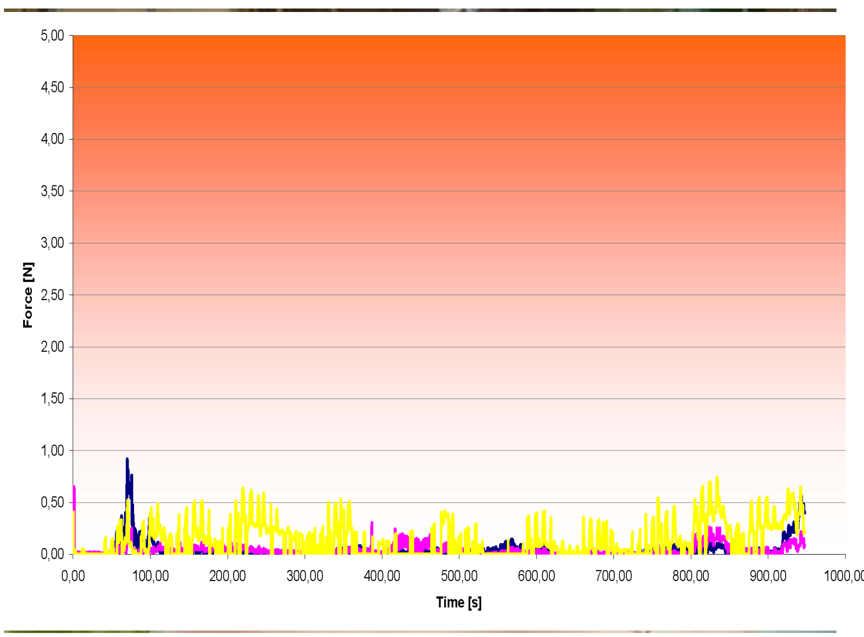
**E2 produces visibly less deformation to the geometry of the sigmoid. The pictures show how the conventional colonoscope is forcing the bowel to stretch (red arrows).**




Conventional Colonoscopy




$E^2$ endoscopy

:: CONTACT

Endotics

Professional Careers Partner

Int J Artif Organs. 2009 Oct 21;32(8):517-527. [Epub ahead of print]

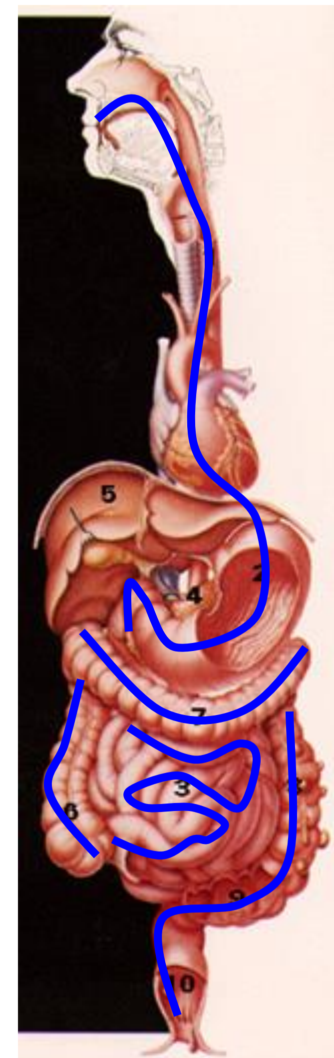
**Functional evaluation of the Endotics System, a new disposable self-propelled robotic colonoscope: in vitro tests and clinical trial.**

[Cosentino F](), [Tumino E](), [Rubis Passoni G](), [Morandi E](), [Capria A]().
Gastroenterology and Digestive Endoscopy, San Giuseppe Hospital, Milan - Italy.

**Abstract**

Objective: Currently, the best method for CRC screening is colonoscopy, which ideally (where possible) is performed under partial or deep sedation. This study aims to evaluate the efficacy of the Endotics System, a new robotic device composed of a workstation and a disposable probe, in performing accurate and well-tolerated colonoscopies. This new system could also be considered a precursor of other innovating vectors for atraumatic locomotion through natural orifices such as the bowel. The flexible probe adapts its shape to the complex contours of the colon, thereby exerting **low strenuous forces during its movement**. These novel characteristics allow for a painless and safe colonoscopy, thus eliminating all major associated risks such as infection, cardiopulmonary complications and colon perforation. Methods: An experimental study was devised to investigate stress pattern differences between traditional and robotic colonoscopy, in which **40 enrolled patients underwent both robotic and standard colonoscopy within the same day**. Results: The stress pattern related to robotic colonoscopy was **90% lower than that of standard colonoscopy**. Additionally, the robotic colonoscopy demonstrated a **higher diagnostic accuracy**, since, due to the lower insufflation rate, it was able to visualize small polyps and angiodysplasias not seen during the standard colonoscopy. **All patients rated the robotic colonoscopy as virtually painless compared to the standard colonoscopy, ranking pain and discomfort as 0.9 and 1.1 respectively, on a scale of 0 to 10, versus 6.9 and 6.8 respectively for the standard device**. Conclusions: The new Endotics System demonstrates efficacy in the diagnosis of colonic pathologies using a procedure nearly completely devoid of pain. Therefore, this system can also be looked upon as the first step toward developing and implementing colonoscopy with atraumatic locomotion through the bowel while maintaining a high level of diagnostic accuracy.

# From “**wired**” painless colonoscopy to “**wireless**” GI endoscopy

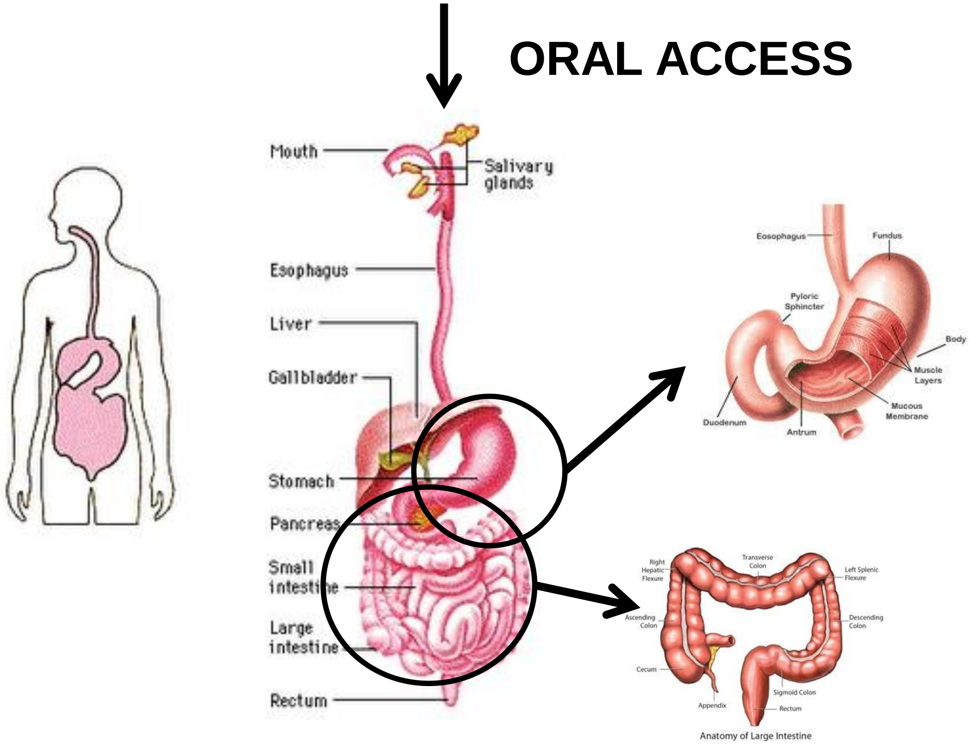


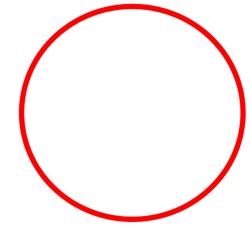
# Lessons learned

Reasons for smooth implementation:

- Easy access (Φ= 20÷60mm)
- Two-ended openings
- Sterilization not required (just disinfection)
- **External energy source available**

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



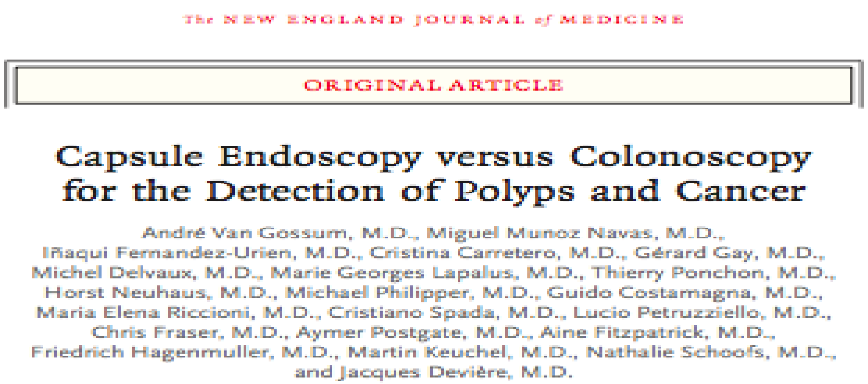
**Oesophageal Tract:**
**Ø = 10 to 15 mm**

# Case Study #2

# Swallowable Endoscopic Capsules

# Passive commercially available wireless capsule endoscopy


G. Iddan, and P. Swain, "History and development of capsule endoscopy",
*Gastrointest. Endos., vol. 14, pp. 1-9, 2004.*


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)

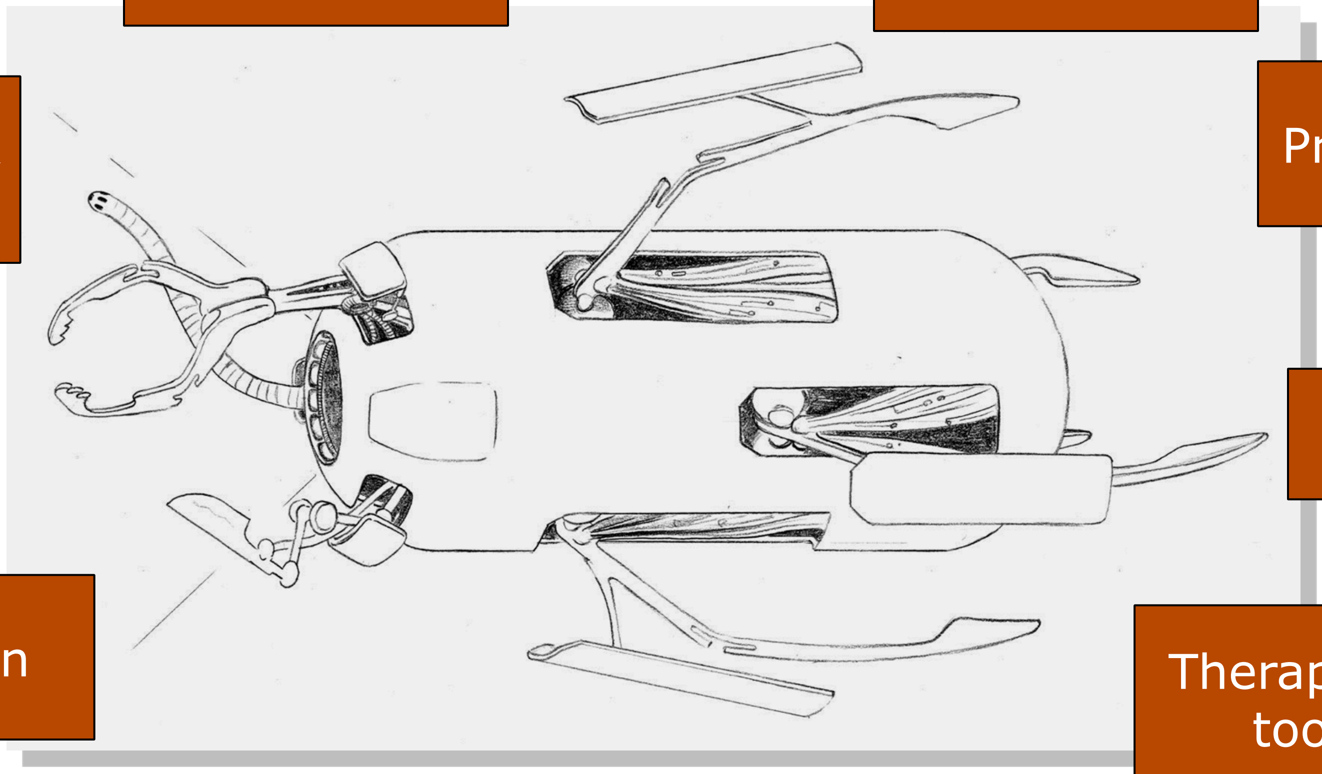
## Benefits:

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

## Limitations:

- **Passive locomotion**
- **False negative results**

# **ACTIVE CAPSULE**: a **wireless endoscopic 'SHUTTLE'**




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

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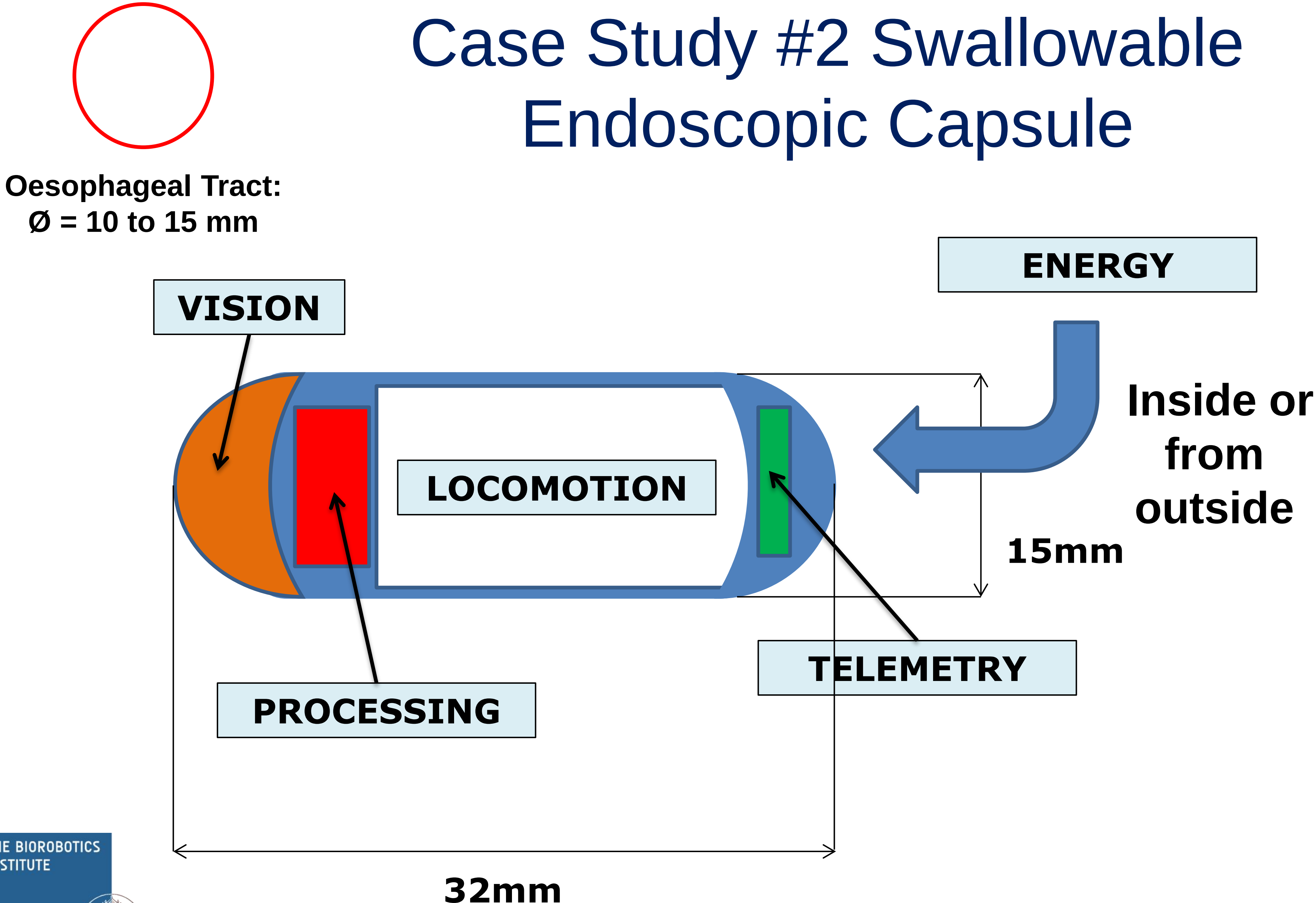
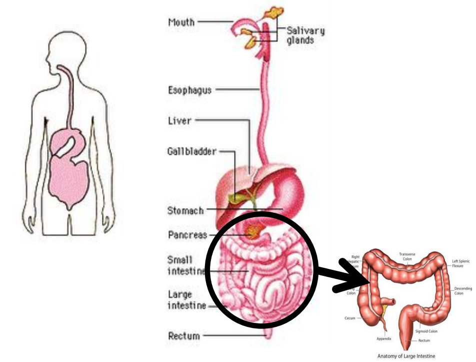
# Case Study #2 Swallowable Endoscopic Capsule



# Attempt #1: Legged capsule

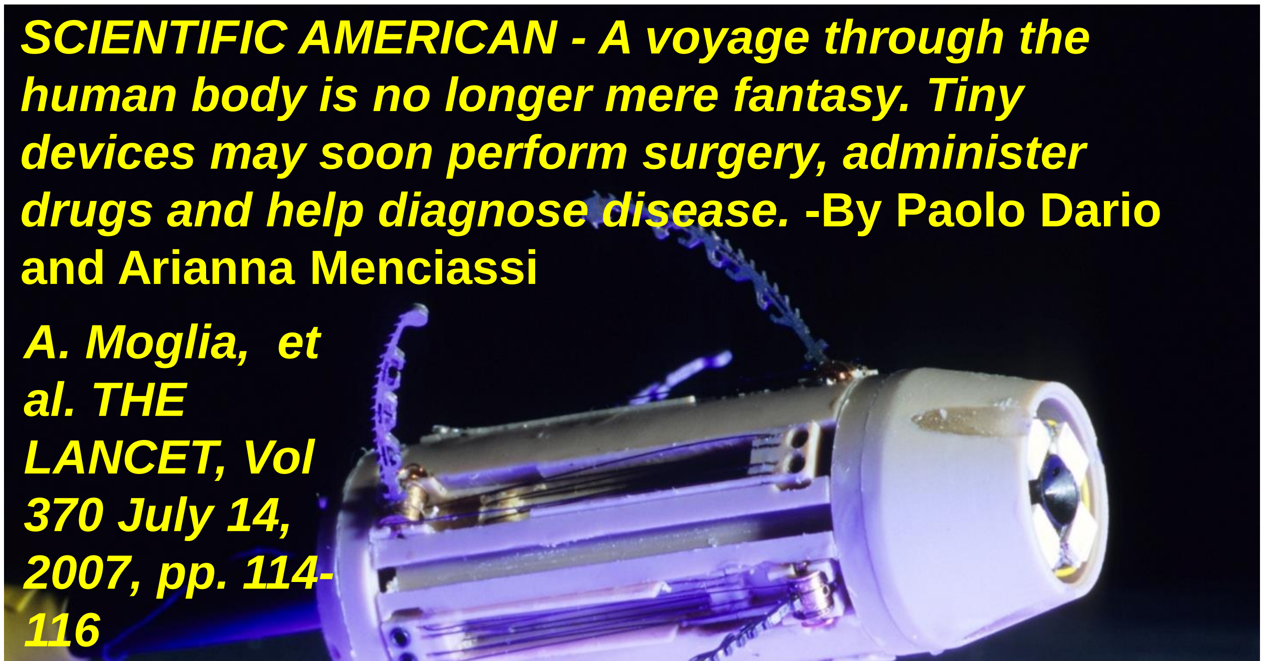
**Oesophageal Tract:**
**Ø = 10 to 15 mm**

ORAL ACCESS

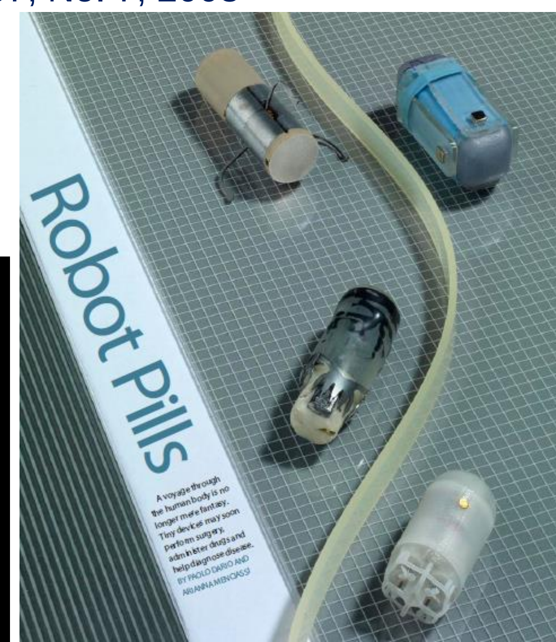



***SCIENTIFIC AMERICAN - A voyage through the human body is no longer mere fantasy. Tiny devices may soon perform surgery, administer drugs and help diagnose disease.*** **-By Paolo Dario and Arianna Menciassi**

***A. Moglia, et al. THE LANCET, Vol 370 July 14, 2007, pp. 114-116***



M. Quirini, et al.
GASTROINTESTINAL ENDOSCOPY
Vol. 67, No. 7, 2008

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# Bioinspired design of an **active** endoscopic capsule

**Problem: pain, difficult maneuverability…**

**Solution: inchworm locomotion, self-adaptability**

**Problem: slow, not adequate for different gut diameters…**

**Solution: legged locomotion, insect-like capsular endoscopy**

**…like a worm in the gut…**

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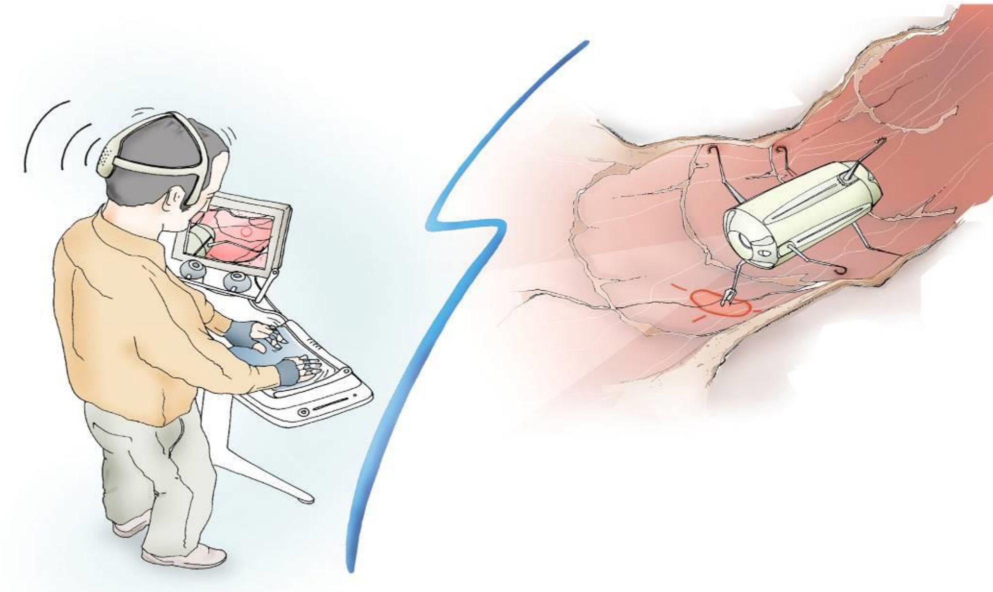
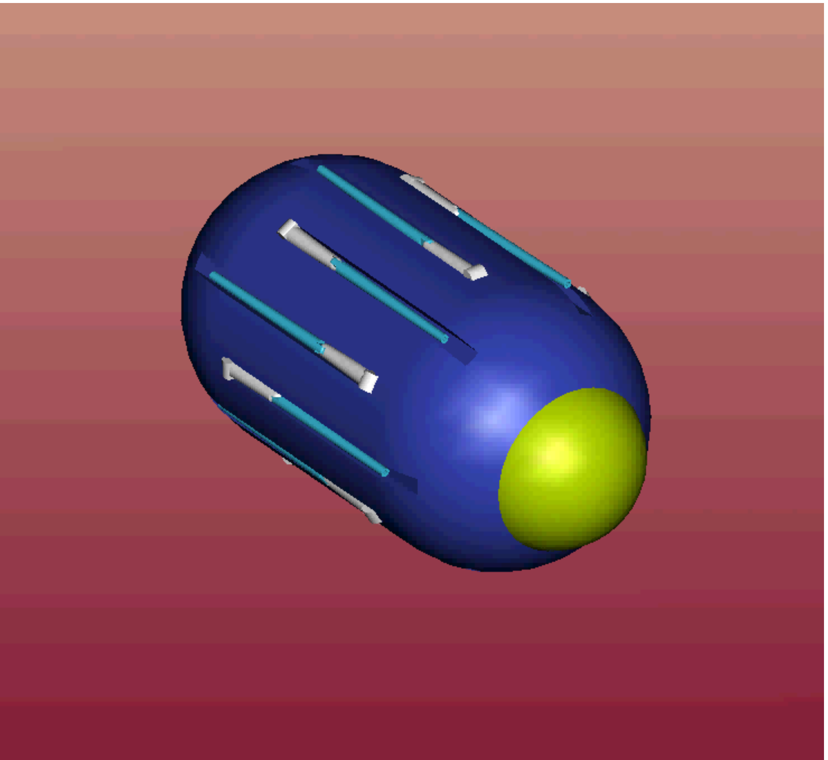
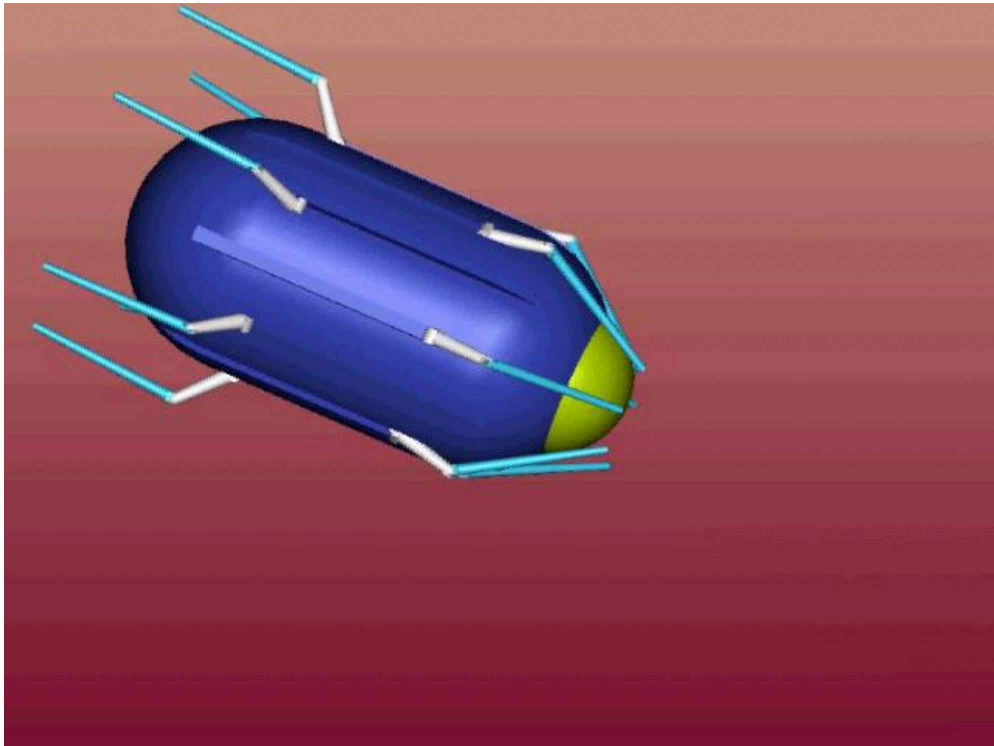
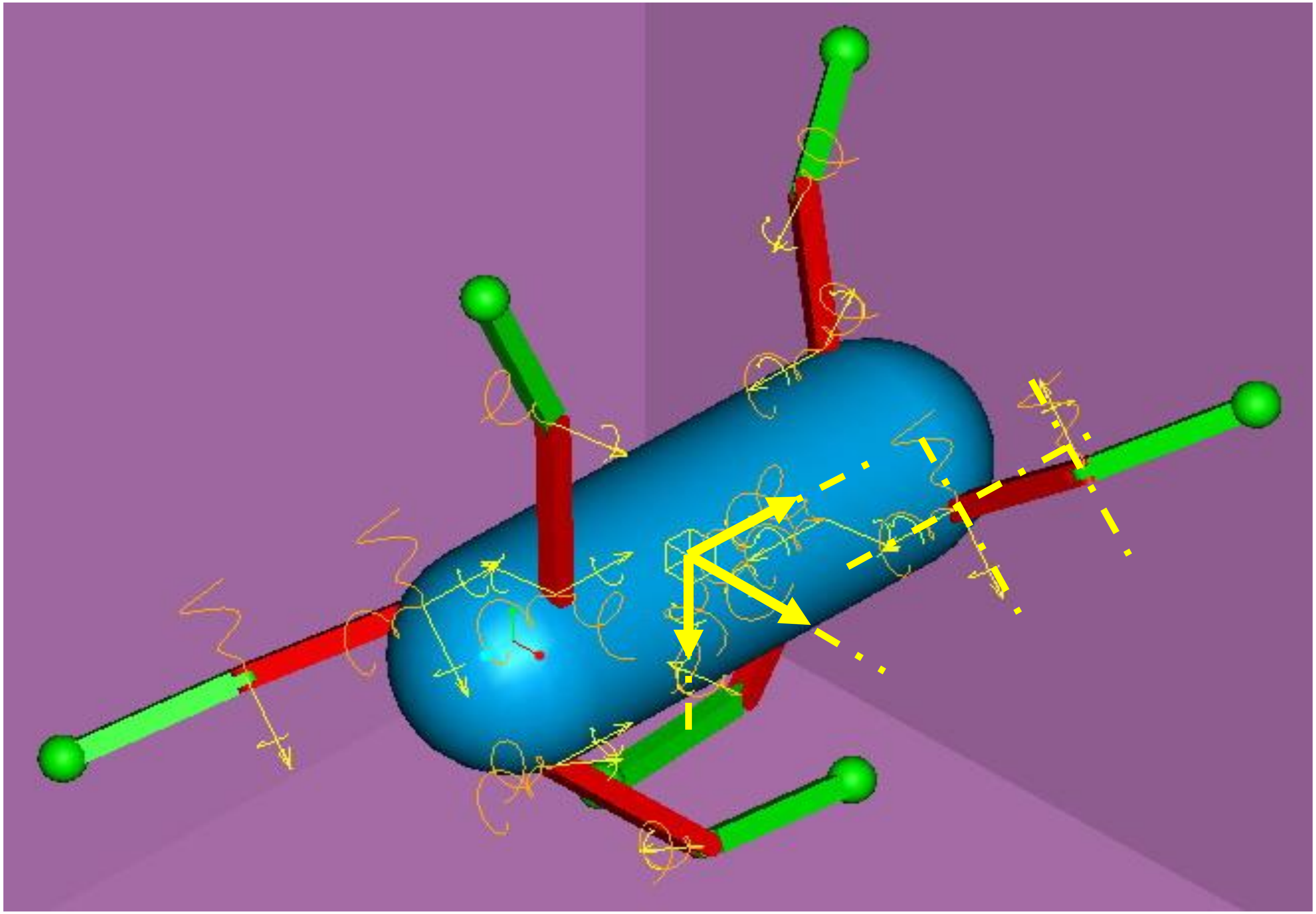
# Active, wireless, miniature capsule for endoscopy in the tubular GI tract







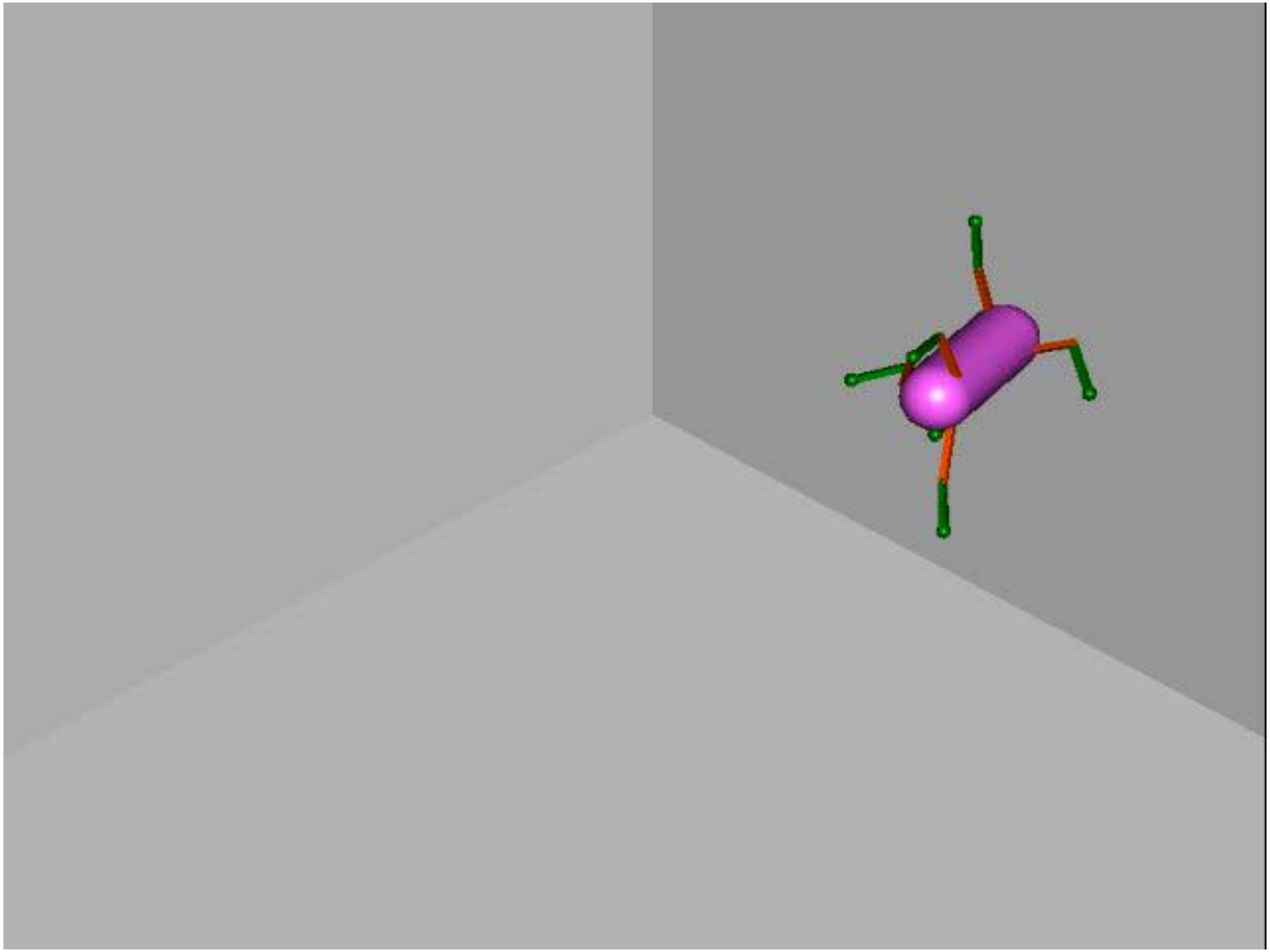
# Free body kinematics





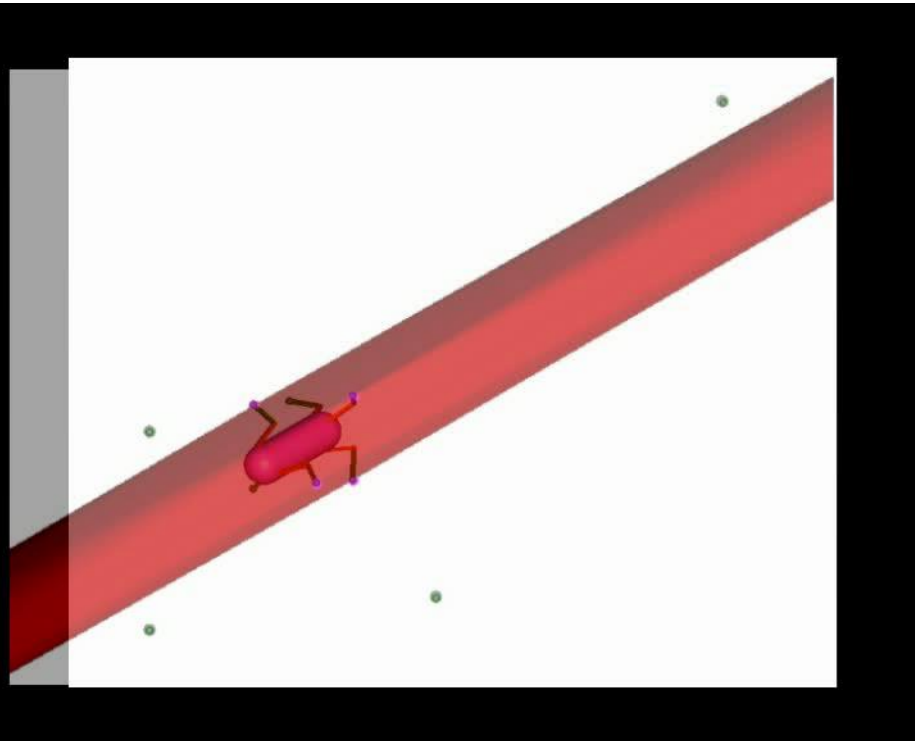
**Modeled degrees of freedom: 3 (body trans.) + 3 (body rot.) + 3n (legs)**

# Free body kinematics



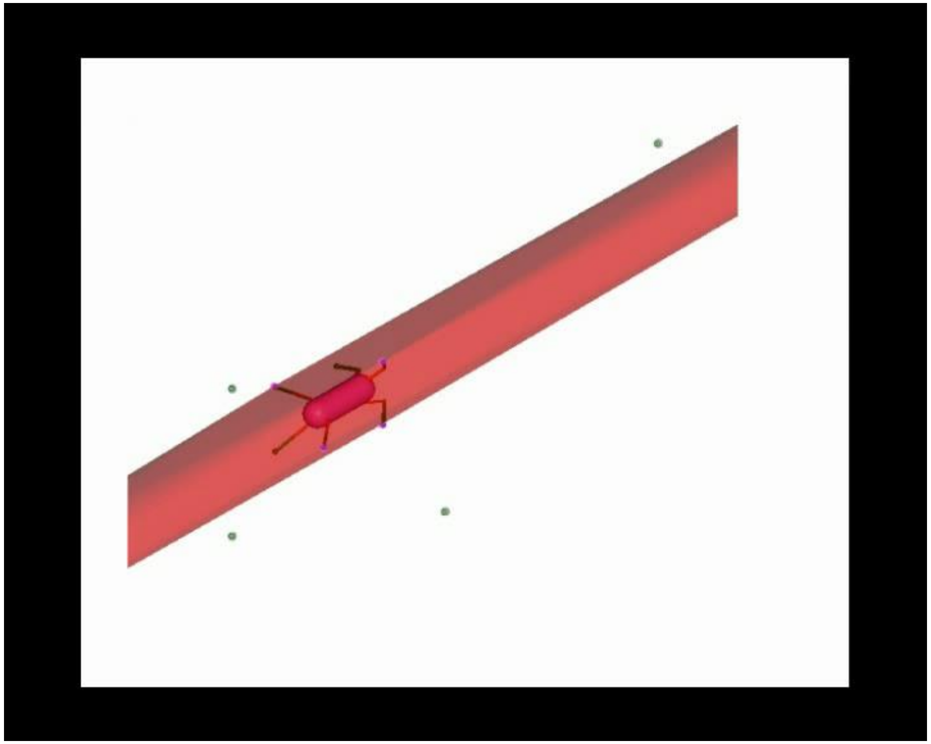
**Modeled degrees of freedom: 3 (body trans.) + 3 (body rot.) + 3n (legs)**

# Comparing different gait patterns



| | |
|---|---|
| **Front/rear phase:** | **0°** |
| **Period:** | **3 s** |
| **Full interval:** | **12 s** |
| **Traveled distance:** | **23 mm** |

**"Rower Gait"**



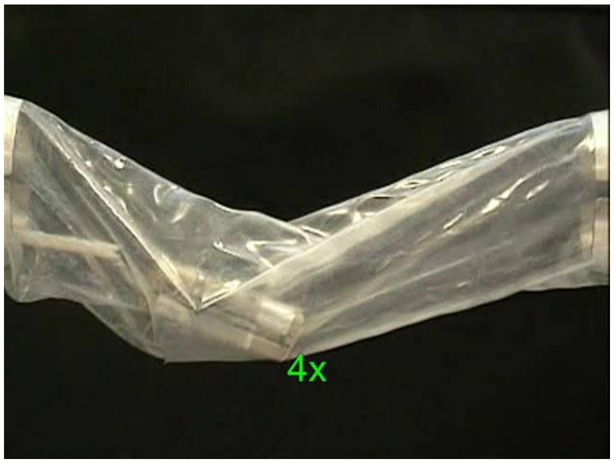
| | |
|---|---|
| **Front/rear phase:** | **180°** |
| **Period:** | **3 s** |
| **Full interval:** | **12 s** |
| **Traveled distance:** | **144 mm** |

**"Out of phase rower gait"**

**mean cycle power: 30 mW**
**energy / distance: 2.5 J/m**

Legged capsule for tubular organs.
From 4 to 8 and 12 biomimetic legs, with the aim of improving locomotion



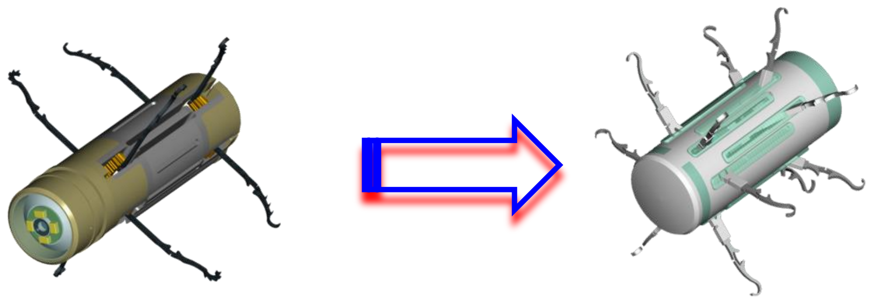


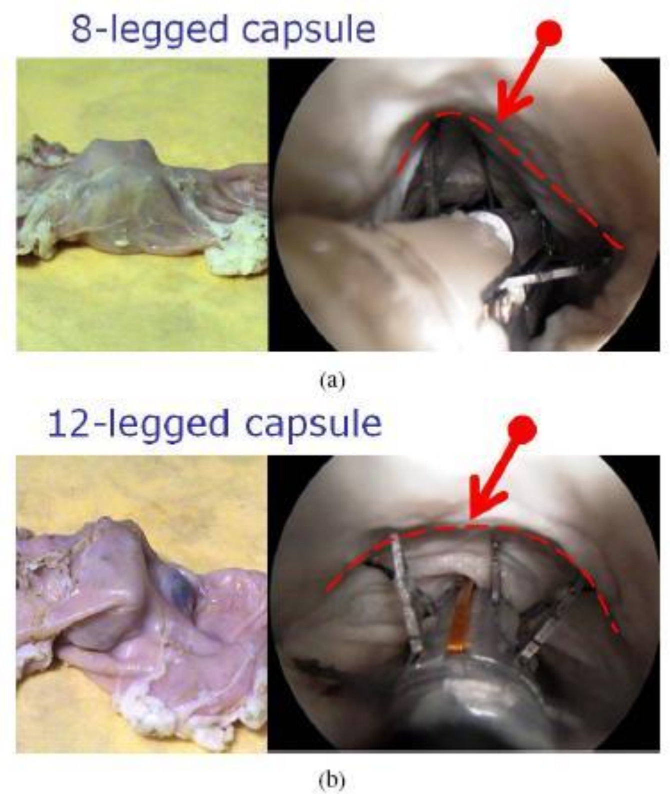


**Features: 12 legs (6 in the front and 6 in the rear part)**
**Dimensions: Φ11 mm; L30 mm**
**Average speed: 5 cm/minute**
**Pulling force: 3.8 N → 0.66 N per leg**


1. 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.
2. 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.
3. 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.

# 4-8-12 legs for a capsule





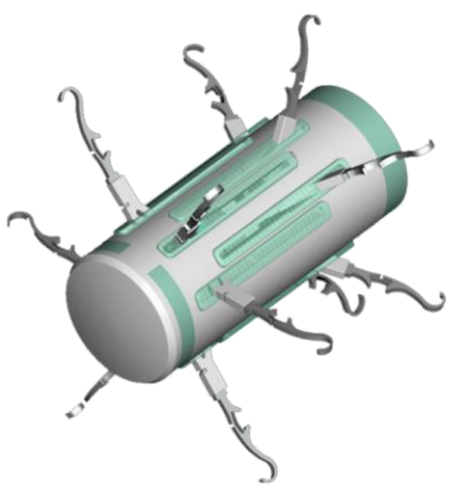

**Increasing the leg number aims at two main goals:**

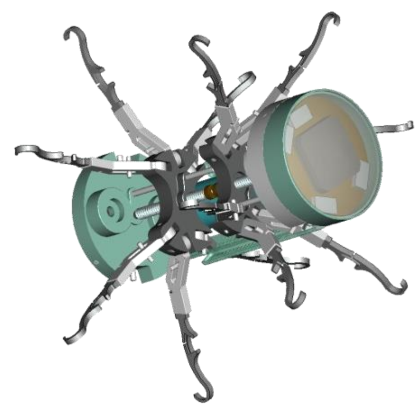
1) **more legs distribute the force necessary to propel the capsule over more points of contact, thus reducing the individual foot force and tissue irritation;**
2) **more points of contact improve the propulsion of the capsule in the folded, loose, highly deformable, unstructured environment of the colon.**

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

1. **Diameter: 11.1 mm;**
2. **Length: 28 mm (38.5 mm with camera);**
3. **12 legs;**
4. **2 DC brushless motors (NAMIKI);**
5. **Force at the leg's tip of about 1N;**
6. **No frontal latex balloon required;**
7. **On board electronics drivers;**
8. **Power consumption: 0.66 W.**

**The 12-leg capsule main features**



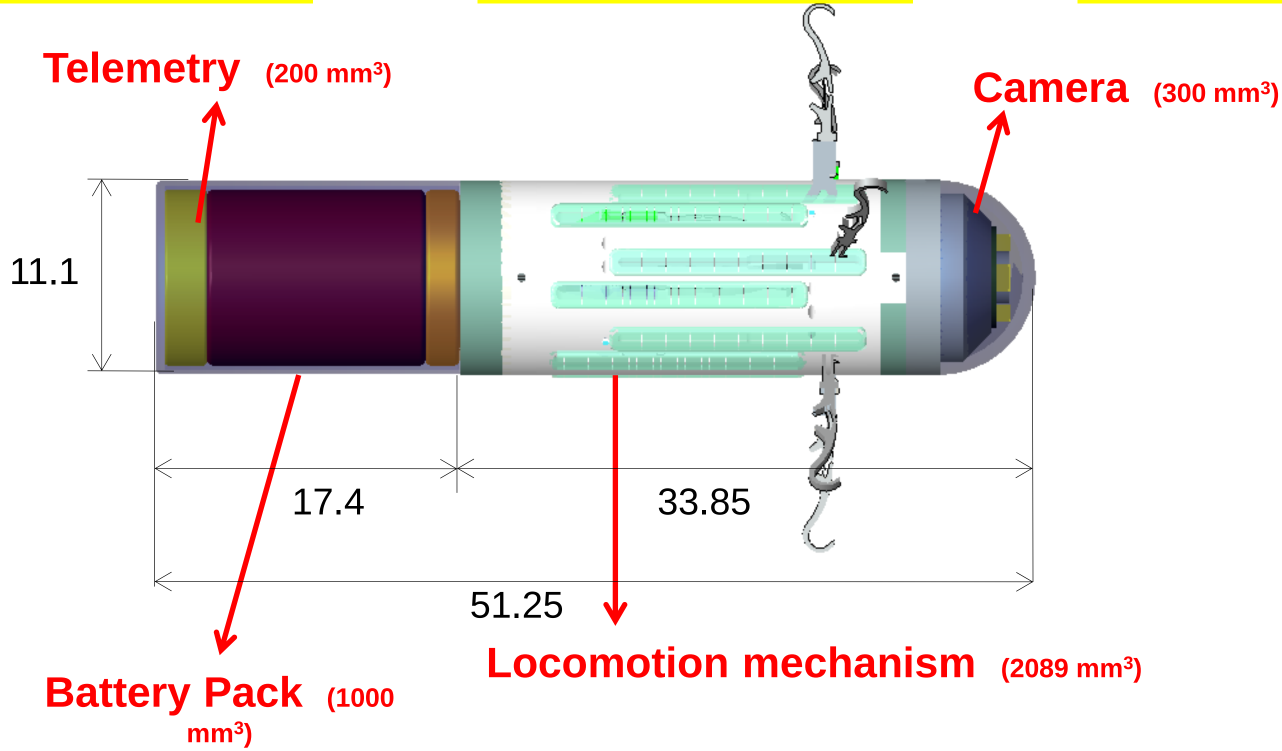


**The capsule includes more than 70 high precision components**

# Wireless Legged Capsule: The Energy Problem

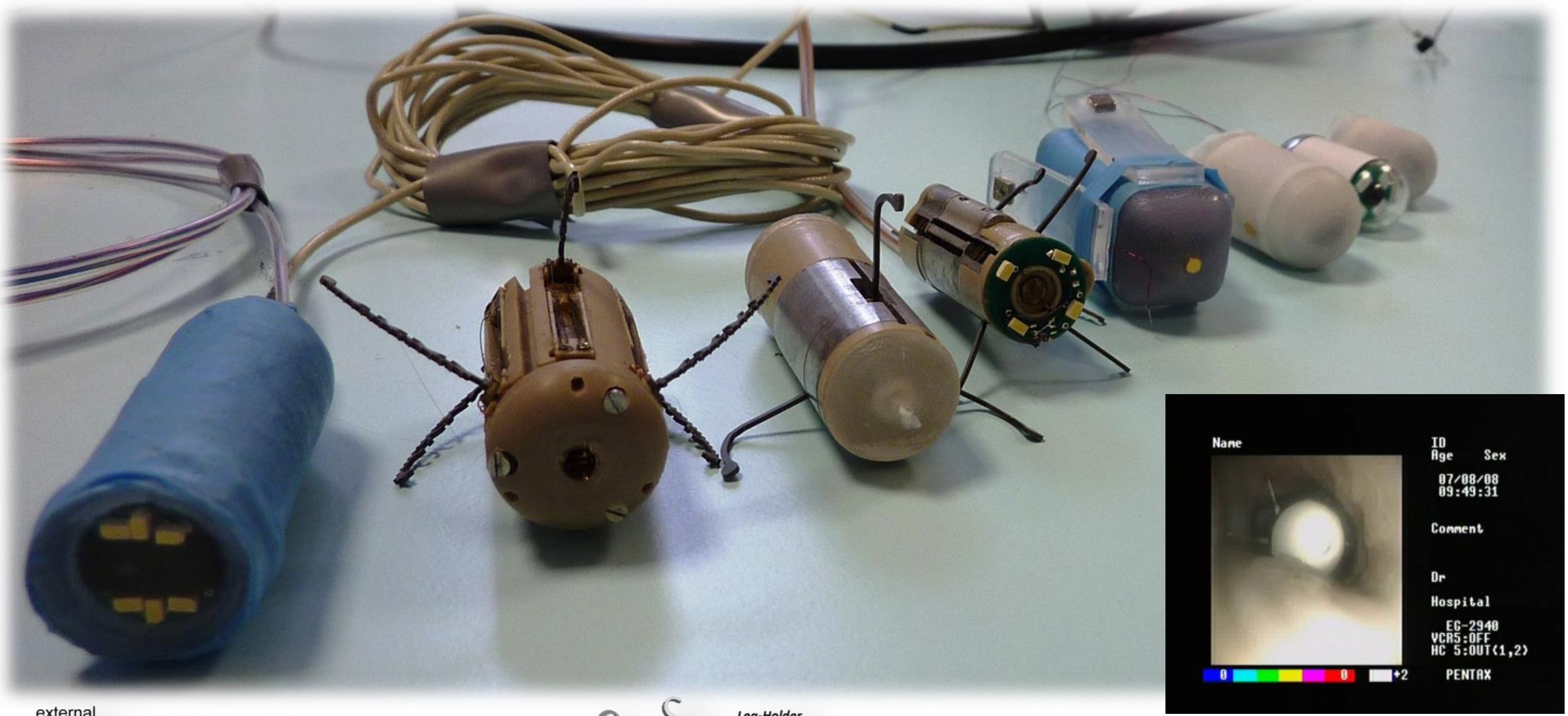
- Spatial constraints
- Locomotion system volume

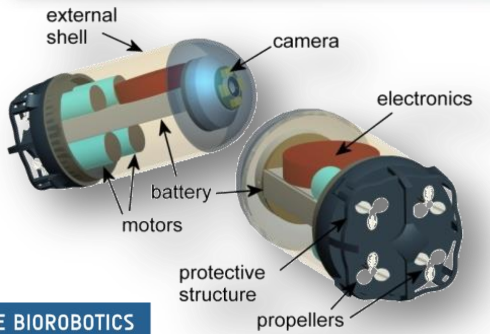
→ Add telemetry, drivers and batteries on board → The pill becomes too long to be swallowed

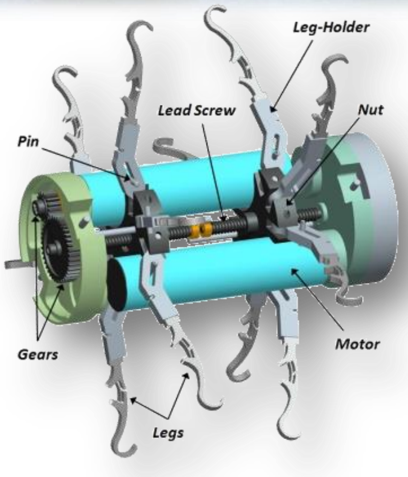


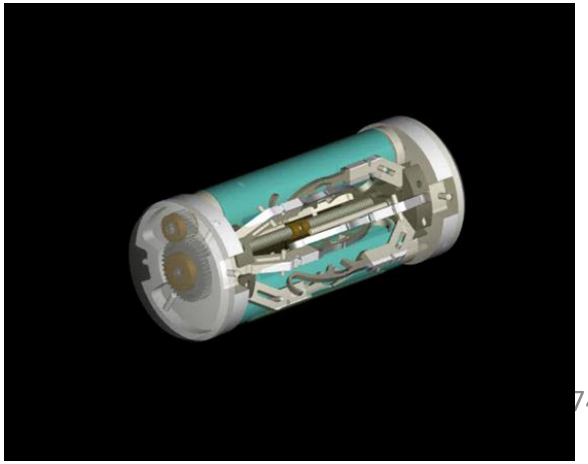

**Total volume: 3789 mm$^3$**

# ACTIVE capsules developed at The BioRobotics Institute



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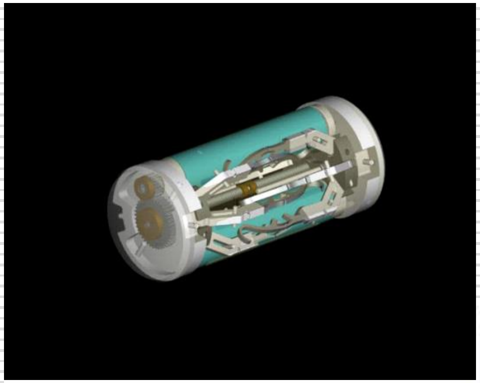
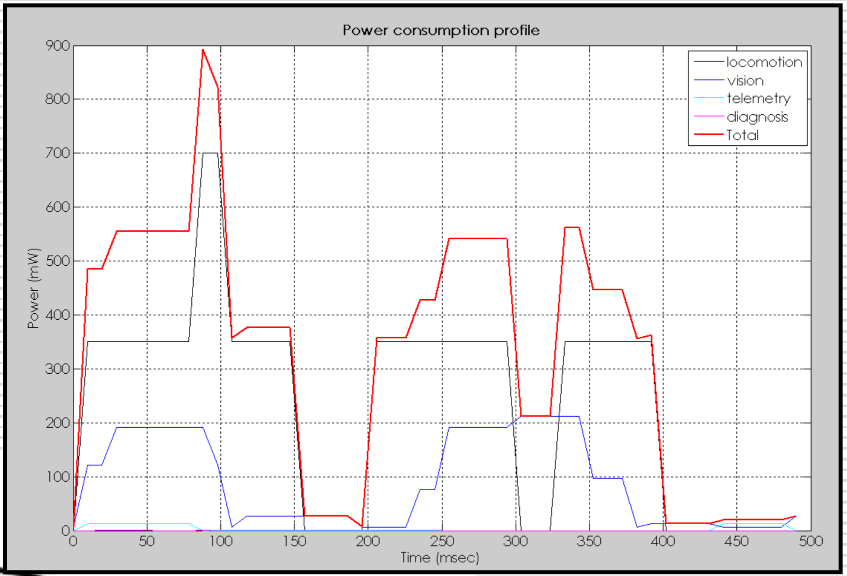
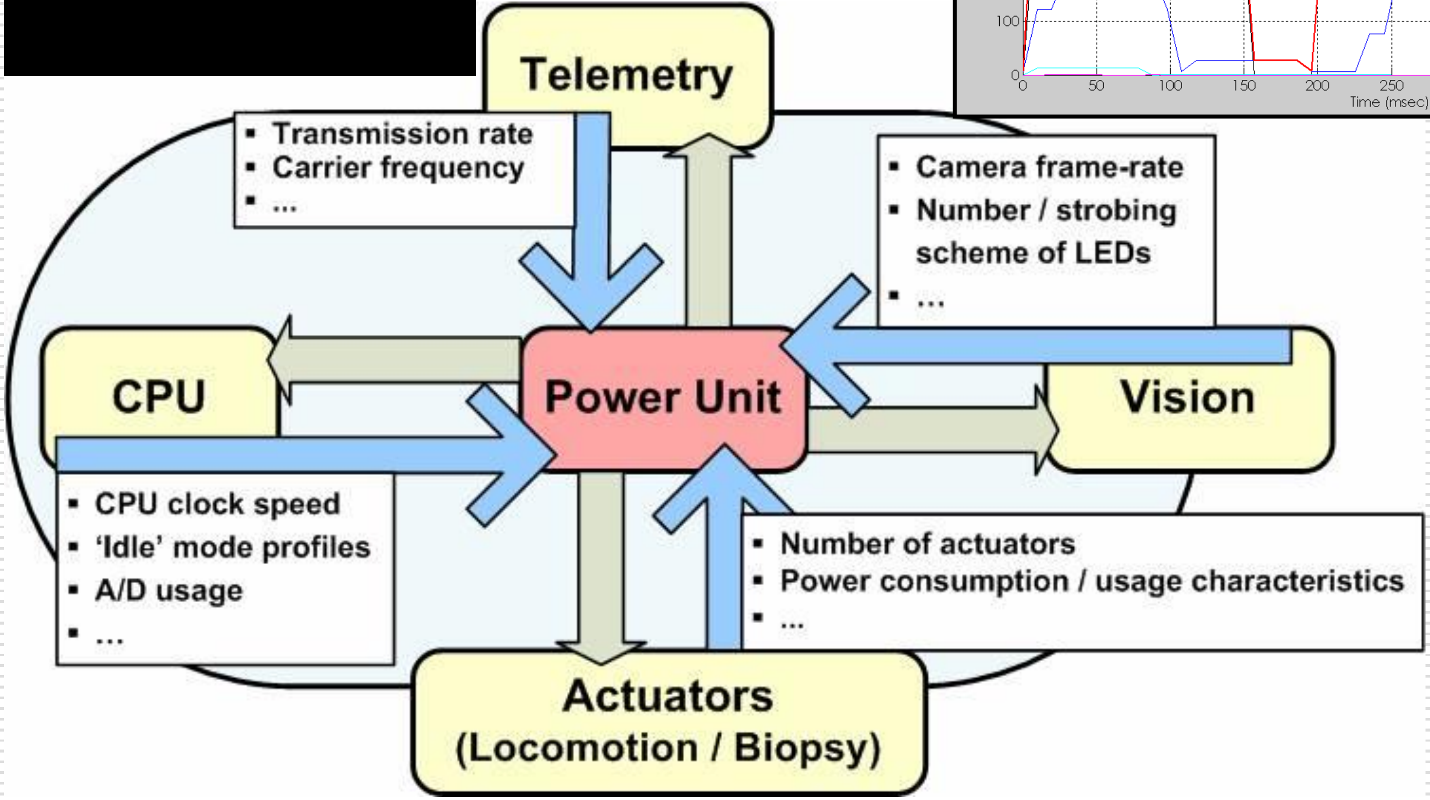
# The MAJOR problem for active, legged endoscopic capsules

# POWER!



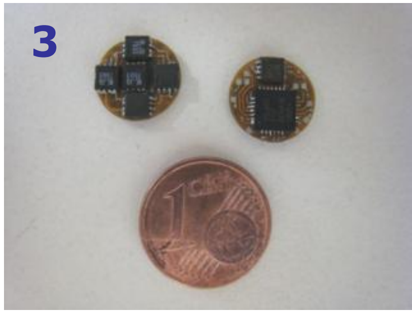



**A legged capsule incorporating state-of-art batteries could only walk for less than 30 minutes along the GI tract**

# Attempt #2: adding modules ("tenders") containing energy sources

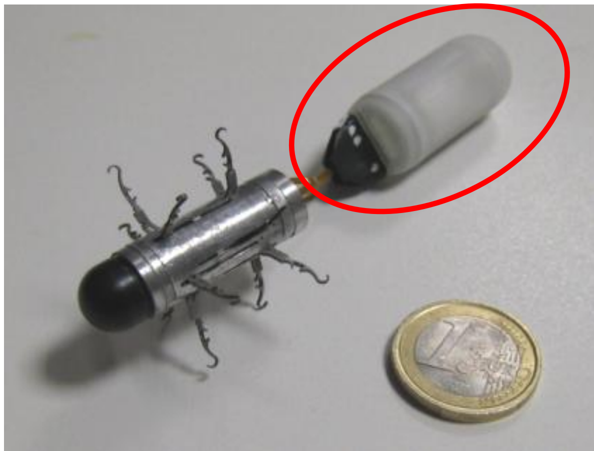
**The capsule has an additional module containing the transceiver unit (for control and telemetry), two batteries and the miniaturised motor control board**


**Tender size: D = 15 mm; L = 35 mm**

1. **2 batteries**: LP20, *Plantarco Ltd.-Canada*, 20mAh, 3.7V, 12x9x3.2mm
2. **Wireless transceiver** RC2300, 12x25 mm
3. **Motor driver board**, D = 10 mm; h = 2.5 mm

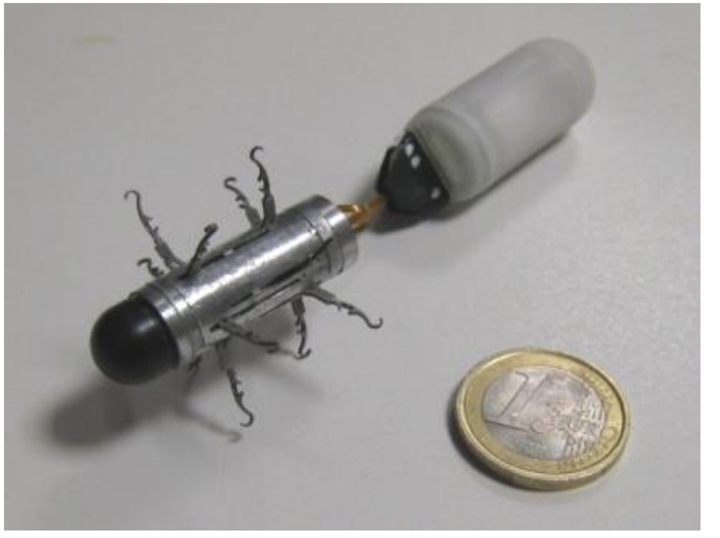
**Duration** = 13 locomotion cycles

***Tender solutions have been also considered by gastroenterologists. E.g.: C. P. Swain, "Method, system and device for in vivo biopsy", WO2005112460***

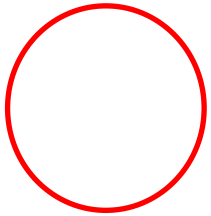
# *Limitations of the "tender" approach*

- *Swallowability*
- *Safety and comfort*
- *Steerability*

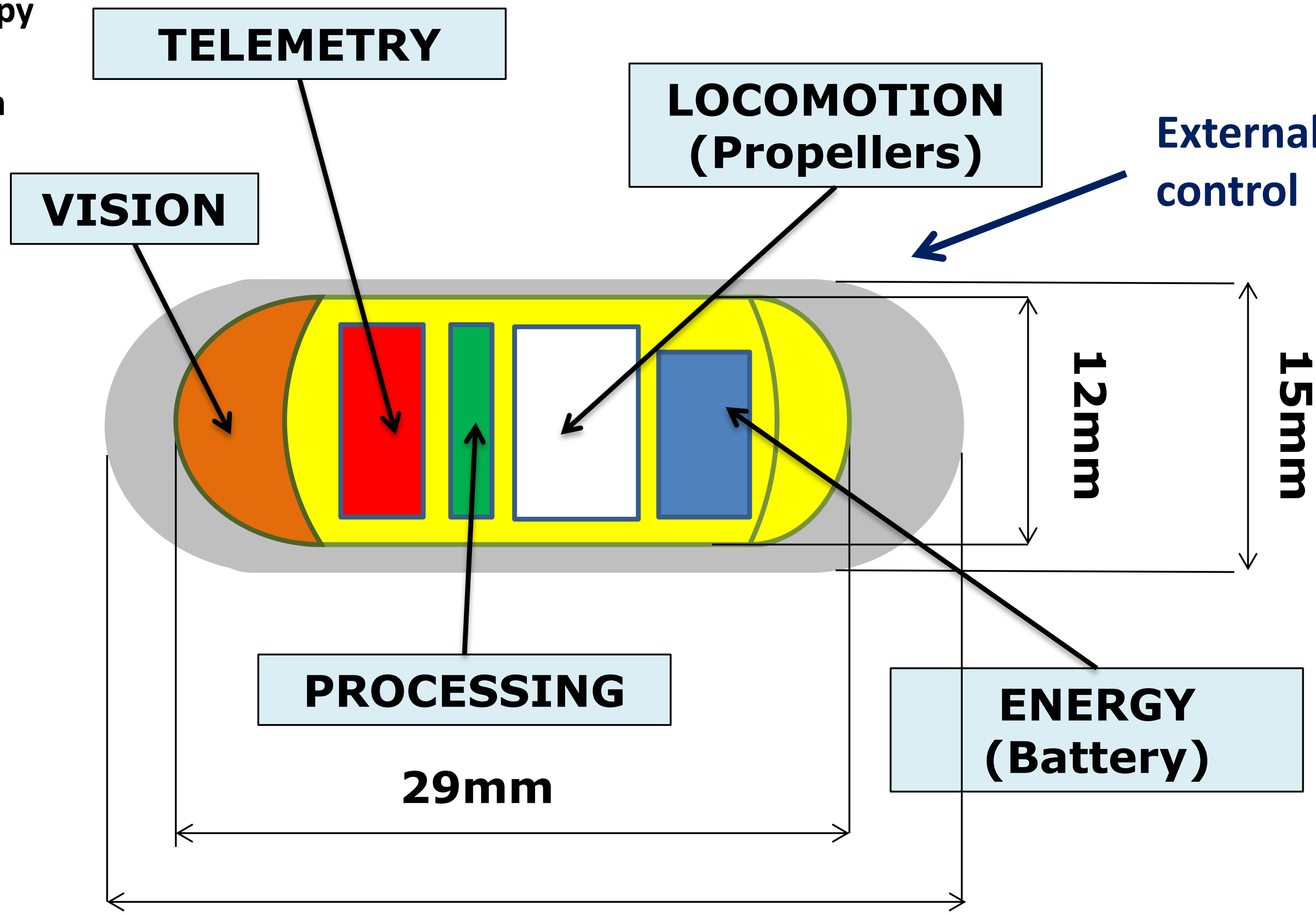


## Attempt #3: Wireless Electromagnetic Guidance

# Attempt #3: Wireless Electromagnetic Guidance

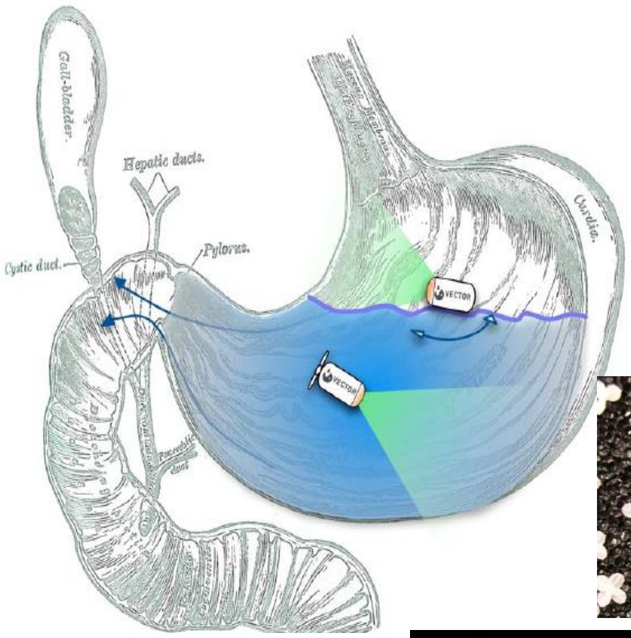


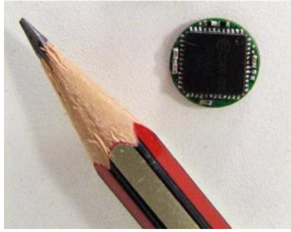
Stomach Endoscopy (Gastroscopy) :
Ø = 10 to 15 mm

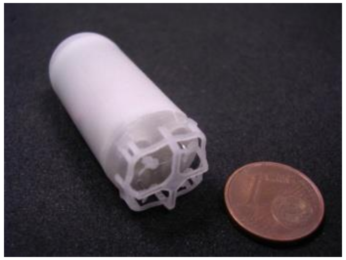


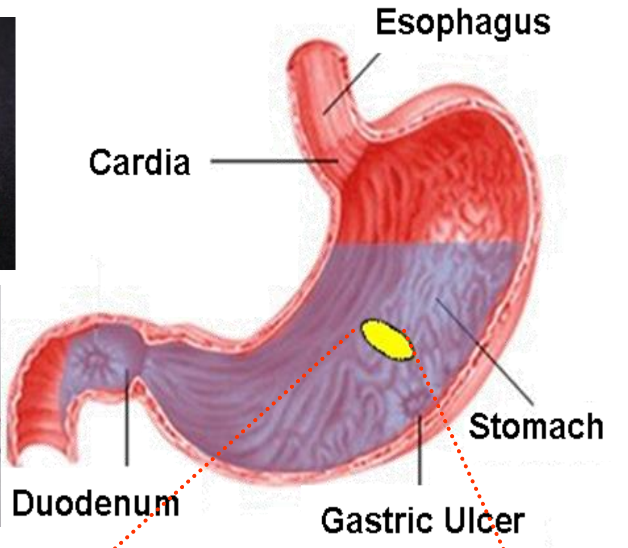
# Wireless Capsule for PAINLESS GASTROSCOPY

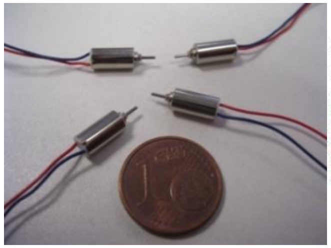
Ingestion of liquid in context with the examination allows to obtain organ distension, thus making possible a low power 3D locomotion in the stomach

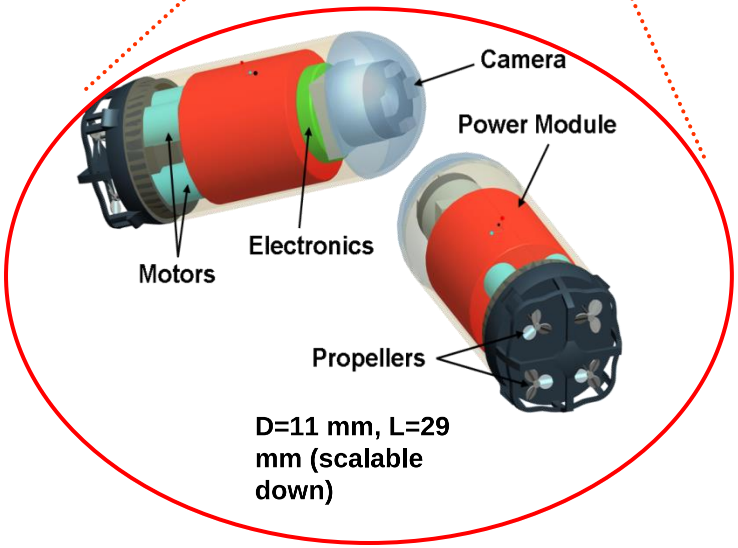


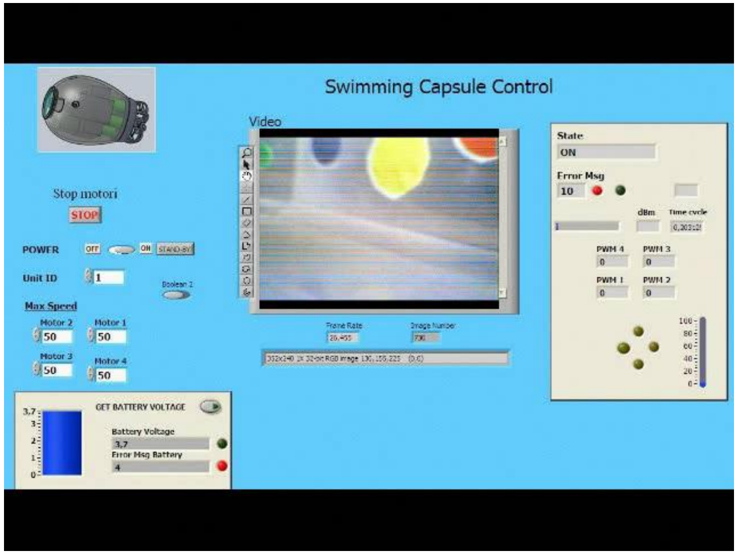





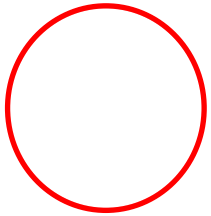


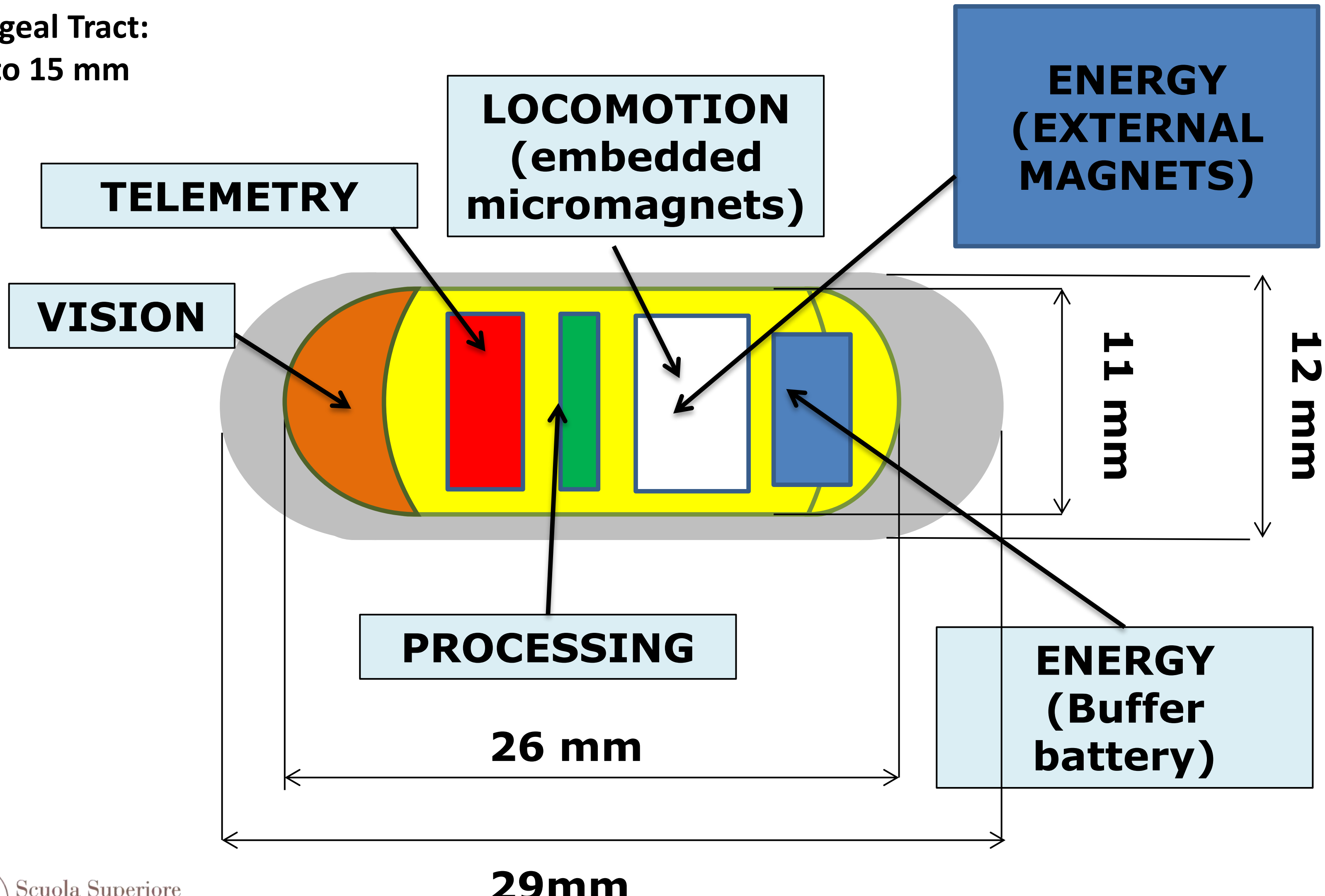


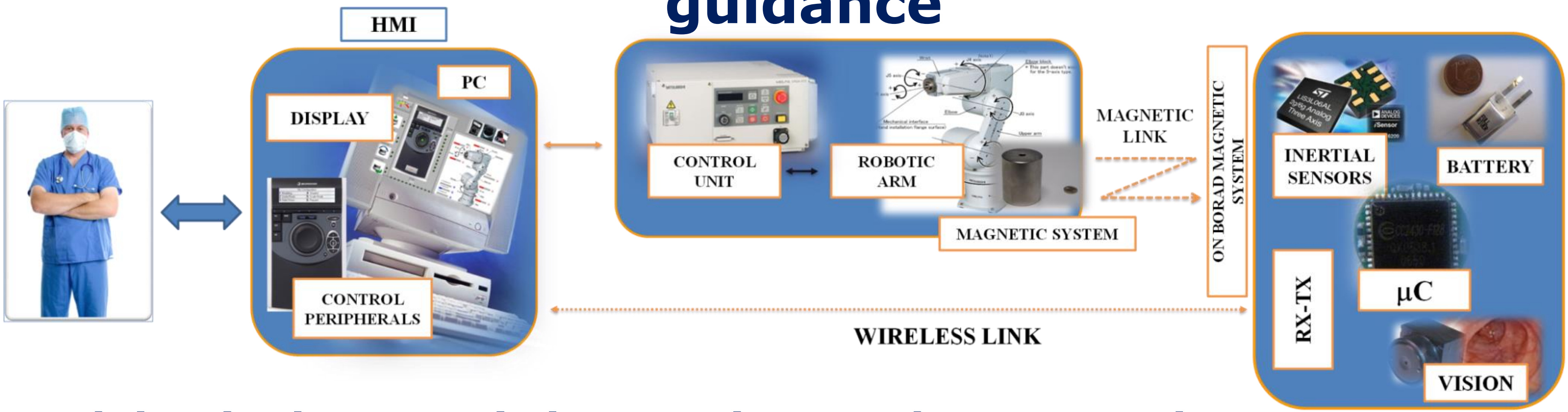
# Attempt #4: Wireless Magnetic Guidance



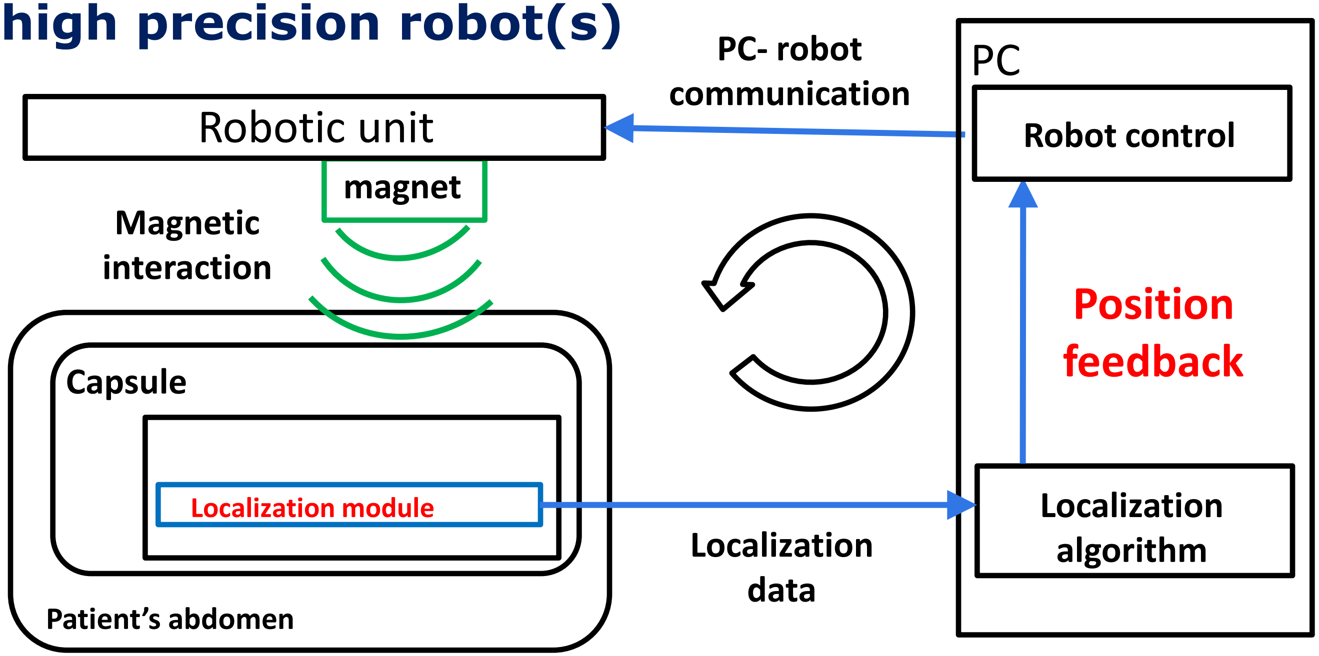
Oesophageal Tract:
Ø = 10 to 15 mm

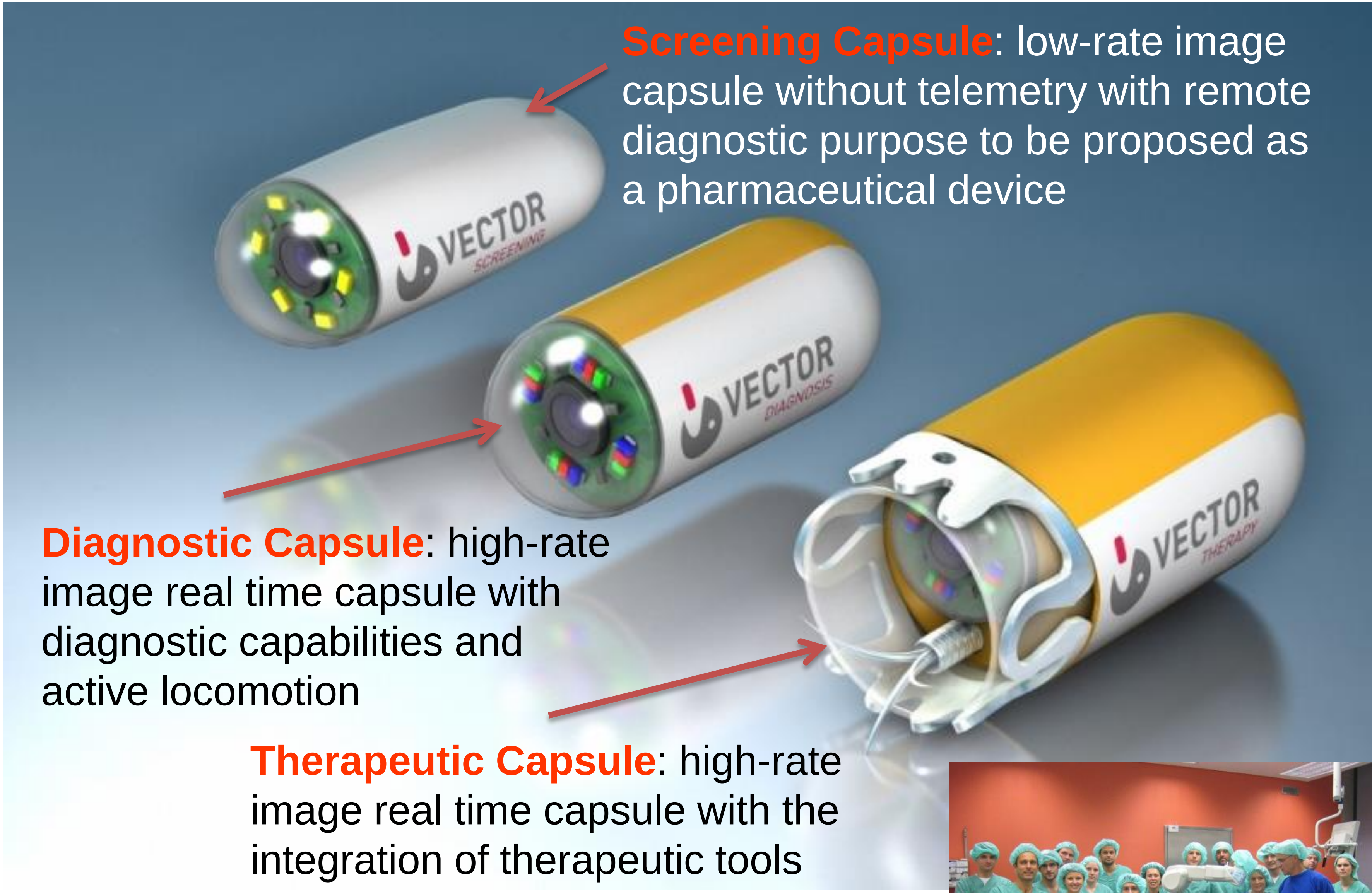


# A solution to overcome the energy problem in active capsular endoscopy: **robot-assisted wireless magnetic guidance**




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






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

**Diagnostic Capsule**: high-rate image real time capsule with diagnostic capabilities and active locomotion

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

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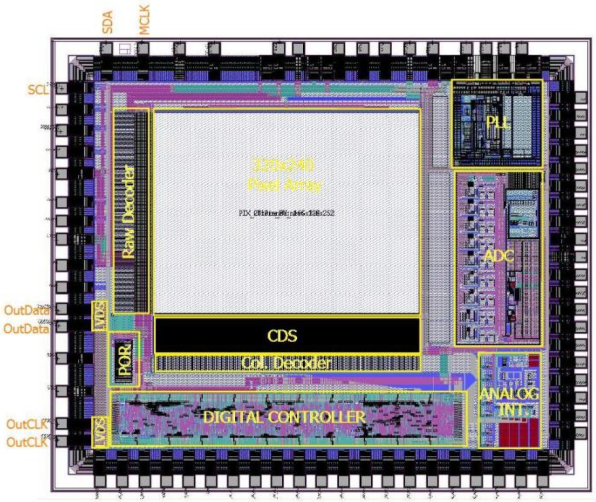
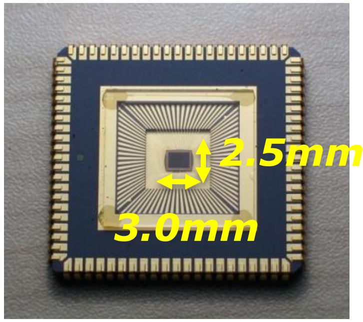
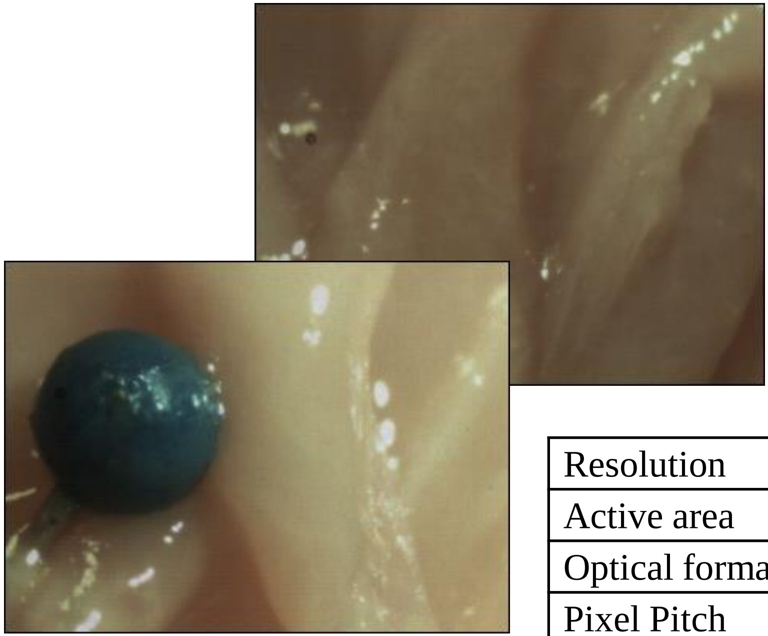
**The EU VECTOR and the Korea IMC Projects**

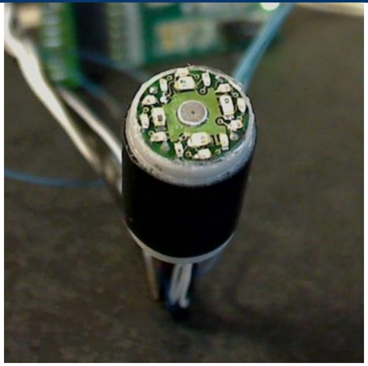
# Camera on Chip

## Custom image sensor





Multispectral illumination

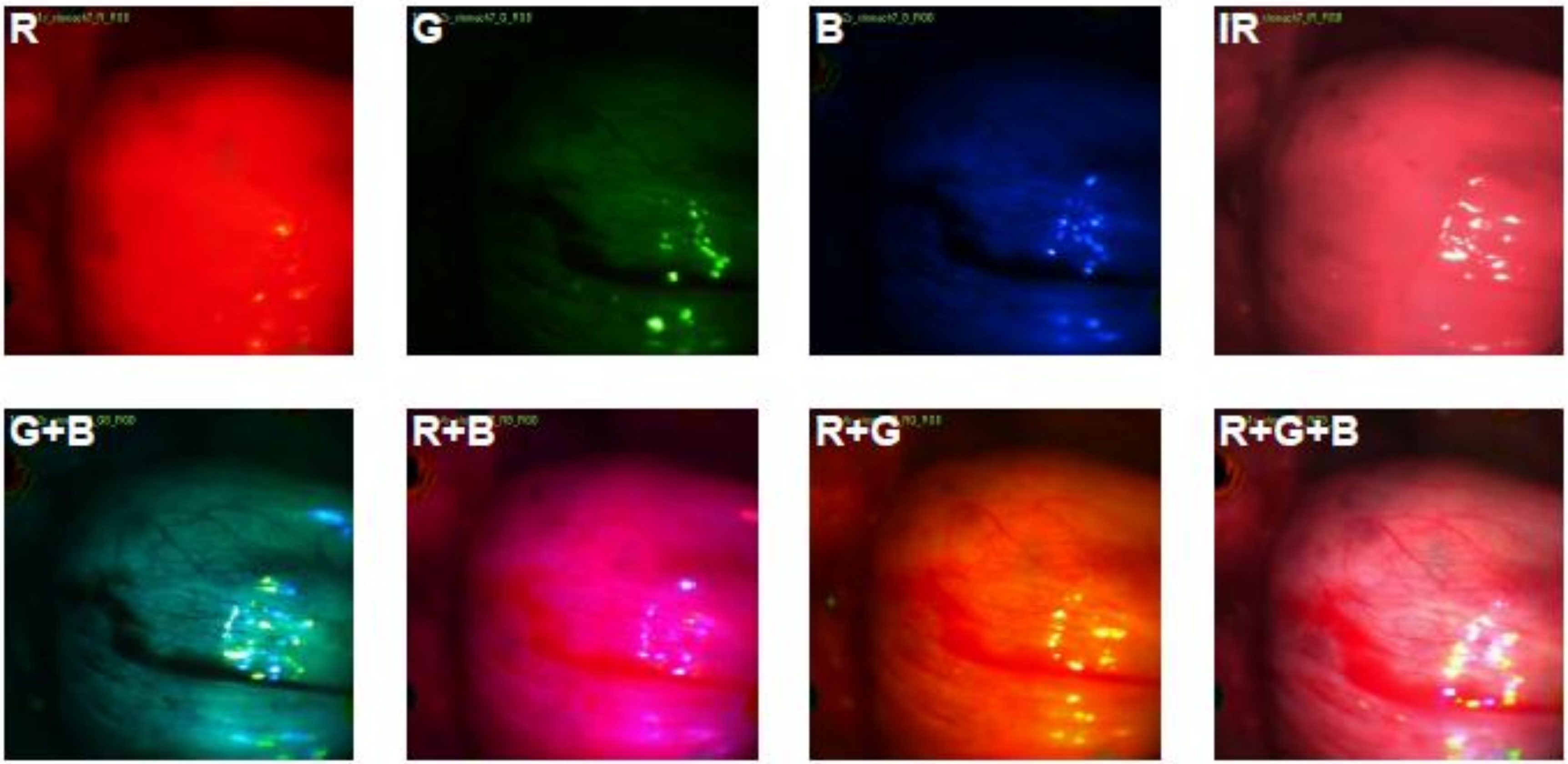
| | | |
|---|---|---|
| Resolution | | QVGA |
| Active area | | 320×240 |
| Optical format | inch | 1/11 |
| Pixel Pitch | $\mu m^2$ | 4.4×4.4 |
| Shutter type | | rolling |
| Die dimension | $mm^2$ | 2.5×3.0 |

| | | |
|---|---|---|
| Sensitivity | lux | 0.1@555nm,27° C, 30msec. |
| | $W/m^2$ | $1.7\times10^{-4}$@27° C, 30msec. |
| Responsivity | V/lux*sec. | 0.52@555nm, 27° C |
| | $V/W/m^2$*sec. | 360@@27° C |
| Dynamic range | dB | 50 |
| SNR | dB | 46(max) |
| Pixel Noise | % | 0.70 |
| Fixed Pattern Noise | % | 0.86 |

# Raw images with multispectral illumination and positive lens

# Narrow Band Imaging

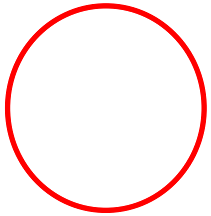
## In vivo images from pig open stomach



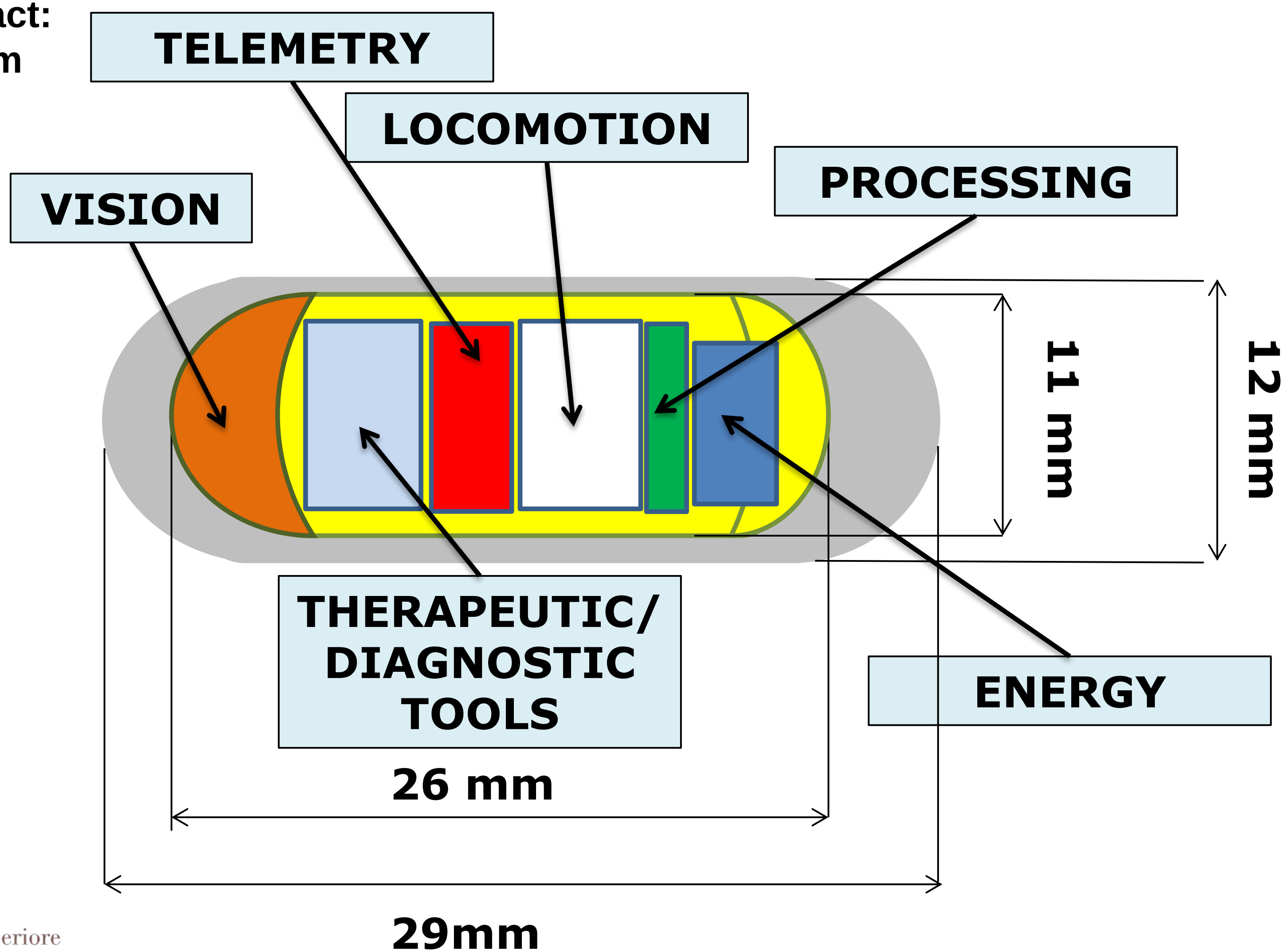
# Robot-guided, magnetically actuated endoscopic capsule

G. Ciuti, R. Donlin, P. Valdastri, A. Arezzo, A. Menciassi, M. Morino and P. Dario: Robotic versus manual control in magnetic steering of an endoscopic capsule. Endoscopy, vol. 42, pp. 148-152, 2010.

# Attempt #5: Swallowable, active endoscopic capsules with additional therapeutic and diagnostic capabilities



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

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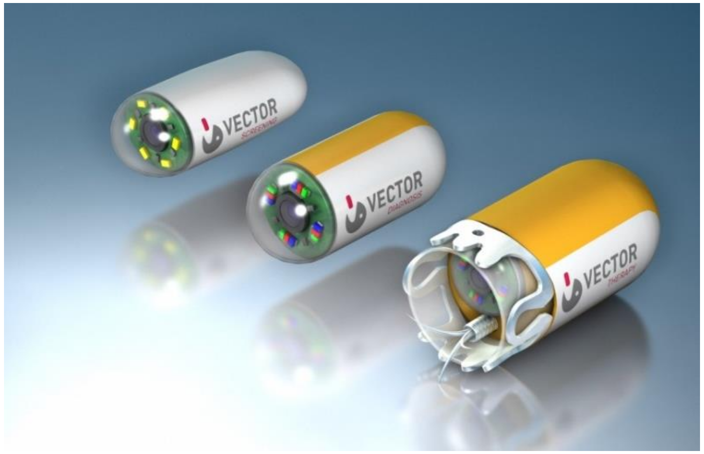
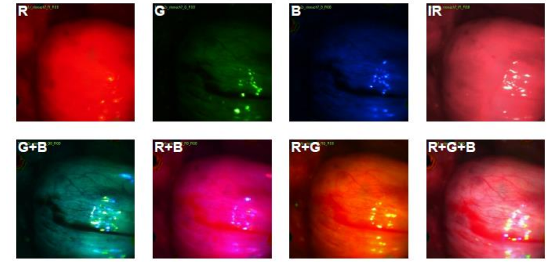




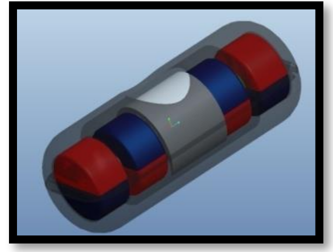


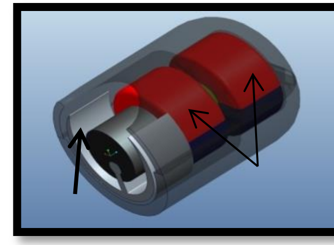

# Endoscopic capsules with imaging capabilities AND additional functionalities

- ❑ Biopsy capsules
- ❑ Capsules for painless colonoscopy
- ❑ Capsules releasing “components”

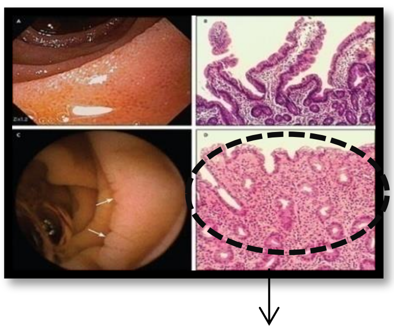
# Biopsy Capsule

## Magnetic actuation



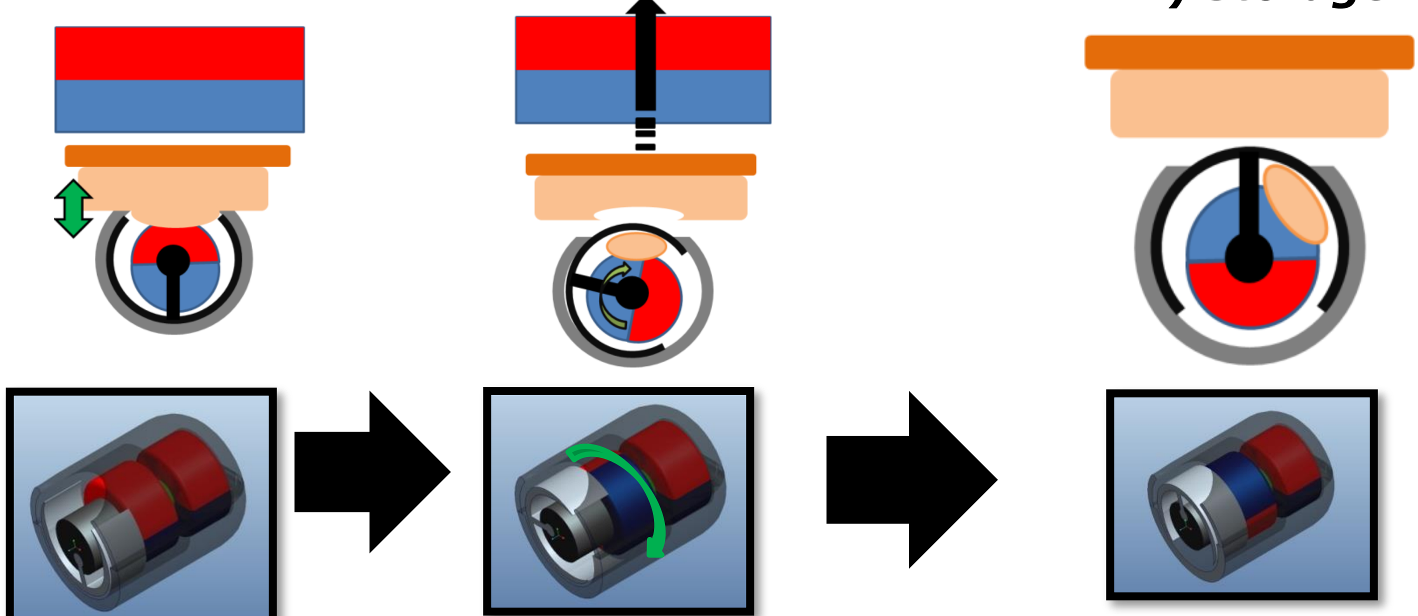



- ✓**bistable mechanism (**closed capsule without external field**)**
- ✓**activation by external field** (no internal motor)
- ✓**effective adhesion to bowel wall** (by magnetic attraction force)



*CD (Coeliac Disease) (duodenal biopsy required)*

**I)** ***Adhesion*** **II)** ***Sampling*** **III)** ***Storage***



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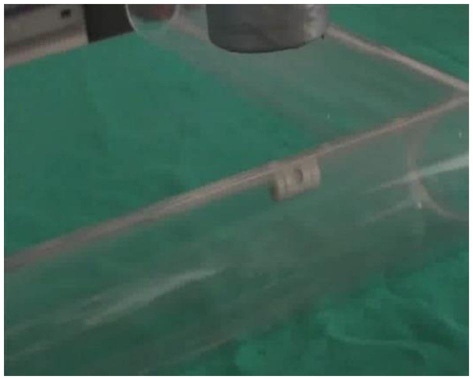
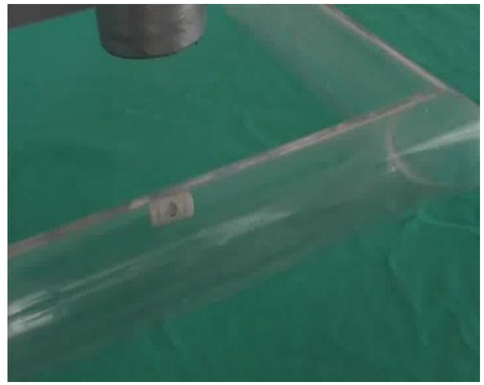
# Biopsy Capsule

## *In-vitro Tests*

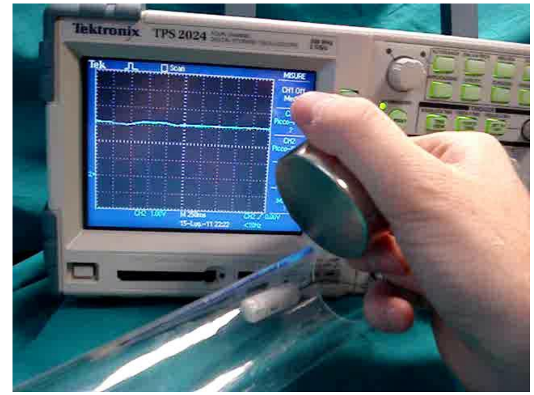
**MAGNETIC LOCOMOTION**



**EXTERNAL ACTIVATION**

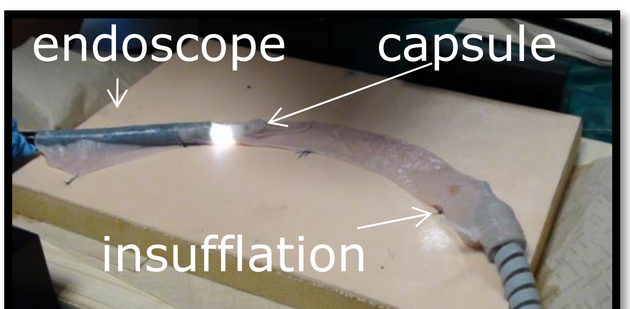


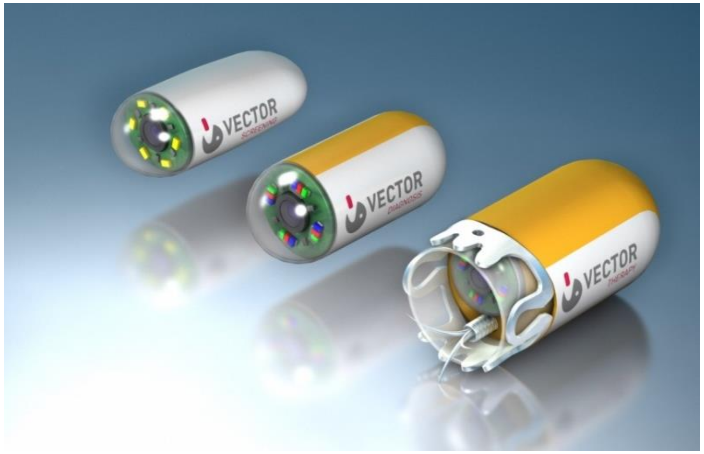
**CLOSED LOOP CONTROL (wired capsule)**




## *Ex-Vivo Tests*

- *mechanical prototype*
- *section of porcine small bowel*



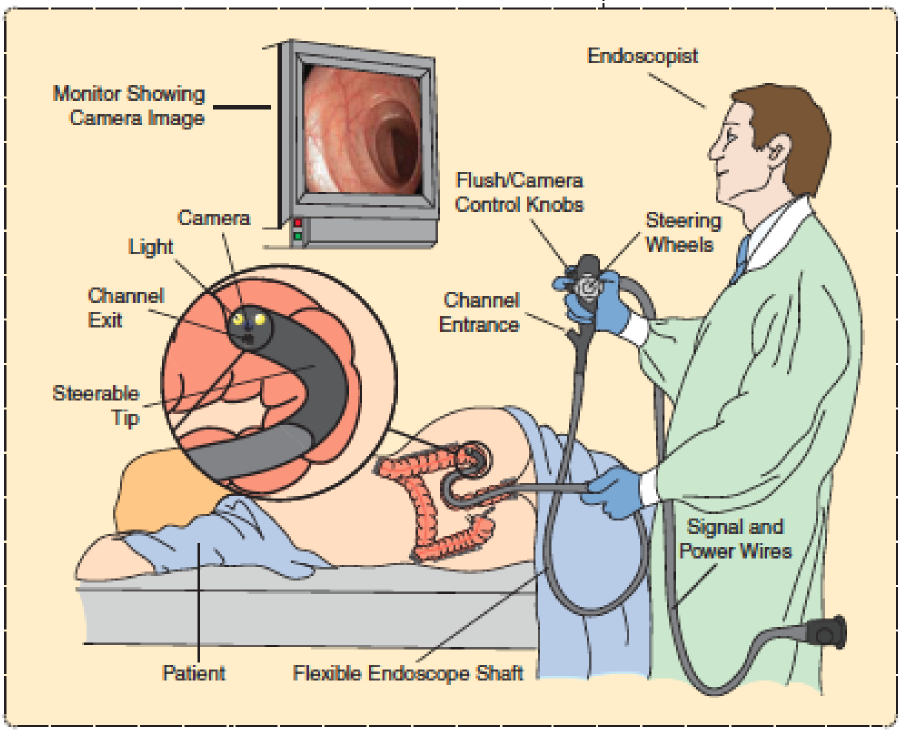



# Endoscopic capsules with additional functionalities

- ❑ Biopsy capsules
- ❑ Capsule for painless colonoscopy
- ❑ Capsules releasing "components"

# Traditional vs. robotic capsule colonoscopy

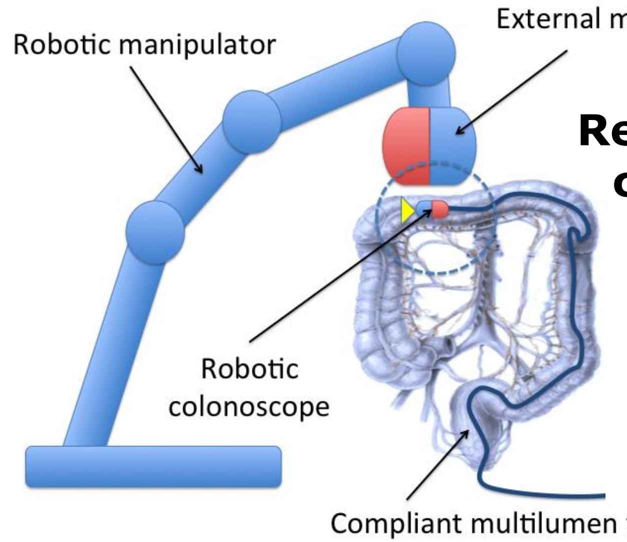
## *Traditional colonoscopy*



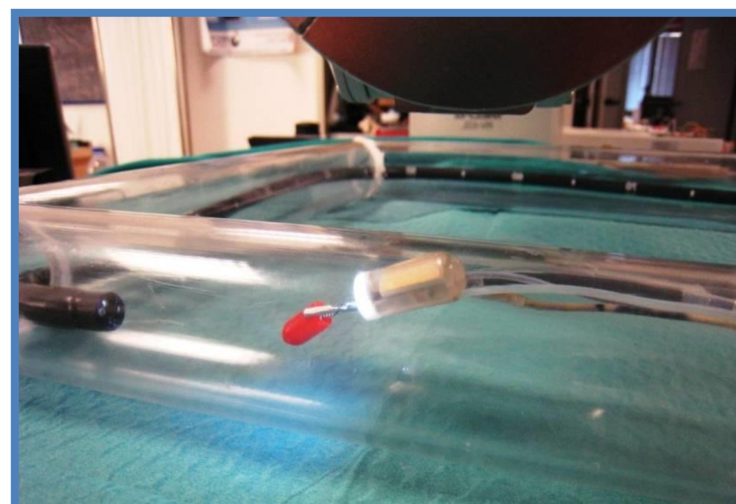

**User controller**

**Loeve Arjo, Paul Breedveld, and Jenny Dankelman. "Scopes too flexible... and too stiff."** ***Pulse, IEEE*** **1.3 (2010): 26-41.**

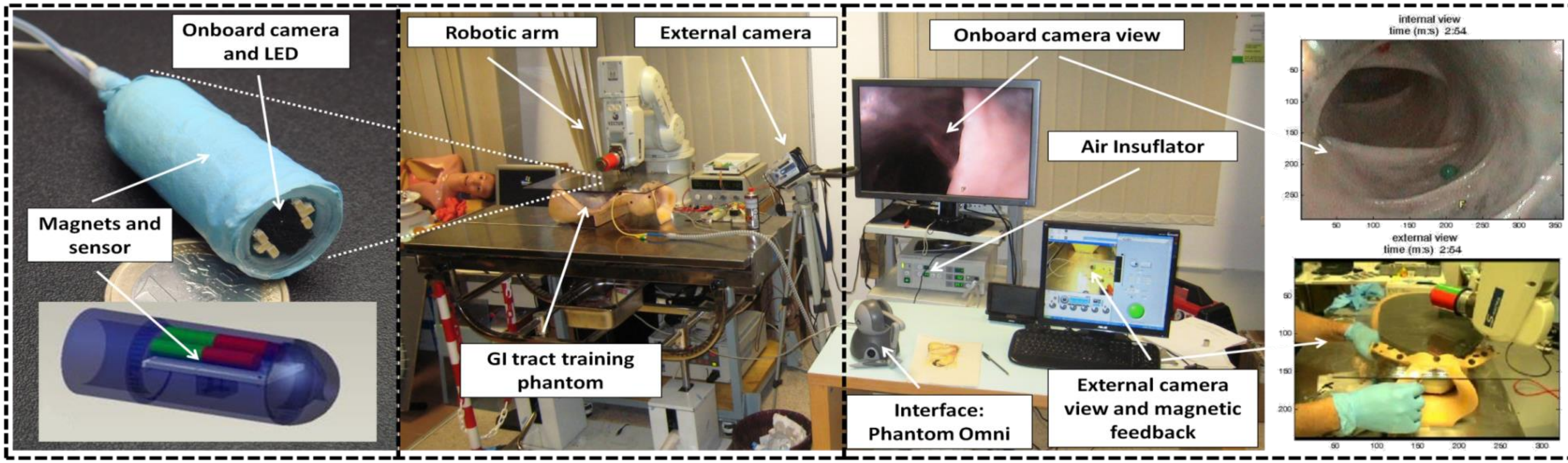
## *Robotic capsule colonoscopy*




**Remote user controller**

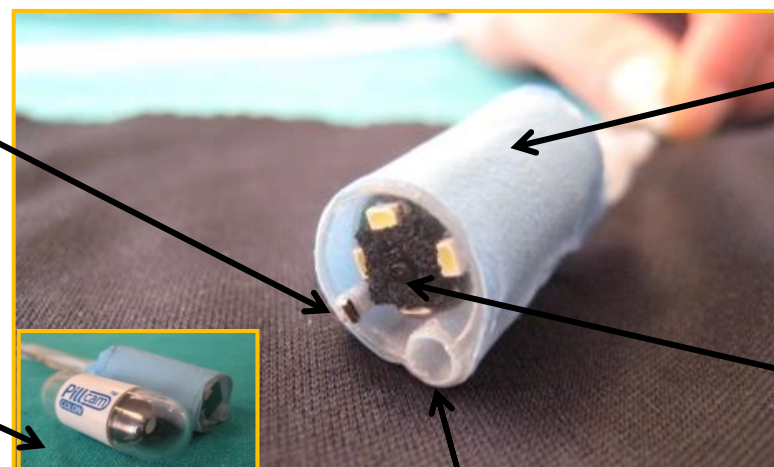


# Robot-guided, magnetically-actuated endoscopic device for *painless colonoscopy*




***Washing system:***
**injection of water for the glass cleaning from a dedicated channel and nozzle**

***Capsule shell:***
26mm in length and 11mm in diameter, less than the commercial PillCam Colon (11mm × 31mm)



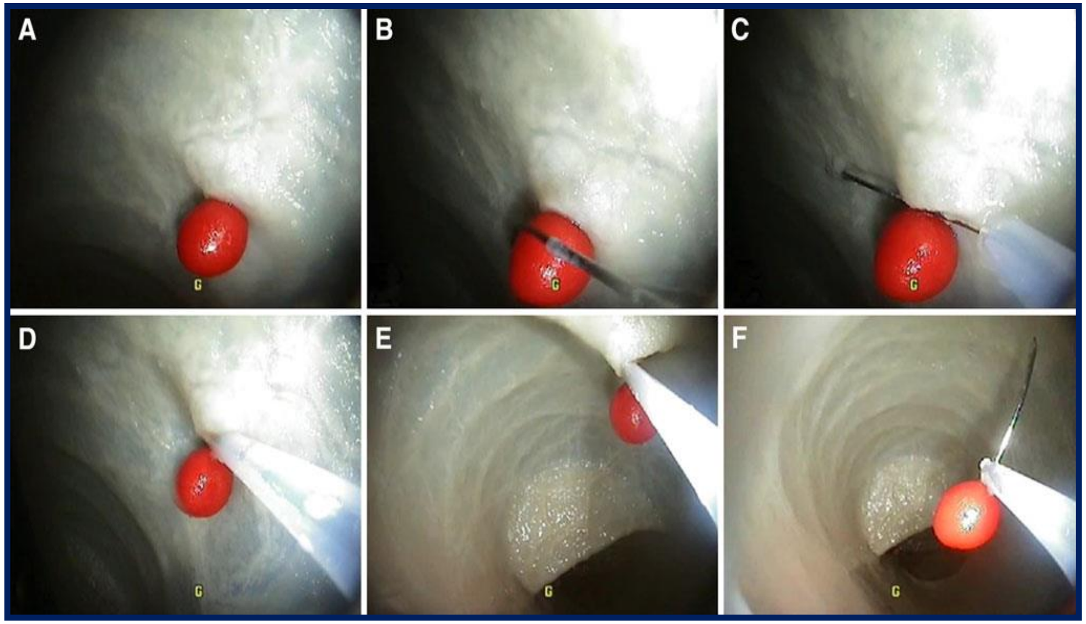
***Hall-effect sensor:***
**on-board magnetic field sensor that provides real-time clues about the magnetic link strength**

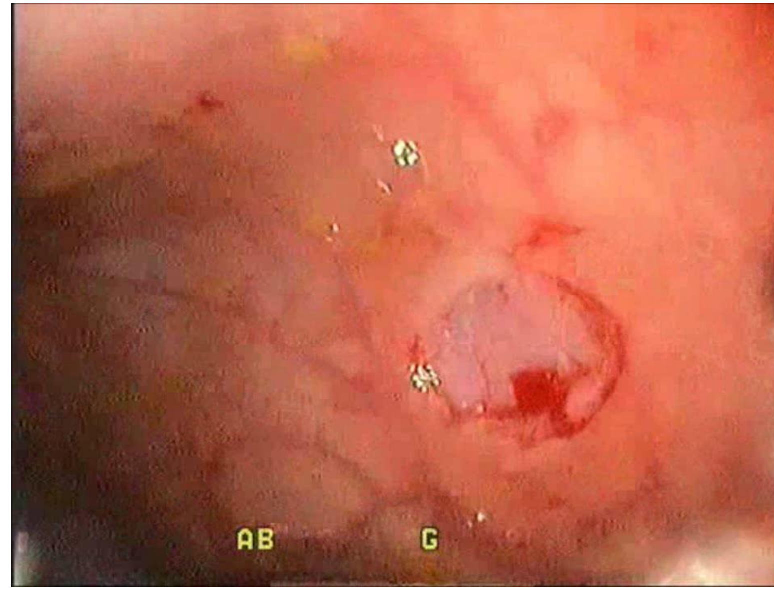
***Video module:***
**color VGA camera and 4 light emitting diodes (LED)**

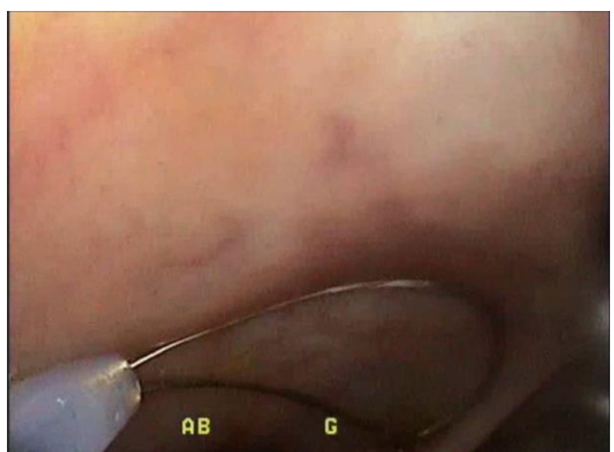
***Operating channel:***
**air and water injection and endoscopic tools introduction for therapeutic and surgical procedures**

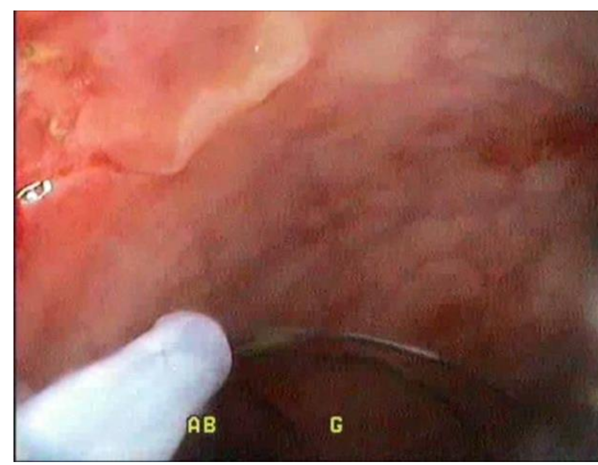
# Magnetically-Actuated Capsule for Painless Colonoscopy

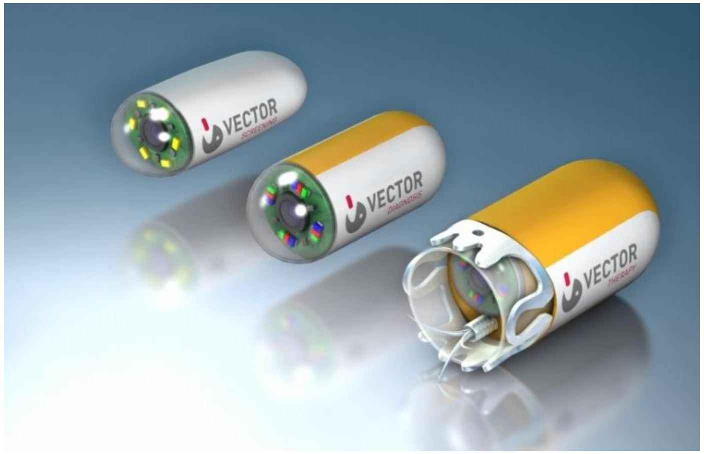
## In-vitro, ex-vivo and in-vivo experimental tests



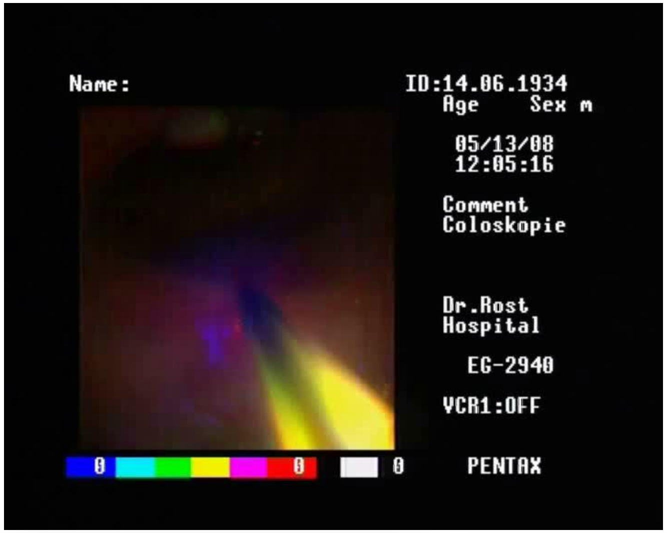






# Endoscopic capsules with additional functionalities

- ❑ Biopsy capsules
- ❑ Capsule for painless colonoscopy
- ❑ Capsules releasing "components"

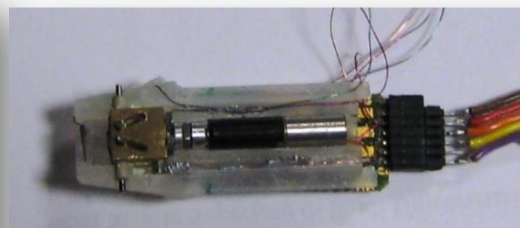
# Endoscopic capsule releasing a superelastic clip



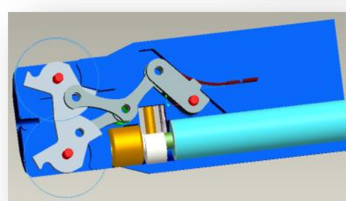

**Main Components**

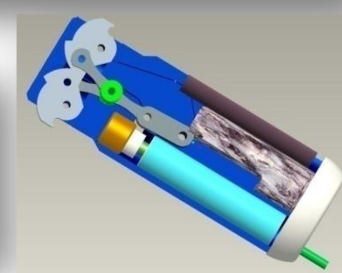
- Magnets for external magnetic steering
- Motor and mechanism for clip releasing
- Wireless motor controller

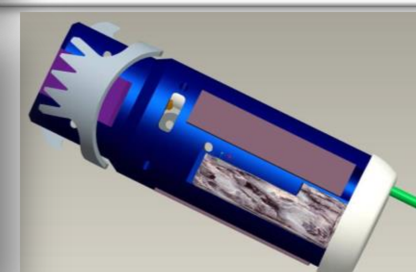
For the treatment of **gastrointestinal bleeding** and for **endoscopic digestive organ wall closure**.



OTSC CLIP







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ovesco

Bench testing demonstrated a tear-off force between 2.5 N and 5.3 N

# Capsule for medicated μ/n-film delivery

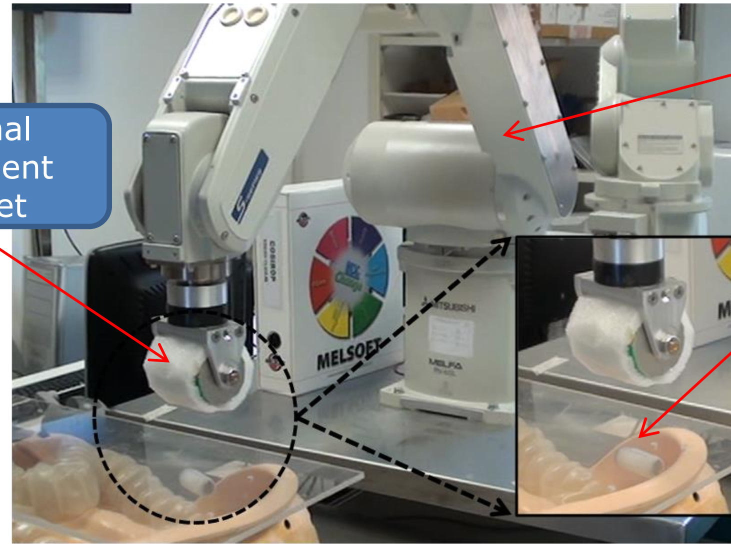
The capsule is magnetically guided to target location

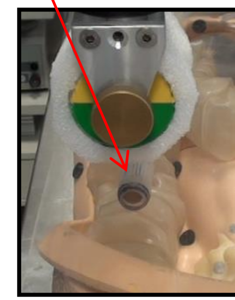
| Main Features |
|---|
| Size: ϕ13 x 36 mm (currently) |
| Locomotion: magnetic |
| Powering: on-board battery |
| Actuation: SMA (trigger) |
| Area for film: ~ 1 $cm^2$ |
| Can remove mucus from tissue |

Robotic arm

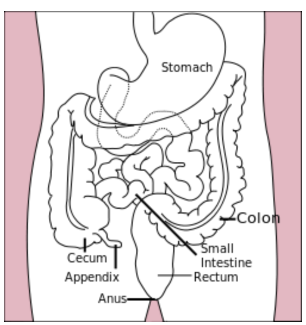
External permanent magnet

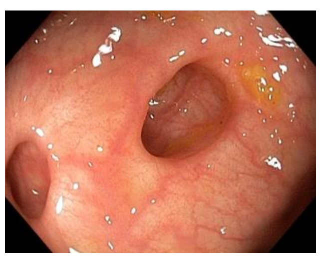
Robotic capsule device



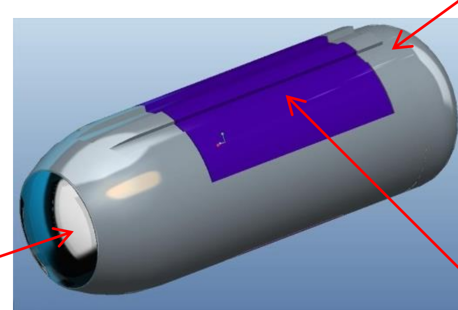



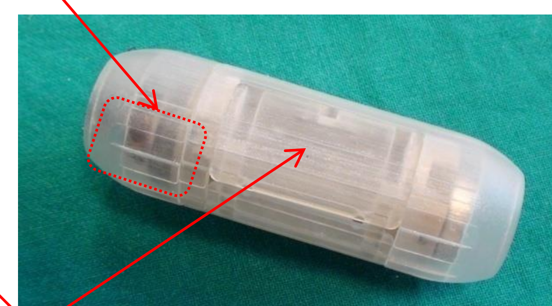
**Mucus can be removed from target tissue by capsule scraping (roll motion)**



Grooves for mucus displacement





Camera

N.2 mobile covers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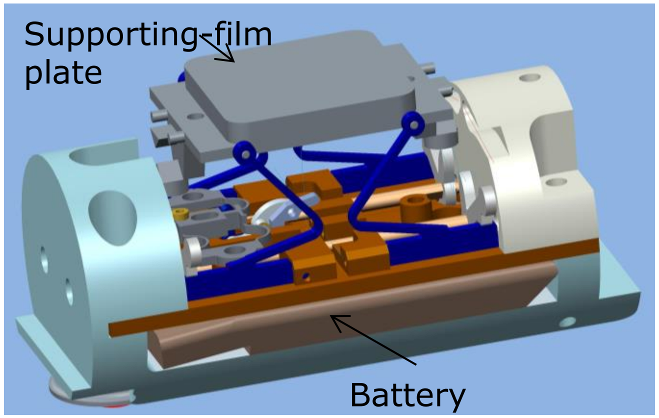
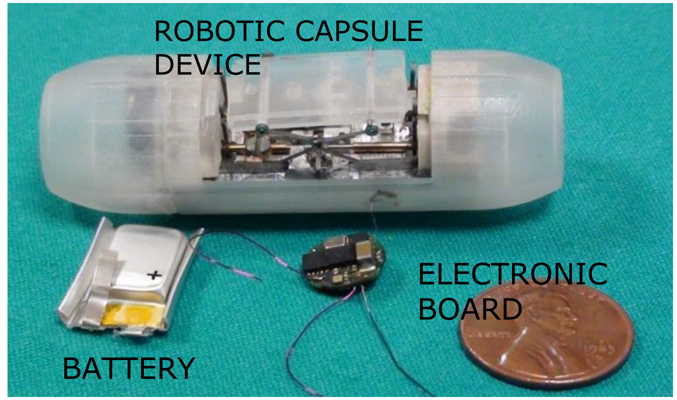
# Capsule for medicated μ/n-film delivery

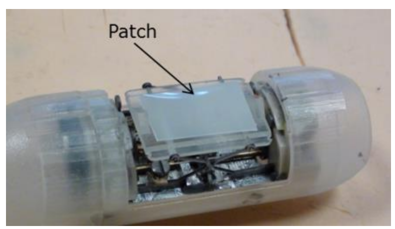
Film is pushed against tissue; capsule (in particular plate) is guided away (yet film sticks)

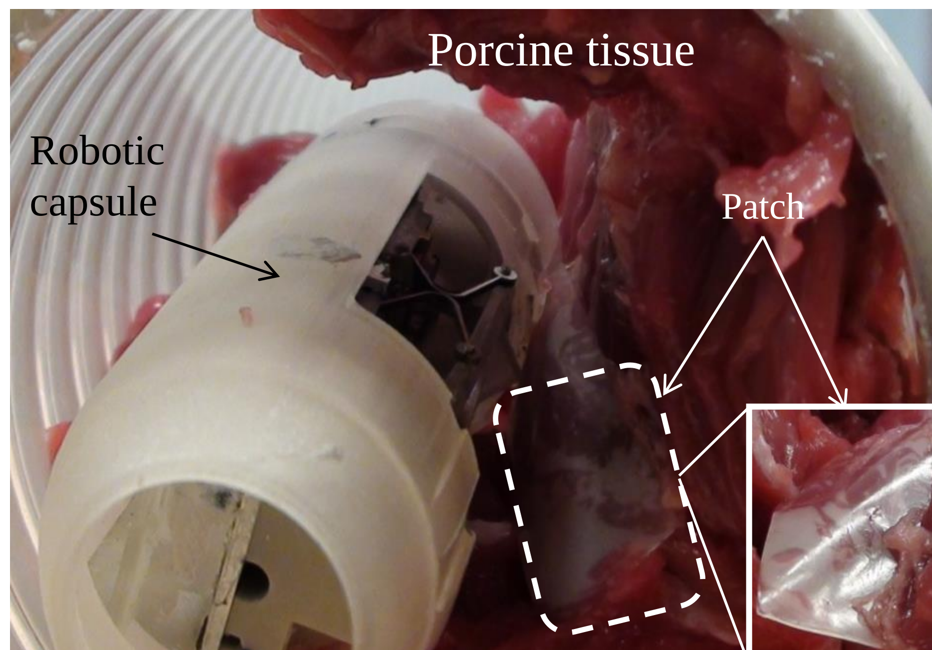



| Main Features |
| --- |
| Size: $\phi$13 x 36 mm (currently) |
| Locomotion: magnetic |
| Powering: on-board battery |
| Actuation: SMA (trigger) |
| Area for film: ~ 1 $cm^2$ |
| Can remove mucus from tissue |

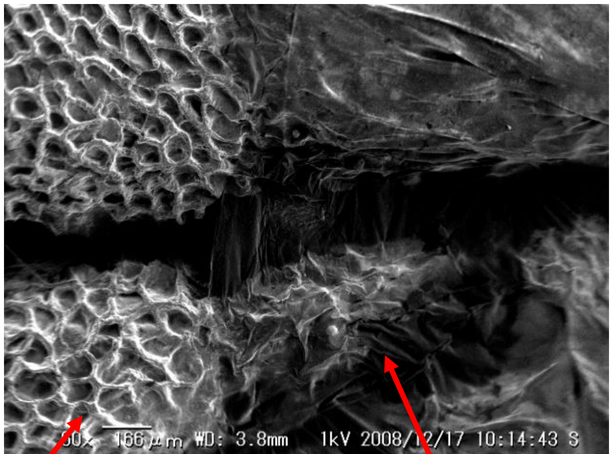
- ❑ System prototype



# Magnetic nanofilms as nanoplaster for endoluminal surgery

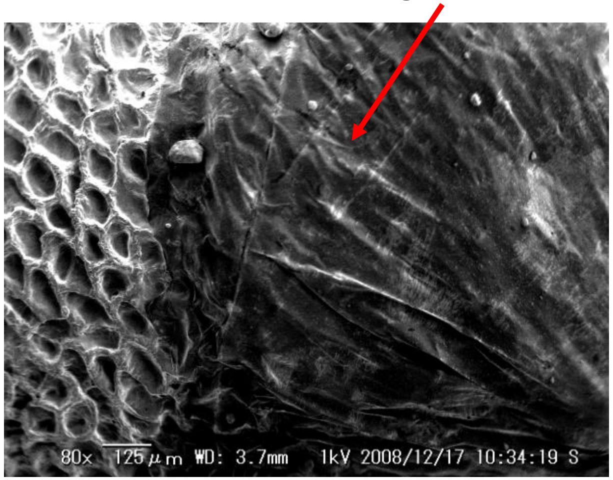
**10 mg/ml NP (200 nm) in PLA 20 mg/ml**



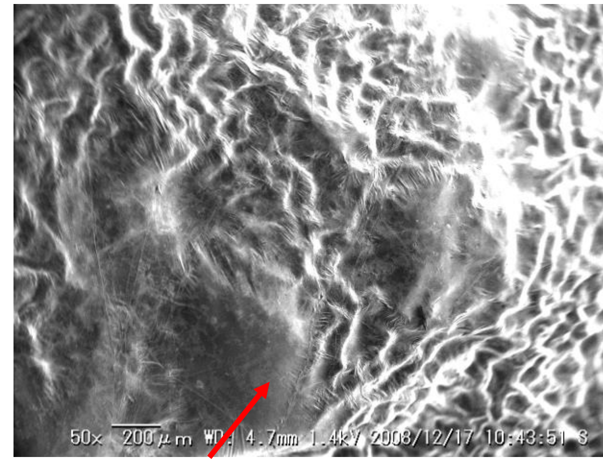

**Film covering an incision on the mucosal wall**

**gastric wall**

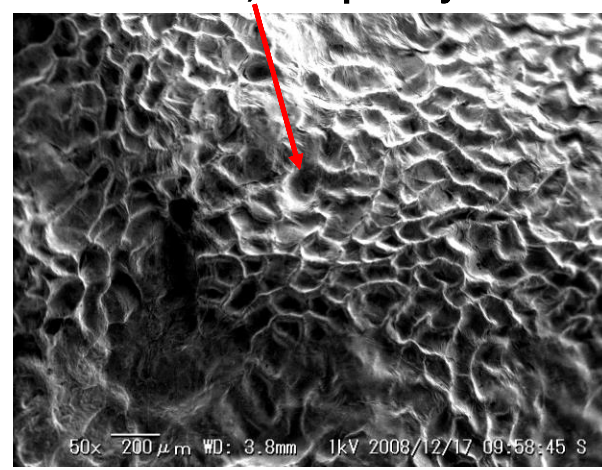
**magnetic nanofilm**

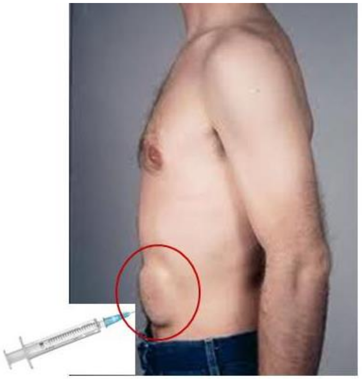


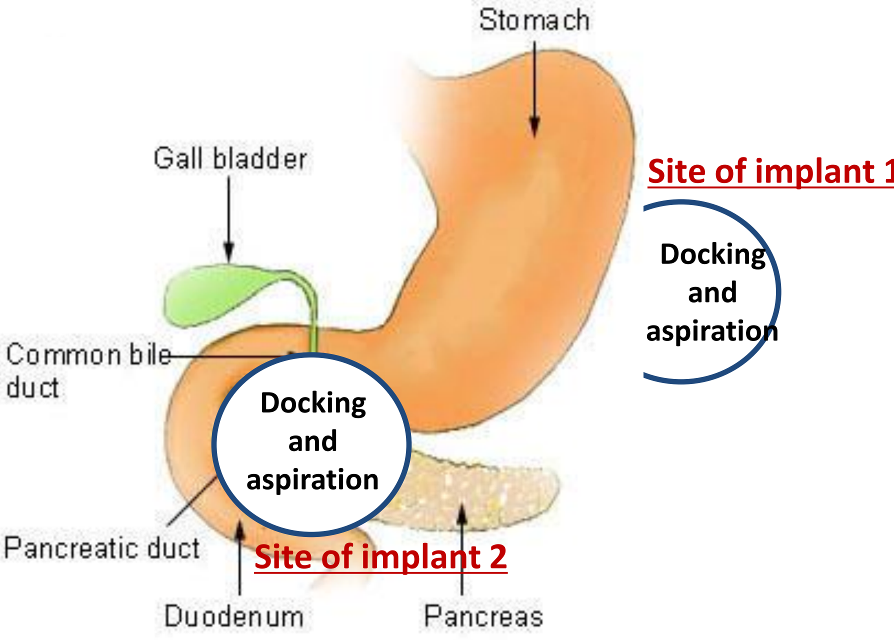

**10 mg/ml NP (40 nm) in PLA 10 mg/ml**




**The film follows the folds of the mucosal wall, completely covering it.**








Having learned the techniques to finely control the positioning of an endoluminal capsule by means of an external robot, we can now envisage a wide class of novel applications. For example, **refilling an implanted artificial pancreas by means of oral capsules containing insuline**

# A Novel Concept: Magnetically-Controllable Insulin-Filled Capsules as Carriers for Diabetes Treatment

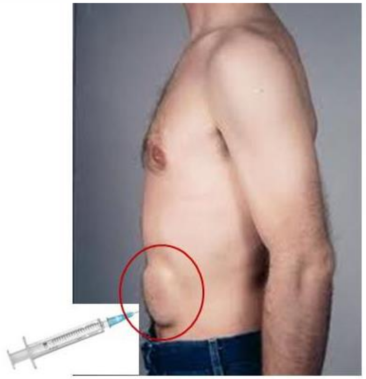
- ❑ 347 million people worldwide suffer from diabetes
- ❑ diabetes deaths are expected to double between 2005 and 2030
- ❑ worldwide diabetes market: from $ 14.9 billion in 2009 to $ 55 billion in 2019
- ❑ lifestyle strongly affected by traditional therapy

<u>Multiple daily insulin injections</u>

- The patient is slave of his/her pathology
- Long-term complications
- Non-physiologic insulin profile

<u>Implanted artificial pancreas</u>

- Limited lifetime
- Need of complicated periodical refilling procedures (surgical operations needed every 3 months)
- Low insulin stability in the implanted device



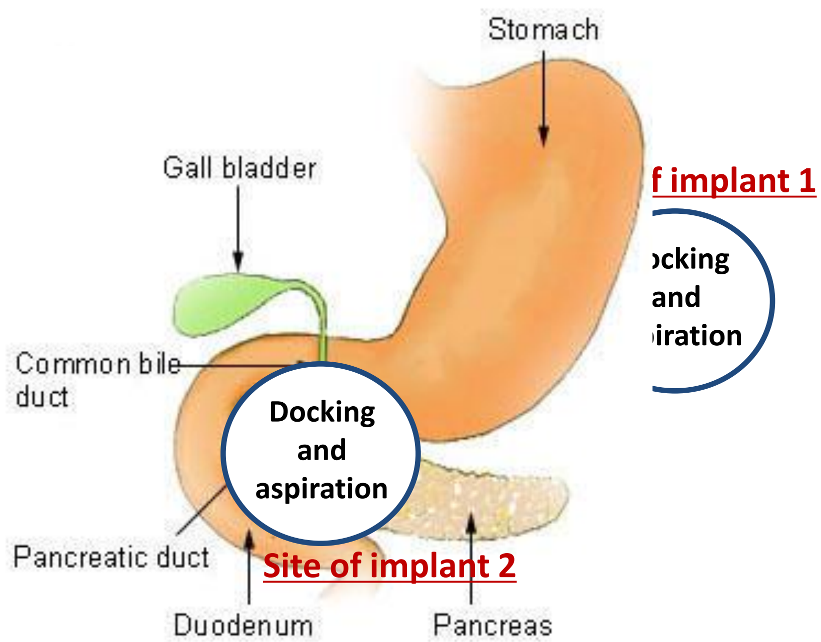

<u>Wearable artificial pancreas</u>

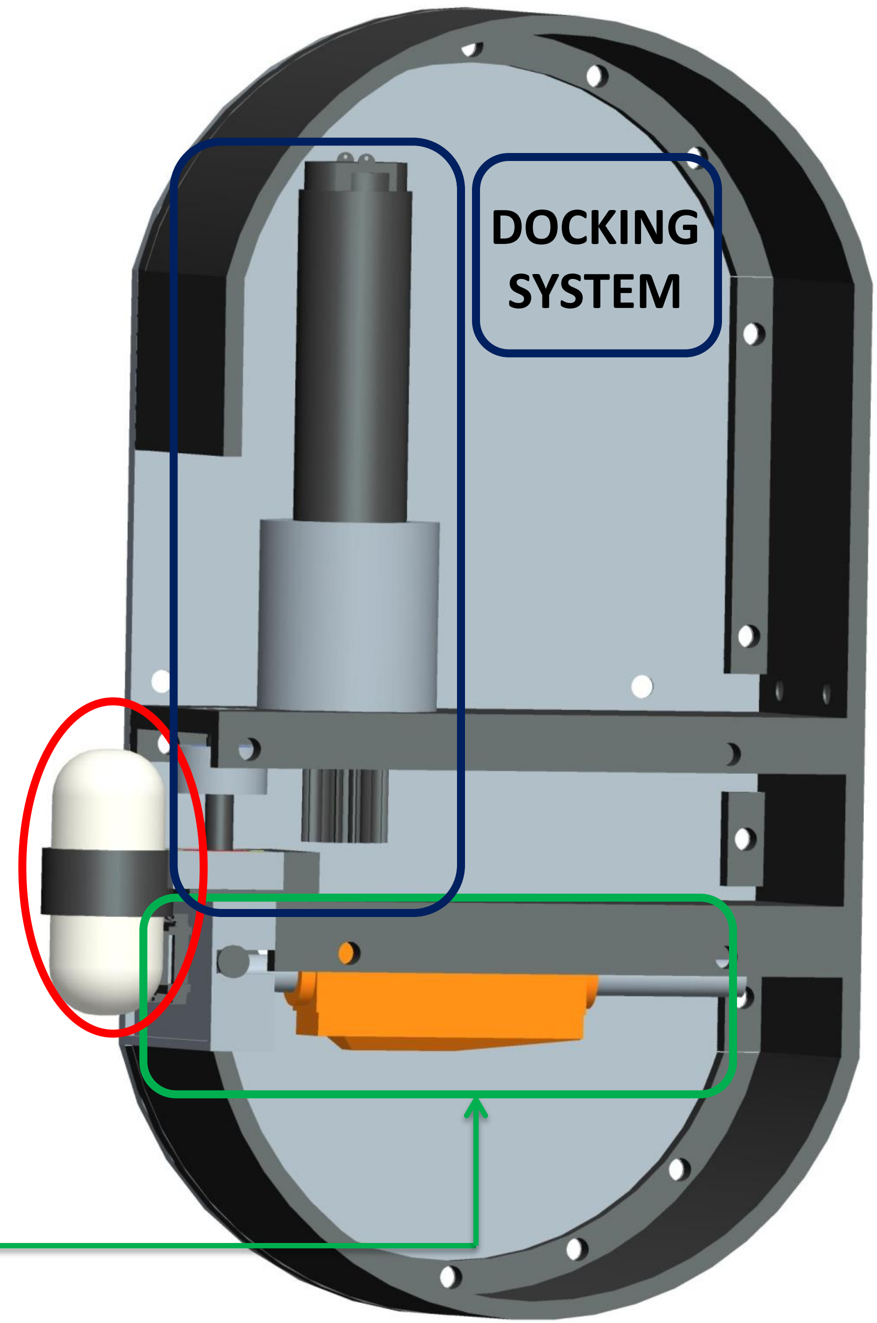
- Delays in insulin adsorption
- Common daily activities strongly affected

<u>Holy Grail of diabetes treatment</u>

**Long-term totally implantable AP refillable through insulin pills**

# Novel implantable artificial pancreas *




* Ricotti et al. PCT Patent WO/2012/011132 , Jan 2012

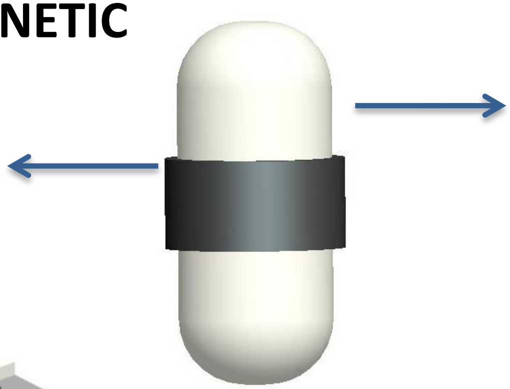
# Sensorized Swallowable Capsule

**FERROMAGNETIC RING**

$\Phi_{ext}$ = 14 mm

$\Phi_{int}$ = 12 mm

H = 7 mm



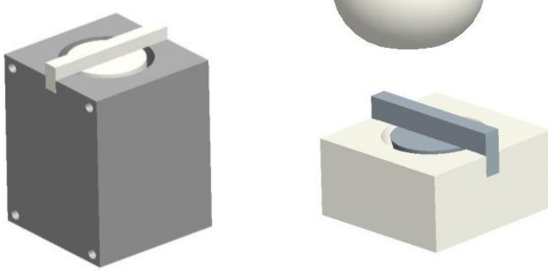
**PDMS CAPSULE**

$\Phi_{ext}$ = 12 mm

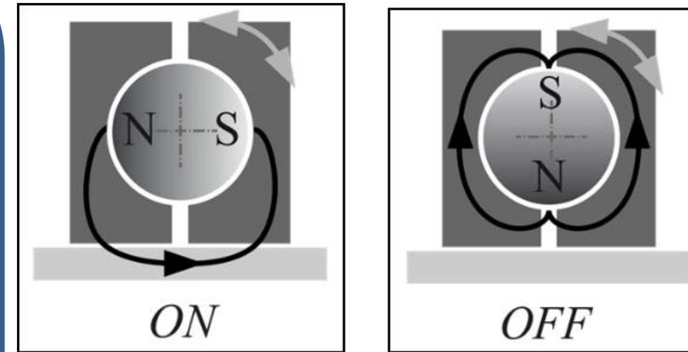
$\Phi_{int}$ = 10 mm

t = 1 mm

H = 30 mm



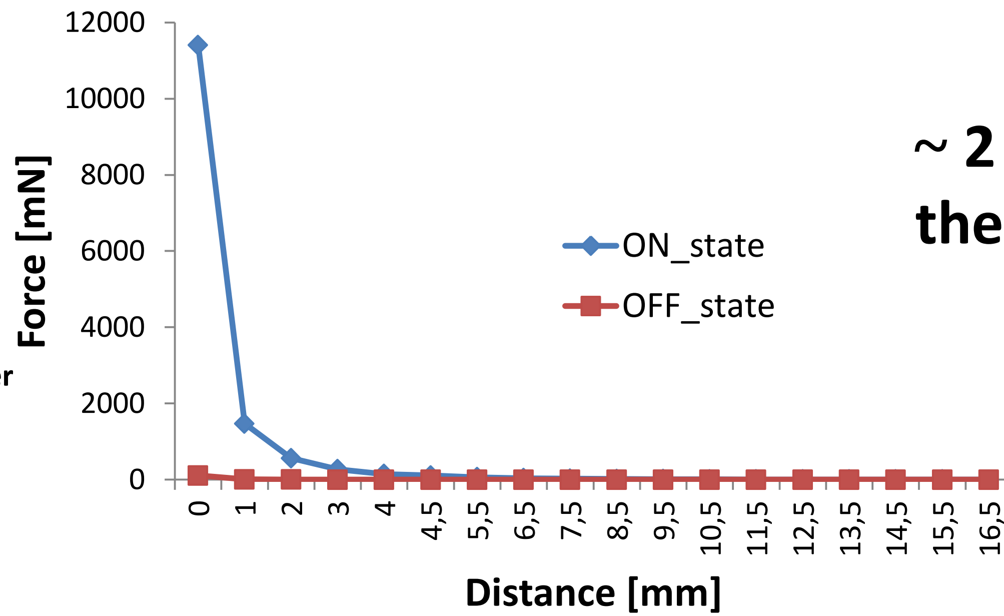
**TEFLON CAPSULE MOULDS**



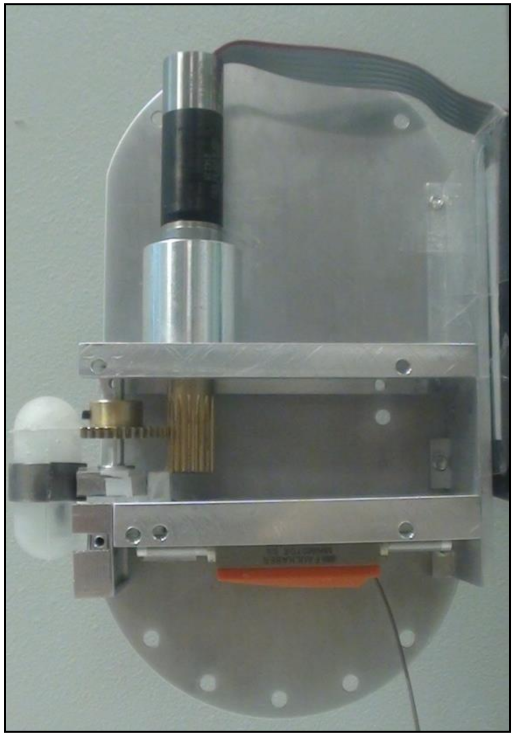

**Insulin content for each capsule ≈ 2 ml**

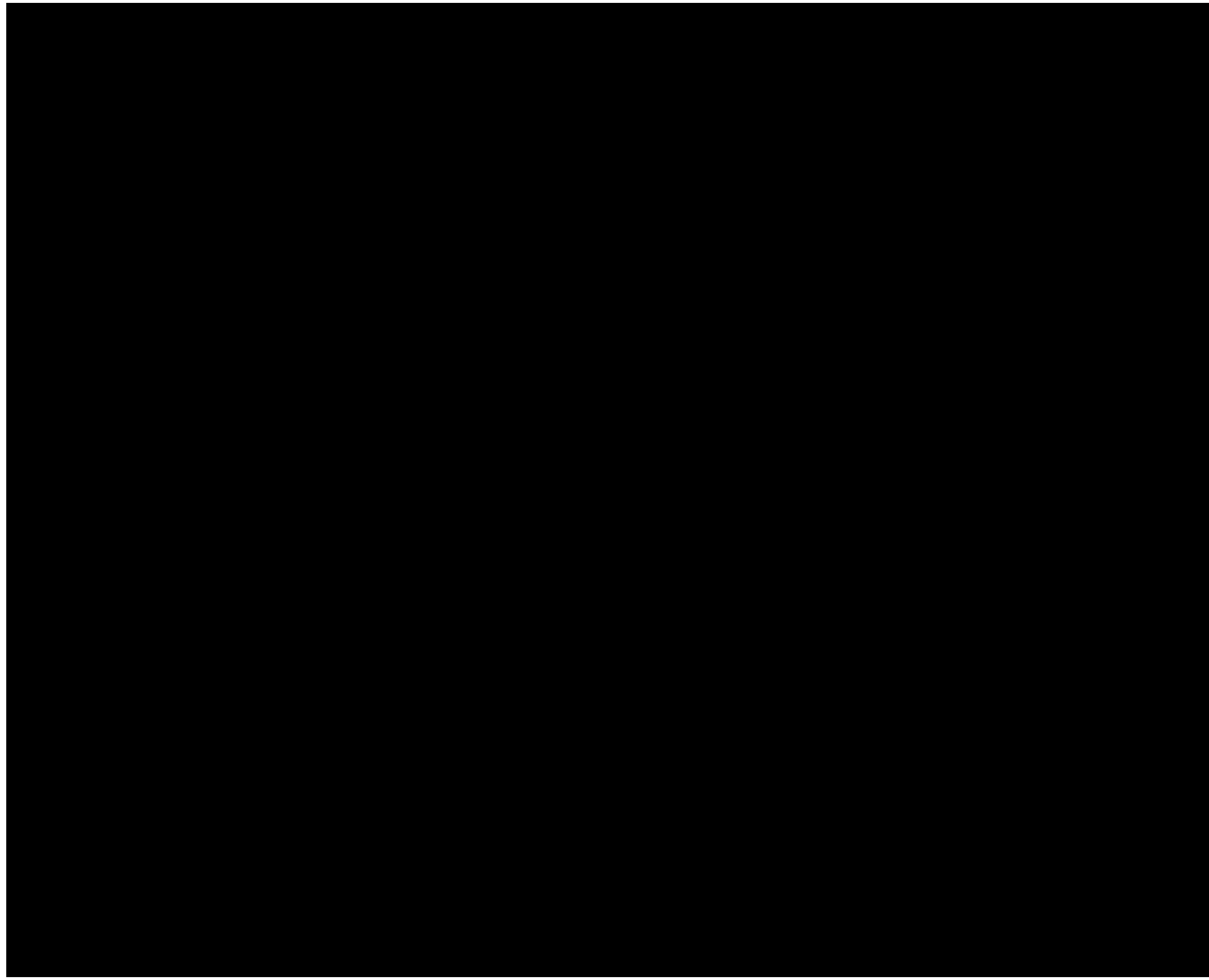
**~ 2 week autonomy for the implanted Artificial Pancreas**

**TI Microreader evaluation Module RI-STU-MRD2**



# Integrated system





# From Case Study #2 to Case Study #3

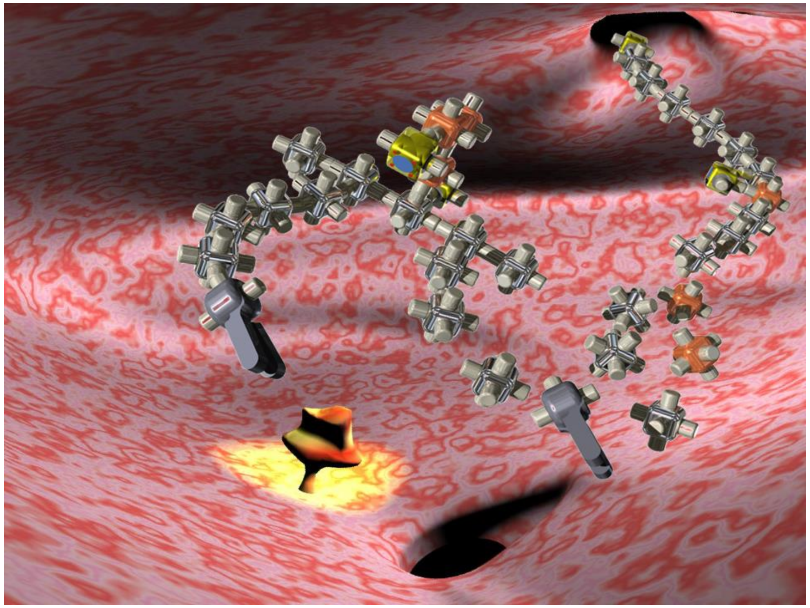
**Gastrointestinal Tract:**
**Ø = 10 to 30 mm**

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

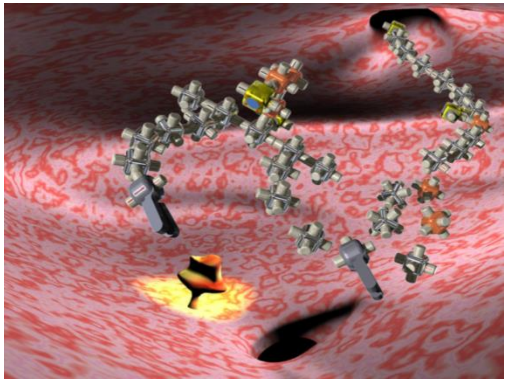
**Simple diagnostic robots (capsule-like) with limited therapeutic capabilities**

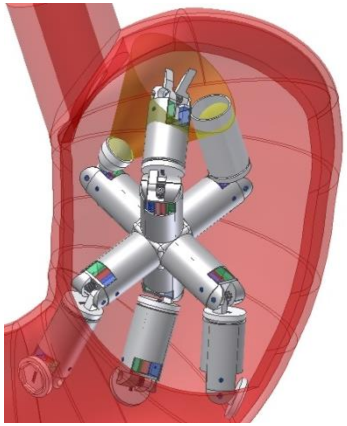
**Dexterous endoluminal robots with diagnostic/ therapeutic/surgical capabilities**

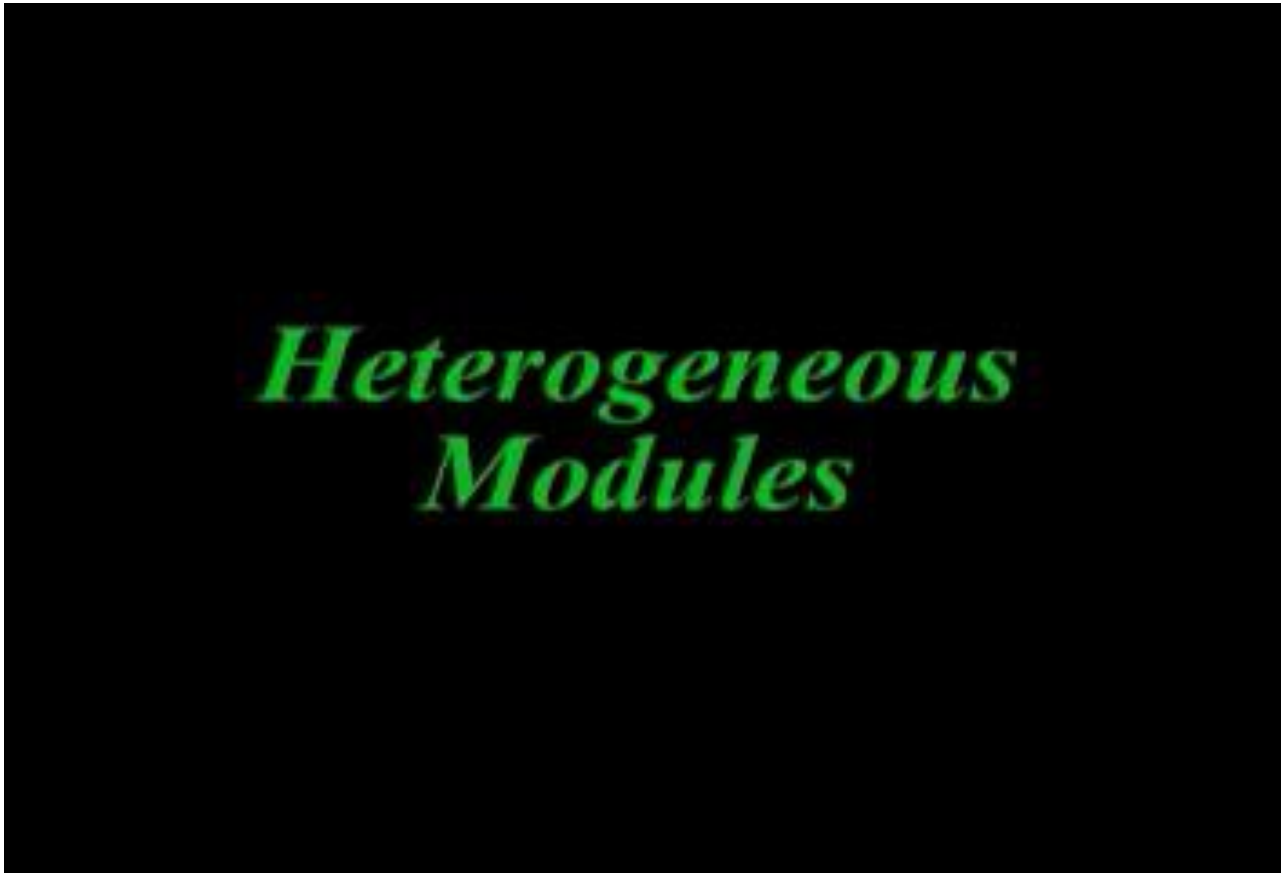
## From one to many capsules: reconfigurable robots for the exploration and for real surgery in the human body

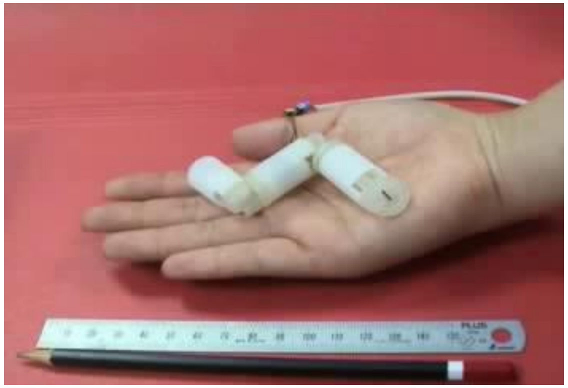


# From **Single** Capsules to a **Molteplicity** of Capsules: **Modular** and **Reconfigurable** Surgical Instruments

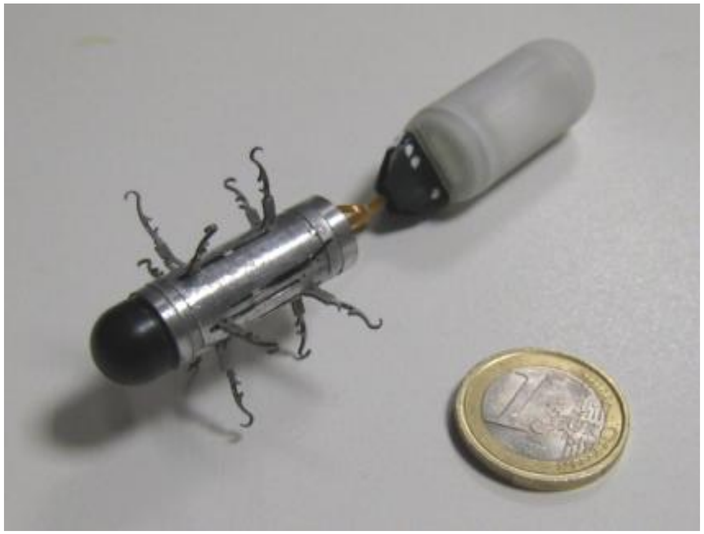




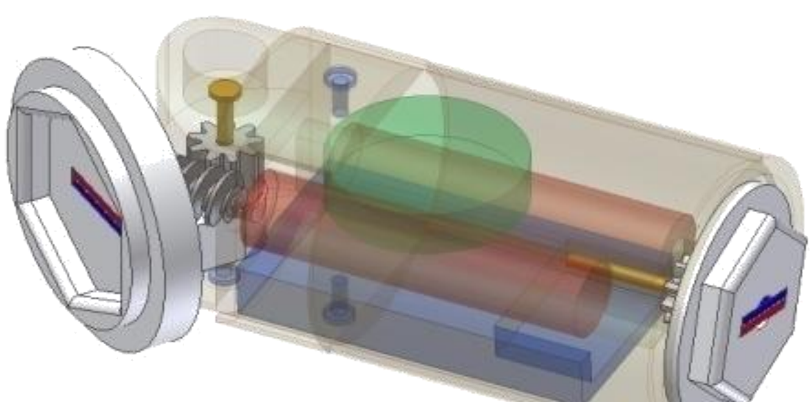


# Case Study #3



Evolution of the “tender” approach: multiple swallowable modules to be assembled and disassembled inside the stomach



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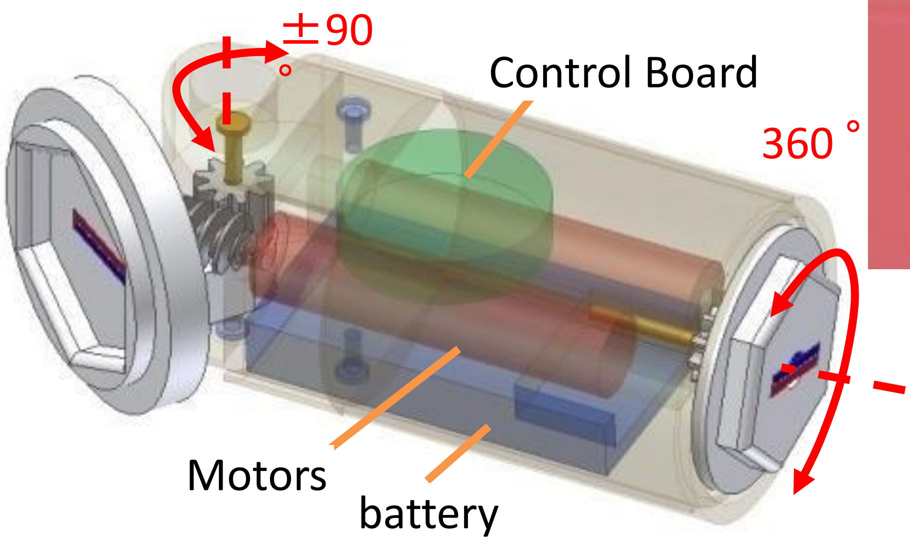
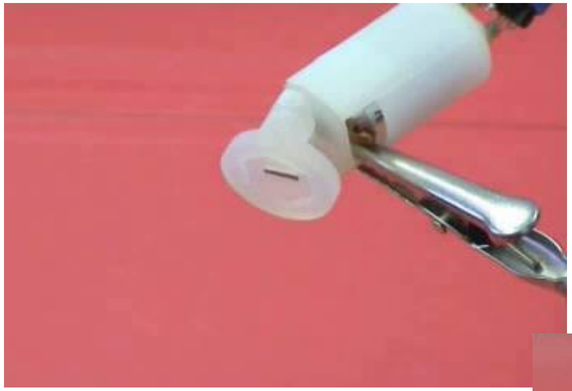
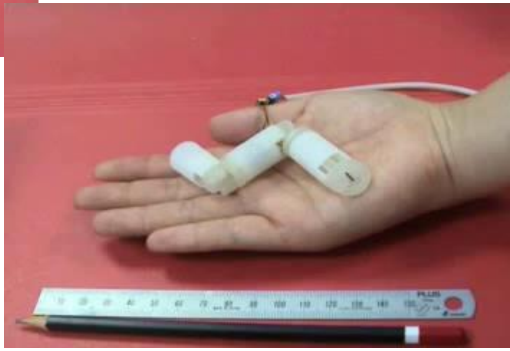
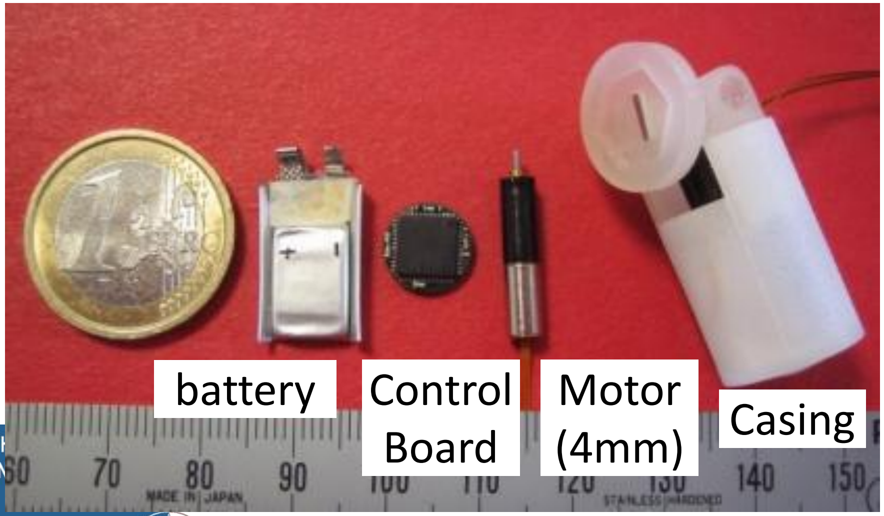
# Prototype of a robotic module

Φ15.4 X 36.3 , 5.6 g, 2 DOF

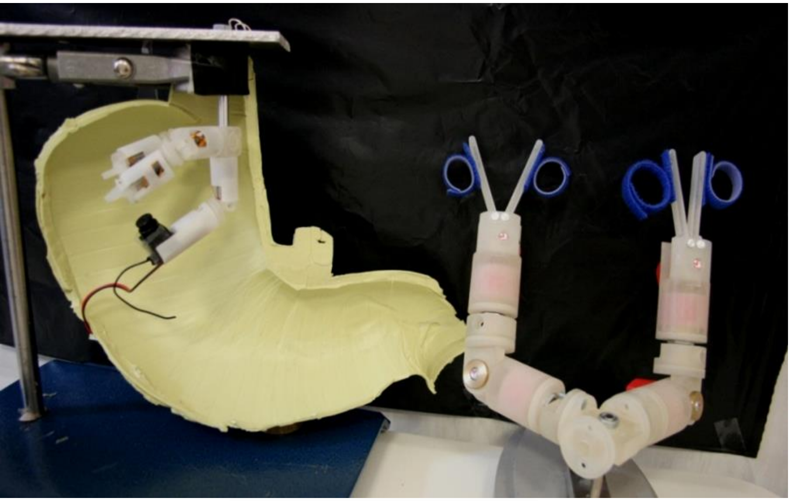


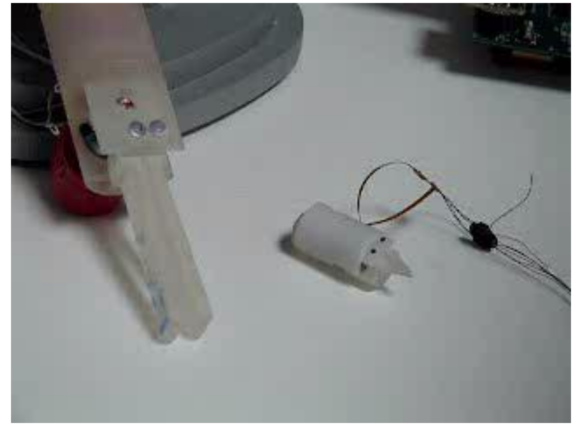



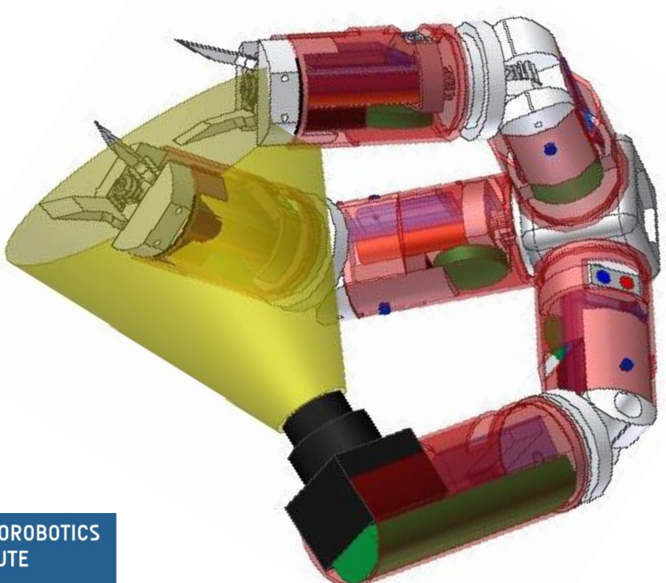


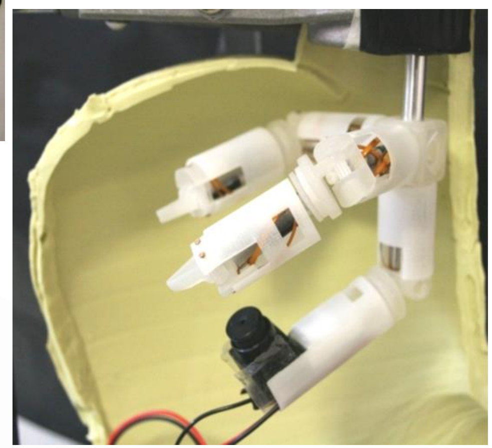


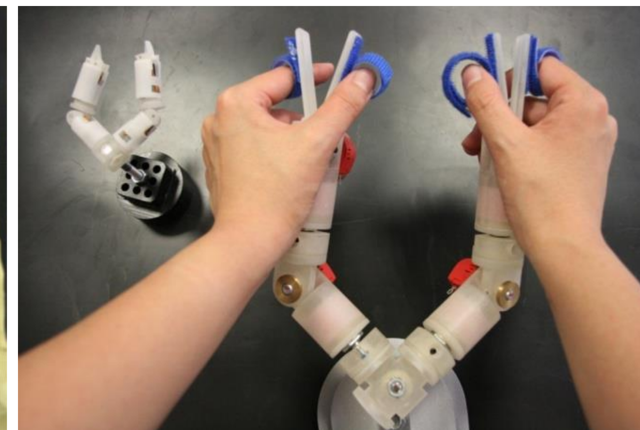

# Teleoperation of a module





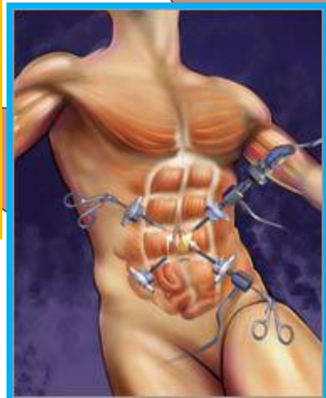


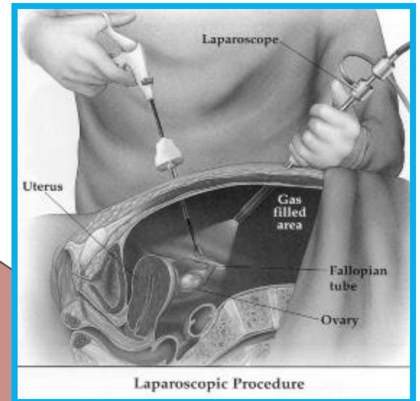




# Scarless Robotic Surgery

**TRADITIONAL TECHNIQUES**






**LAPAROSCOPIC SURGERY**

**ROBOTIC SURGERY**

**SCARLESS ROBOTIC SURGERY**

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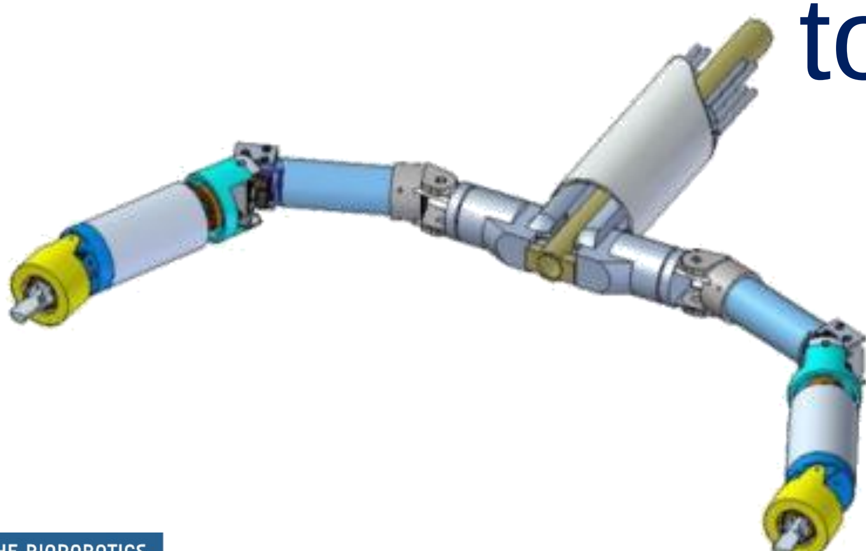
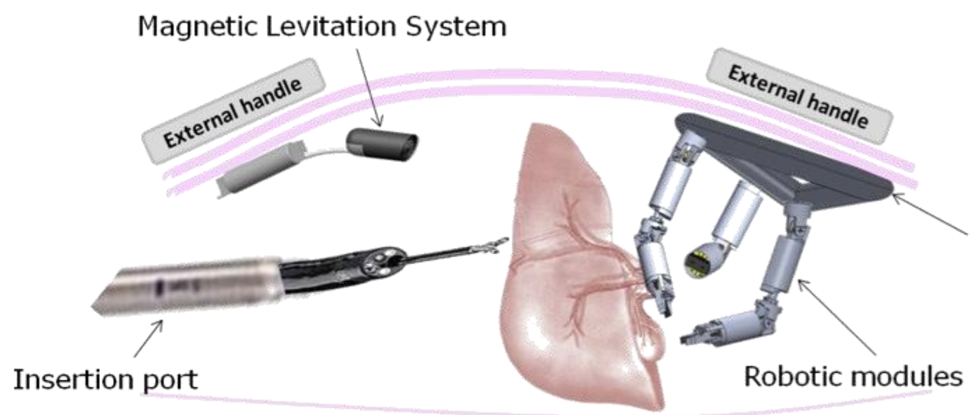
Scuola Superiore Sant'Anna

# Case Study #4

## Evolution of the concept of “modular” approach towards the design of clinically usable surgical tools



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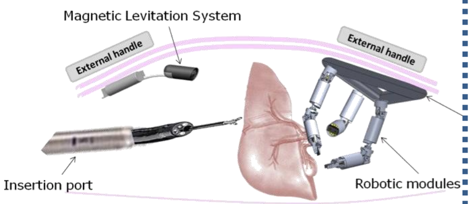
Scuola Superiore Sant’Anna

# Different Accesses

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

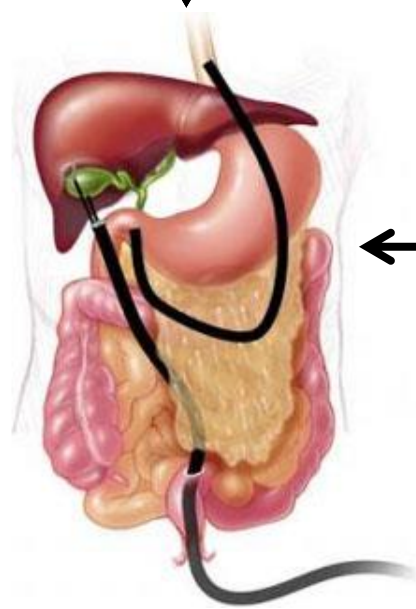



**NOTES (Trans-Oesophageal or Trans-Vaginal**

- Small dimension
- Anatomical constraints
- Safety issues

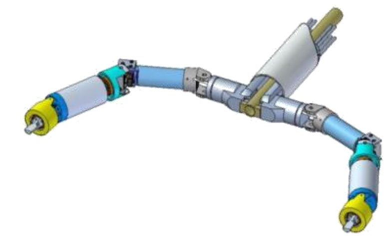
- Totally scarless
- Reduce post-interventional complications

OESOPHAGEAL ACCESS

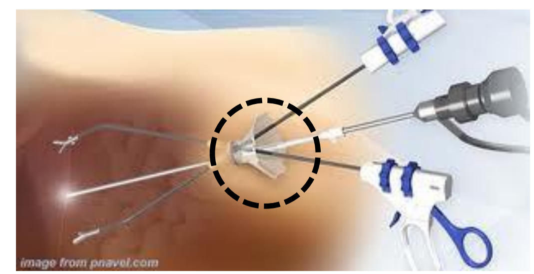


UMBILICAL ACCESS

TRANSVAGINAL ACCESS



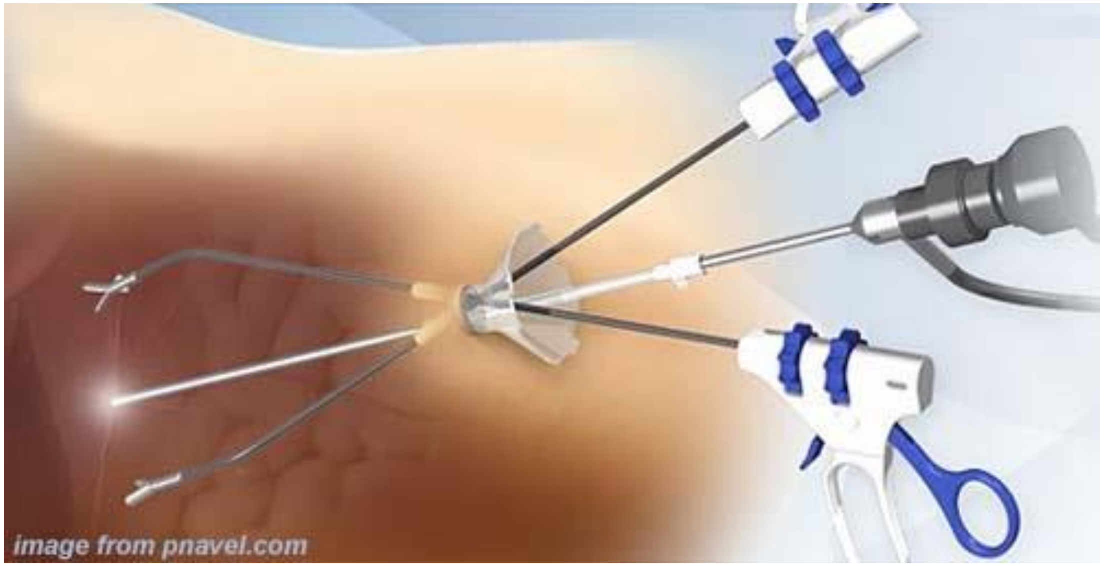
**SINGLE PORT ACCESS (Trans-Umbilical)**



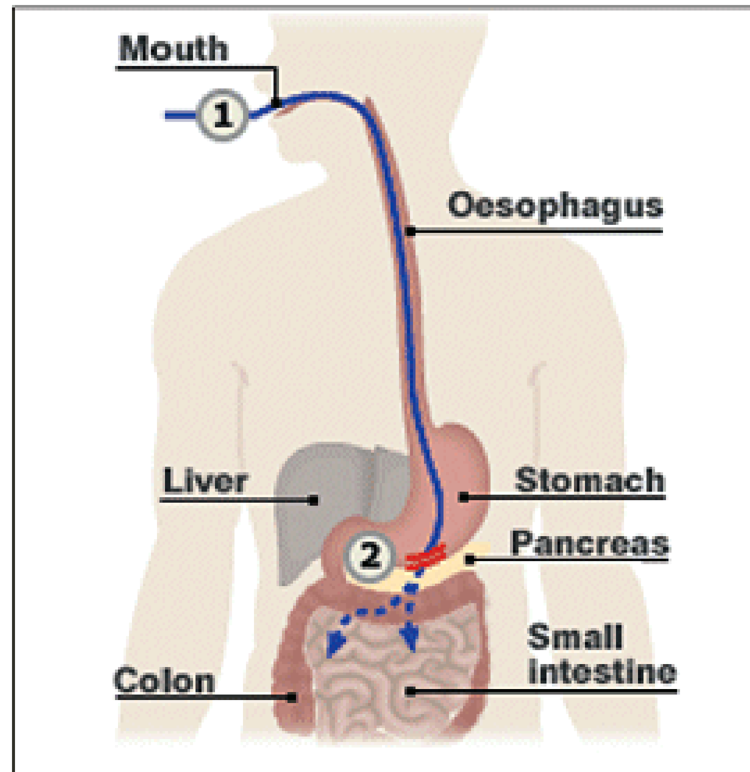

-Fulcrum effect
- Instruments collision
-Triangulation limitation

- Single scarless incision

# The Quest for Miniaturization: Endoluminal Robotic Surgery




**Single-Port Laparoscopic Surgery**




1. The endoscope with incision tools
2. The stomach wall is cut to access the abdominal cavity

**Flexible Endoscopic Surgery (NOTES)**

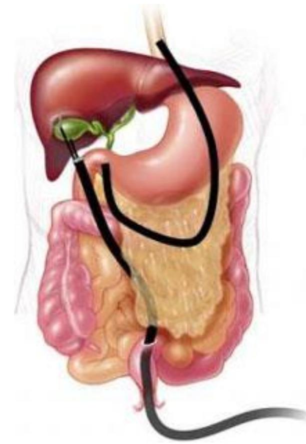
# N.O.T.E.S and **Single Port Laparoscopy**: no visible scars!

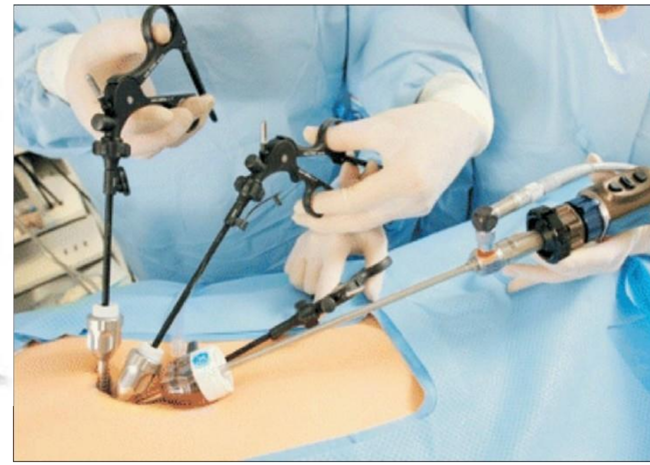
**Open** surgery

Abdominal incision **1 year after open surgery**

**Laparoscopic** surgery

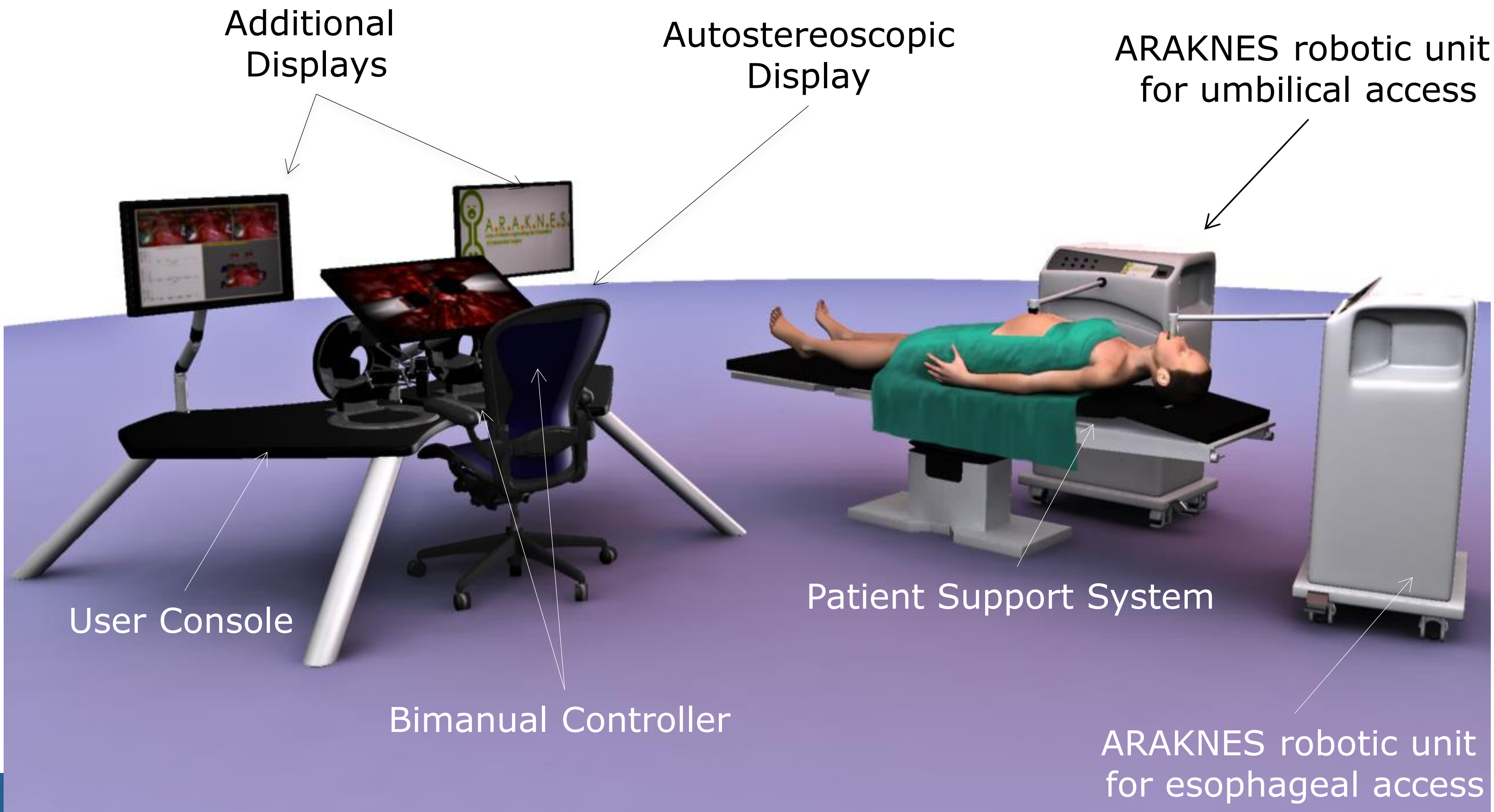
**Laparoscopic scar after 15 days**



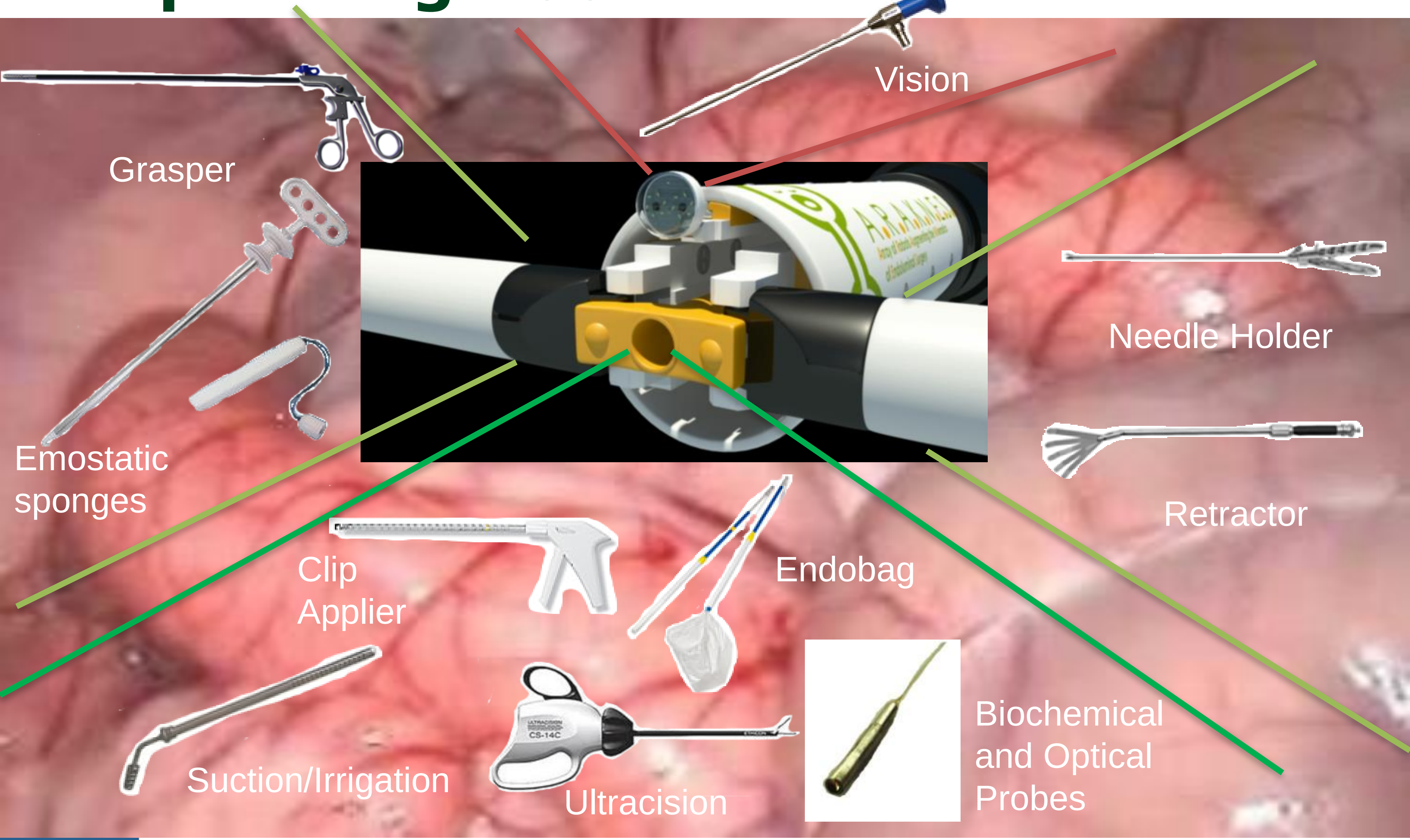


Umbilical incision **3 weeks after single-port nephrectomy** (kidney removal) leaves little to no scarring

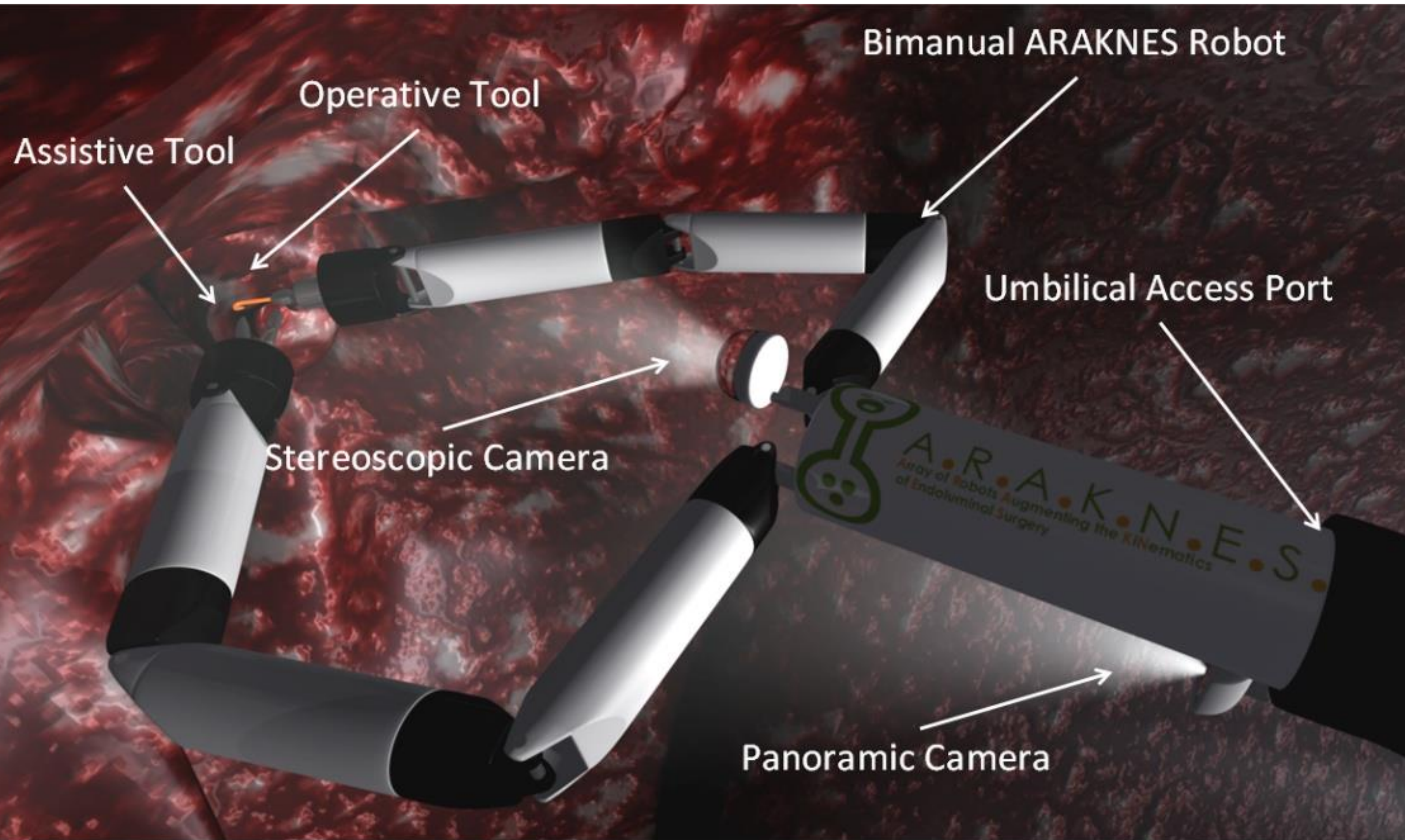
# ARAKNES (Array of Robots Augmenting the KiNematics of Endoluminal Surgery) EU Project (2008-2012)



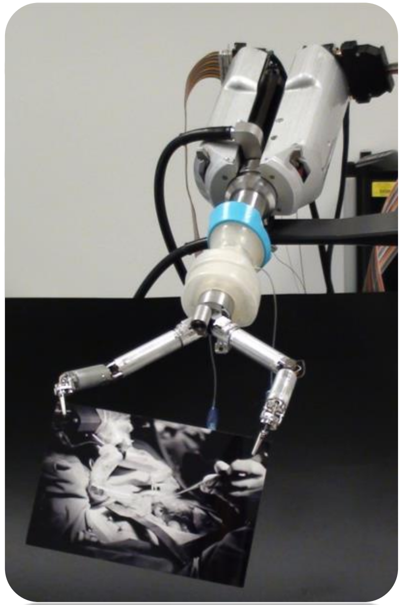
# The ARAKNES Vision: Bringing the Operating Room Inside the Patient



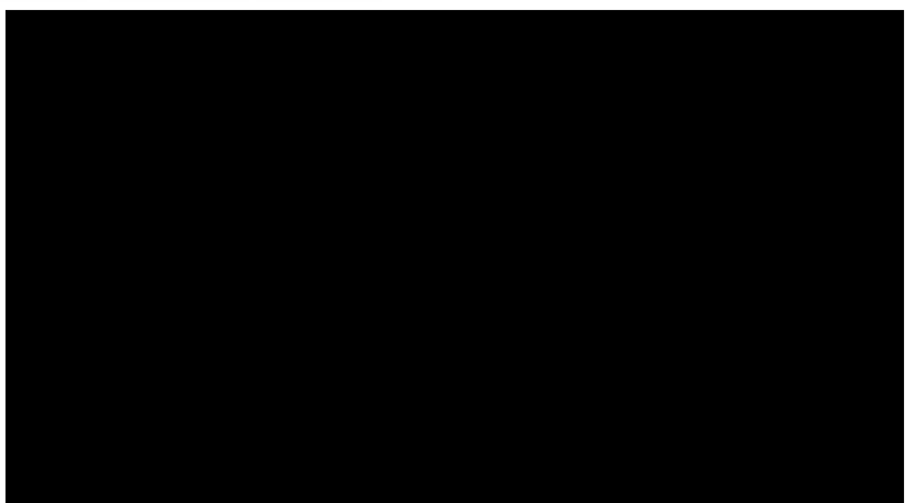
# SPRINT (Single-Port lapaRoscopy bImaNual roboT) robot

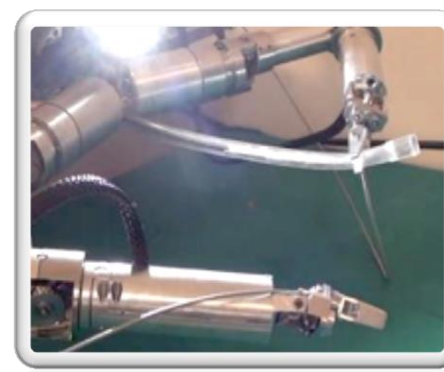


# System Delivery Through the Introducer



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

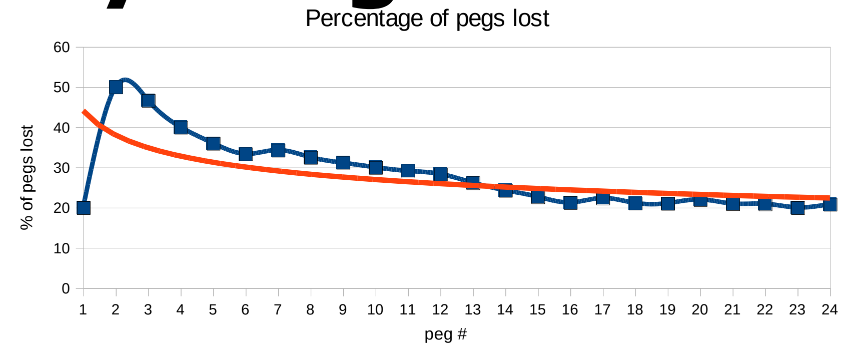


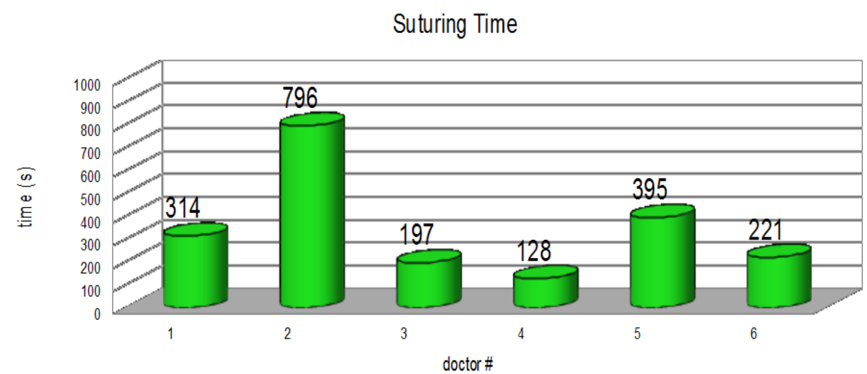


# Characterization by Surgeons

## 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 |

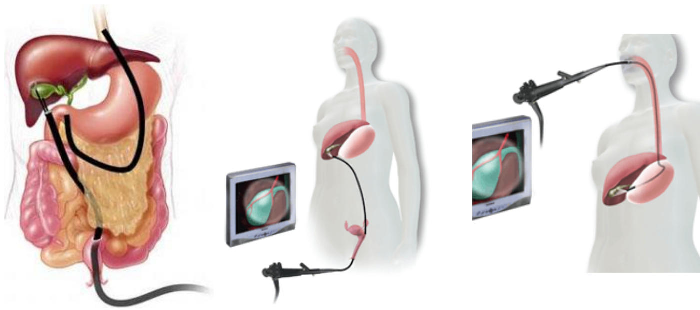
G. Petroni, M. Niccolini, A. Menciassi, P. Dario, A. Cuschieri, *A novel intracorporeal assembling robotic system for single-port laparoscopic surgery,* Surgical Endoscopy, 2012

# 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

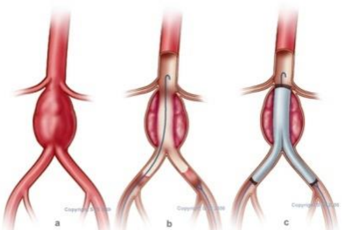
# The Quest for Miniaturization

## ABDOMINAL SURGERY



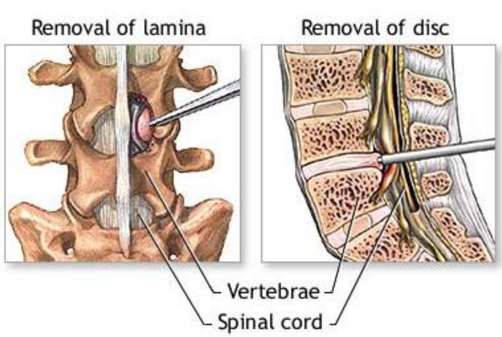
**NOTES (Natural Orifice Transluminal Surgery) SURGERY**
**Reaching** the target (esophagus diameter about 14 mm)
**Bringing** actions to the target

## VASCULAR SURGERY




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

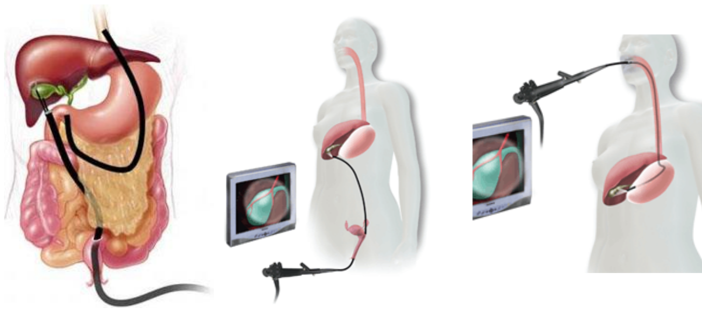
## NEURO ENDOSCOPY




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

# The Quest for Miniaturization

## ABDOMINAL SURGERY



**NOTES (Natural Orifice Transluminal Surgery) SURGERY**
**Reaching** the target (esophagus diameter about 14 mm)
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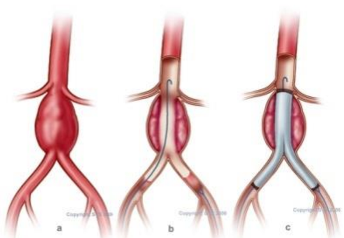
## VASCULAR SURGERY



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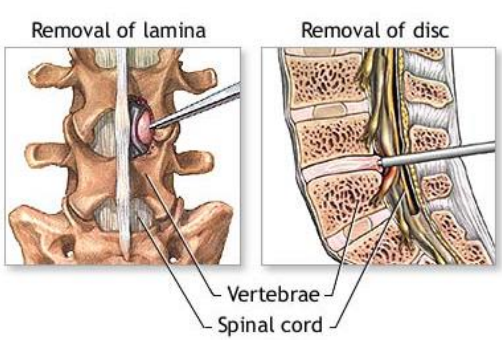
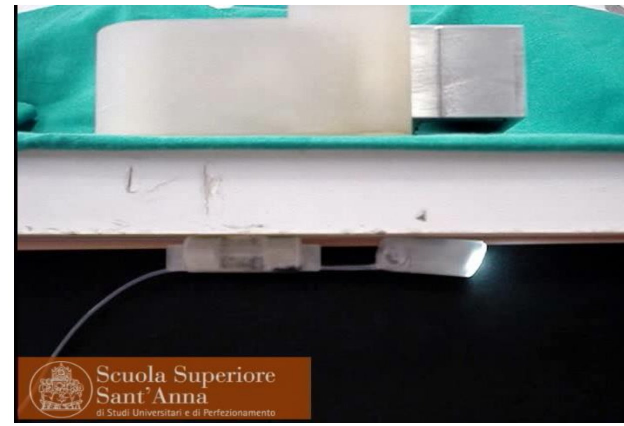
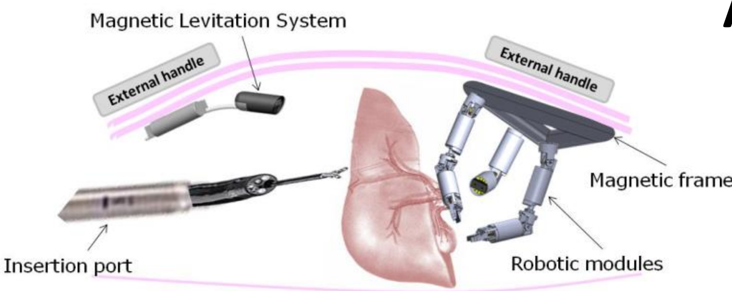



**Challenges in neuro endoscopy:**
**Reaching** the target (spinal cord diameter: **4 to 1.5 mm**)
**Bringing** actions to the target


# 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)

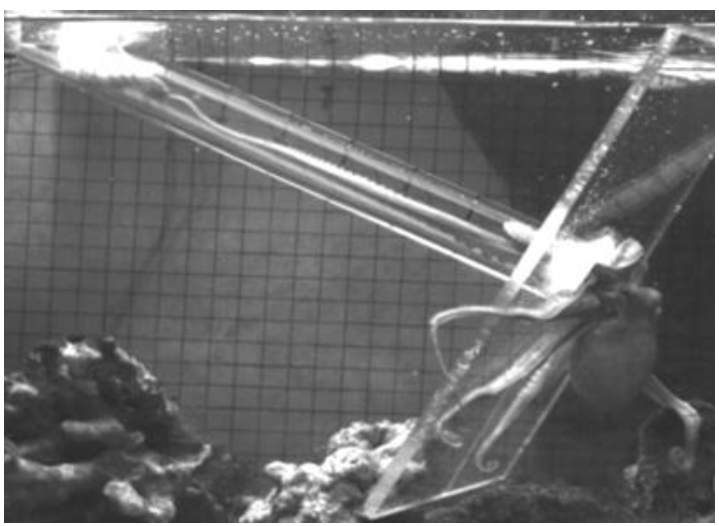
# From bio-inspiration to bio-application for endoluminal surgery

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.

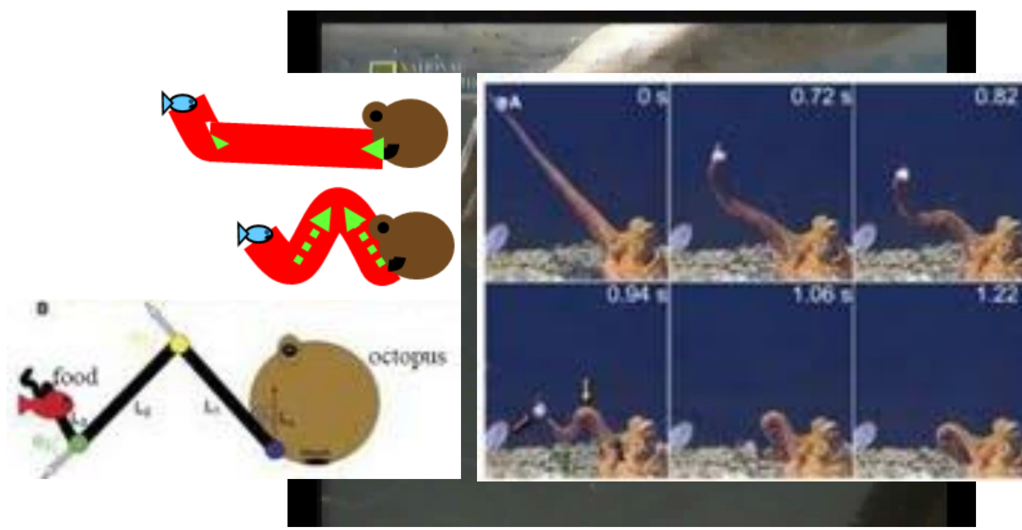
## Bioinspiration

Arms Elongation : 70% of arms mean elongation corresponding to 23% of diameter reduction

Fetching movement: from flexible to articulated structure

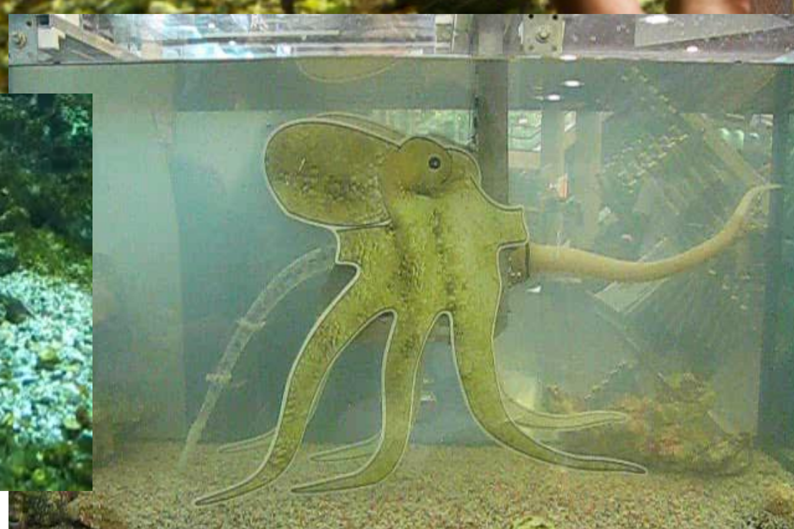


Margheri L., Mazzolai B., Ponte G., Fiorito G., Dario P., Laschi C. (2010) Methods and tools for the anatomical study and experimental in vivo measurement of the Octopus vulgaris arm for biomimetic design, IEEE RAS / EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob 2010), Tokyo, Japan.




Sumbre G, Fiorito G, Flash T, Hochner B (2006) Octopuses use a human-like strategy to control precise point-to-point arm movements. Curr Biol 16:767-772.

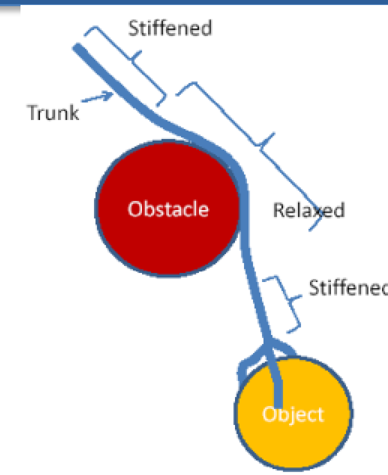
# From Biology to Robotics



OCTOPUS proj 012)

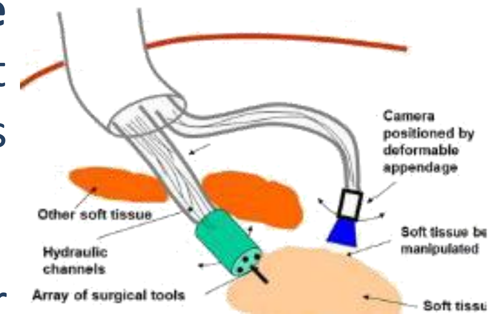
# The STIFF-FLOP EU Project

- To use **biological inspiration** to create novel, flexible manipulator structures that are inherently capable **of morphing their state from completely soft to entirely articulated,**



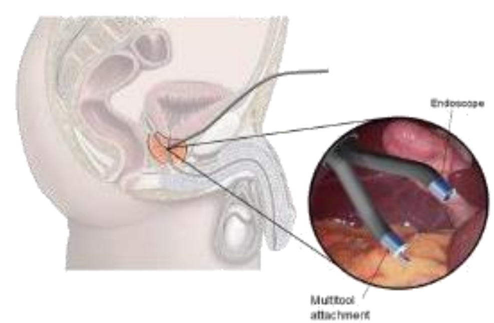

- Distributed tactile/pressure sensing to locally adapt to and compensate for changes in the environment

- To **advance learning and cognitive reasoning in a complete embodiment of a hyper-redundant manipulation** system that experiences and learns from physical interactions with its environment,

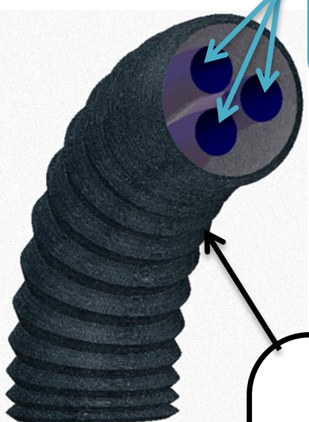


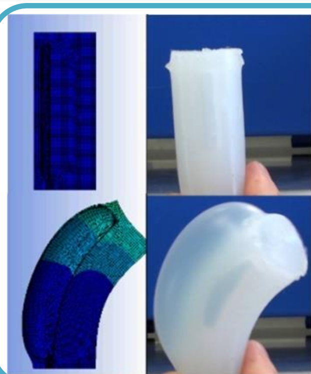

- **Novel 3D haptic feedback providing surgeon with a "feel"** for the remote environment

- Developing **cognitive behaviour** by learning from human in the loop

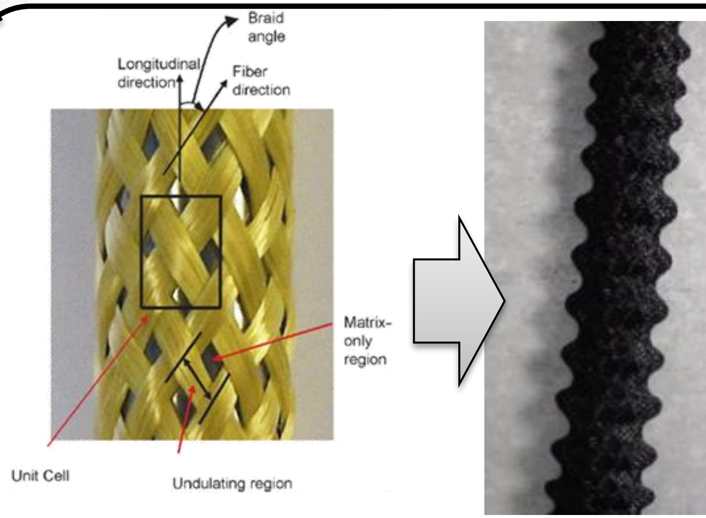


# Multi-Directional Bending Module



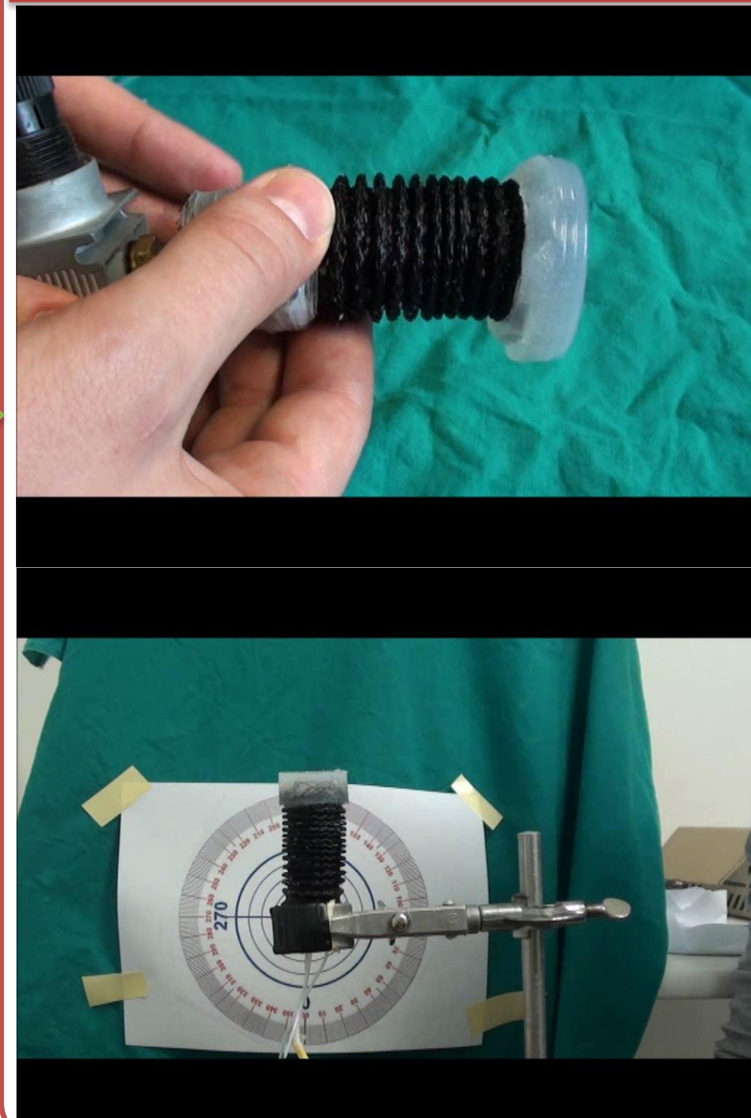


Flexible silicone actuator with three embedded fluidic chambers for <u>multi directional bending</u>



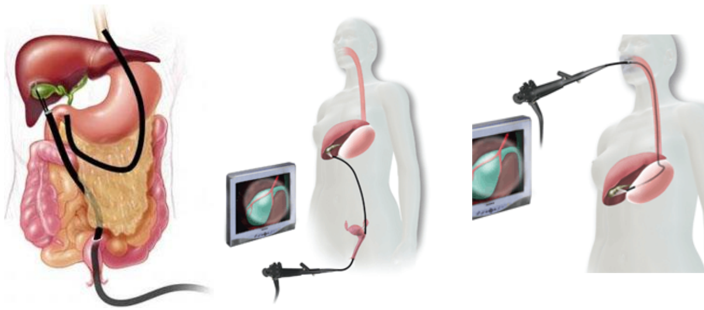

Bellow- shaped braided structure

Up to 115° bending, and 66% elongation.



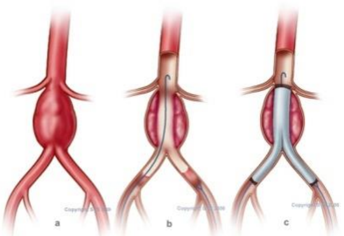
# The Quest for Miniaturization

## ABDOMINAL SURGERY



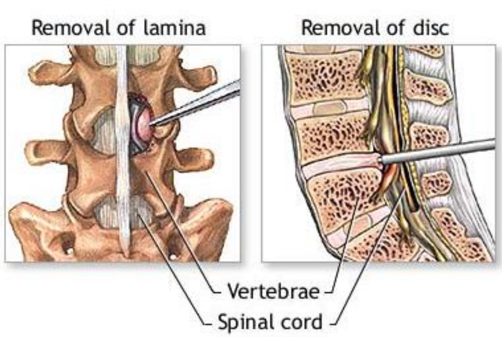
**NOTES (Natural Orifice Transluminal Surgery) SURGERY**
**Reaching** the target (esophagus diameter about 14 mm)
**Bringing** actions to the target

## VASCULAR SURGERY



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

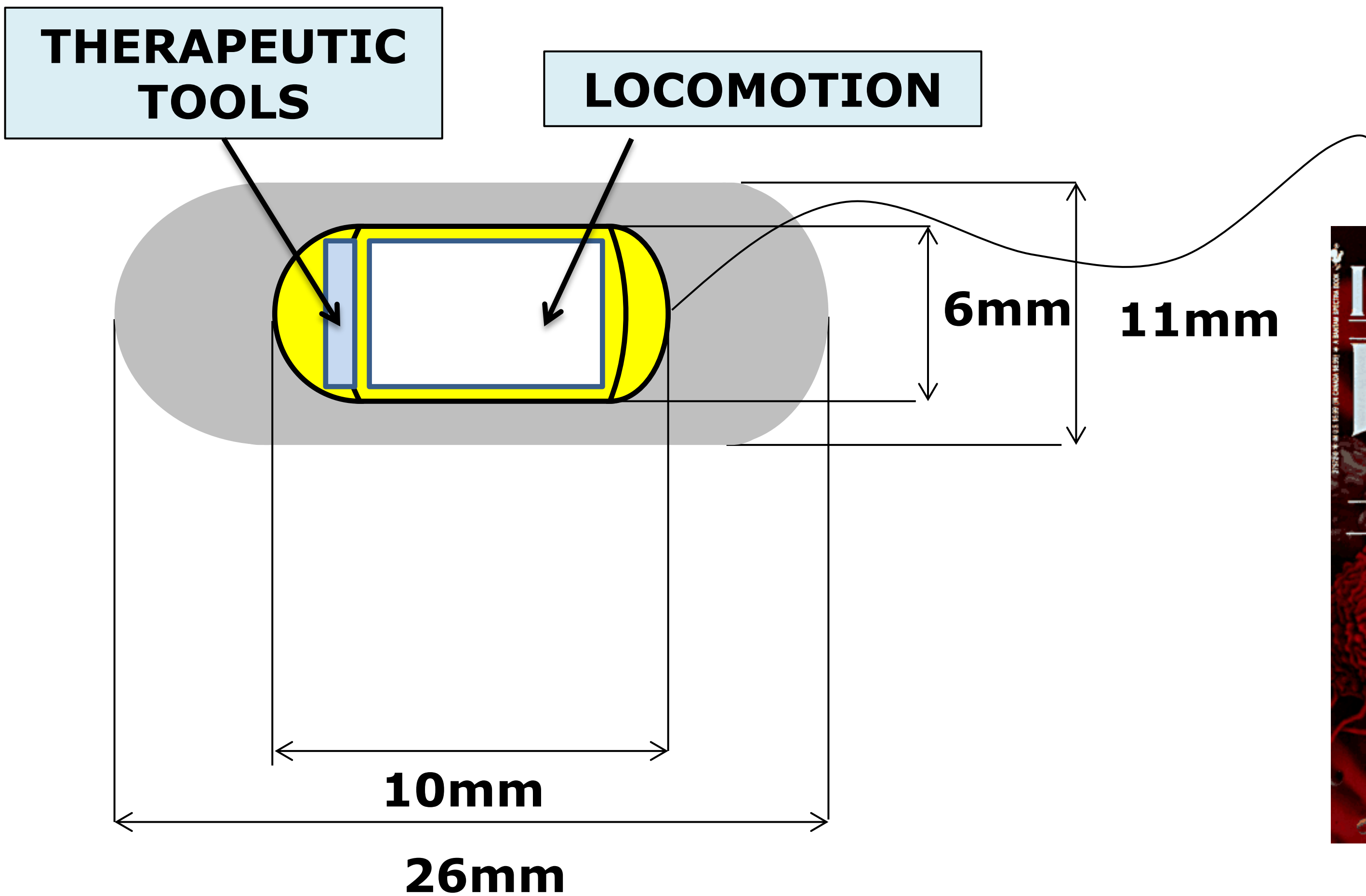
## NEURO ENDOSCOPY

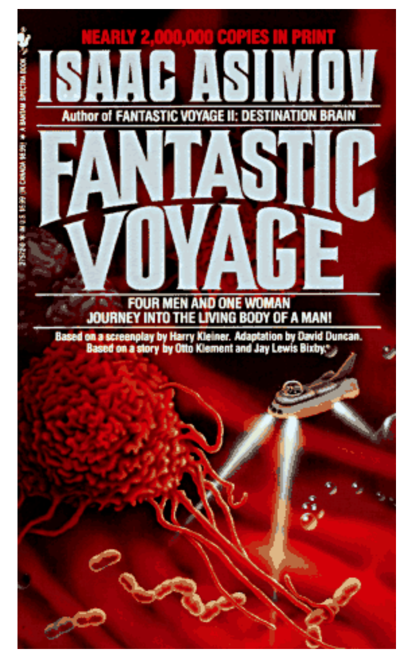



**Challenges in neuro endoscopy:**
**Reaching** the target (spinal cord diameter: **4 to 1.5 mm**)
**Bringing** actions to the target

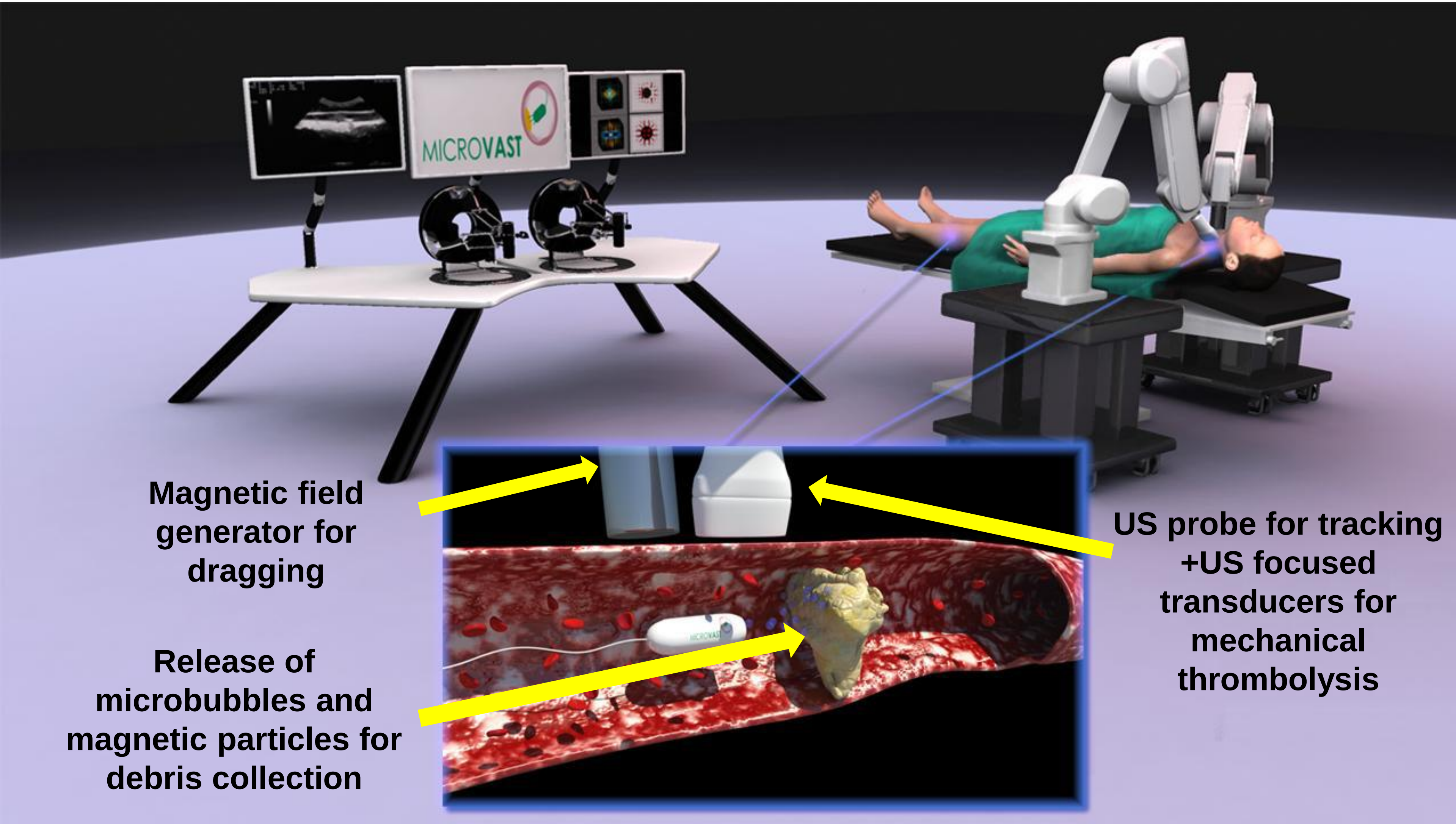
# Case study #6. The GRAND CHALLENGE: from the gastrointestinal tract to the vascular system

**Vascular system**
**Ø = 8 to 6 mm**



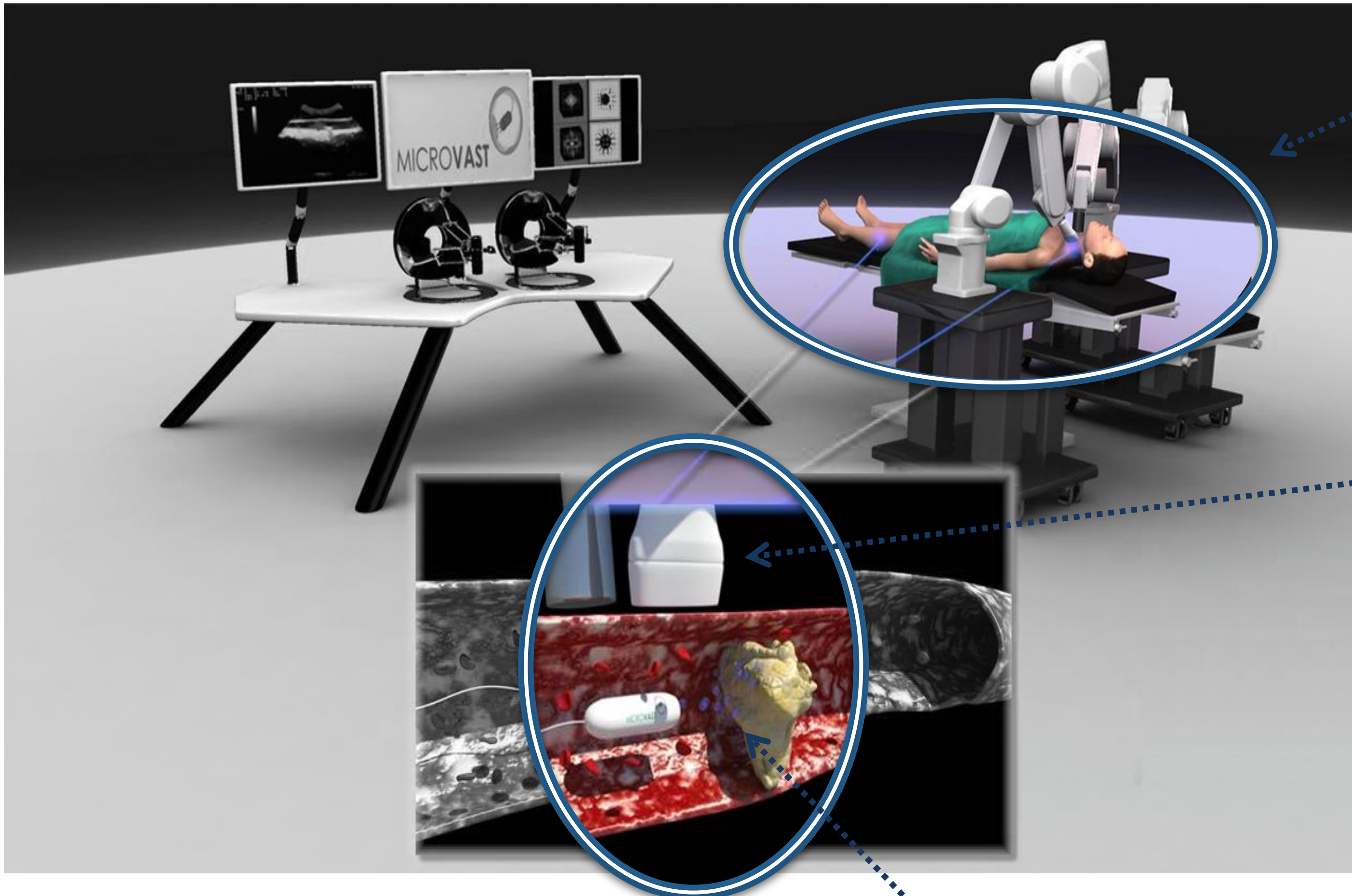



# A computer-assisted robotic platform for soft-wired therapy of vascular obstructions



# The MicroVast Platform

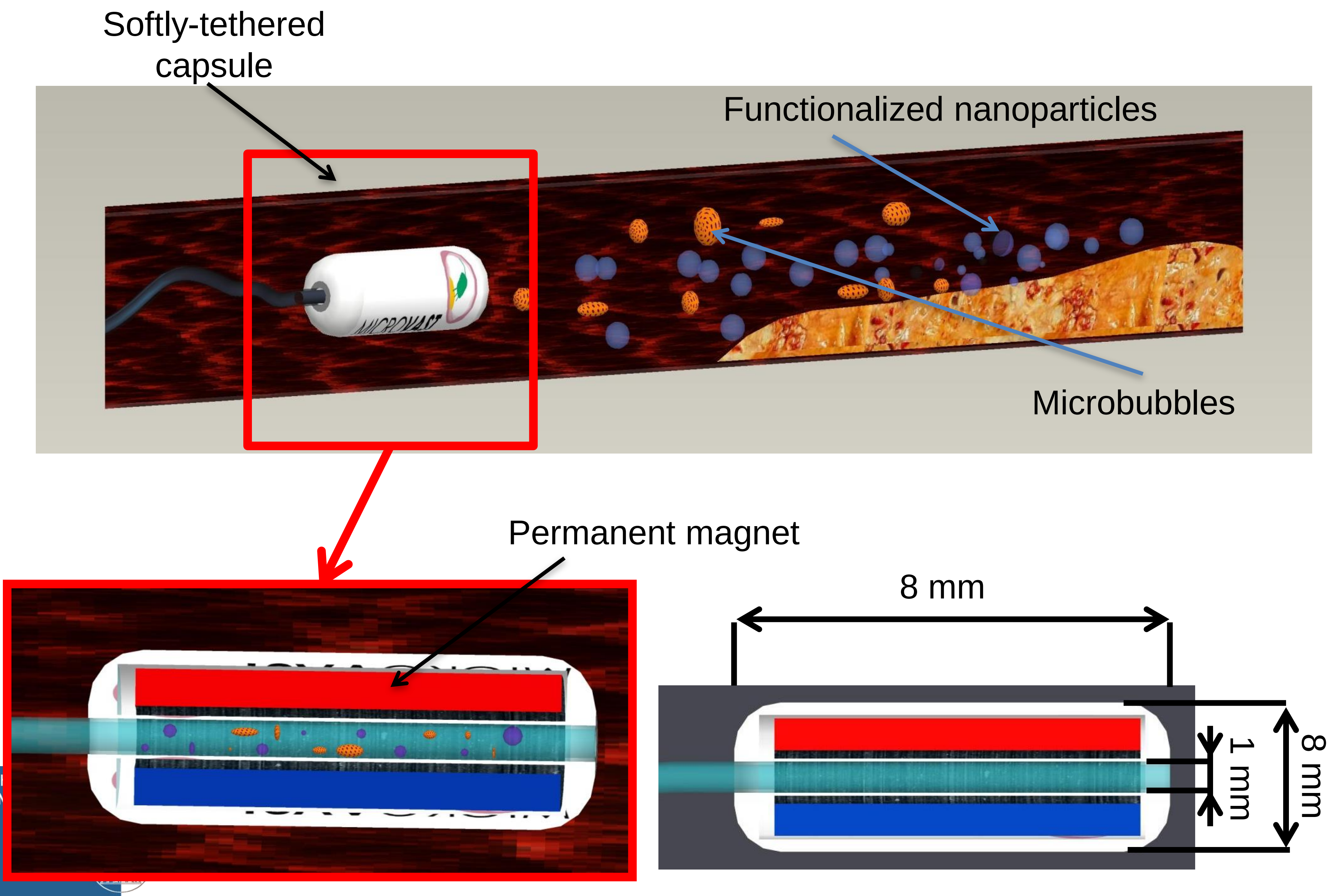
**Navigation module**: **External robots** holding a permanent magnet and a diagnostic US probe.



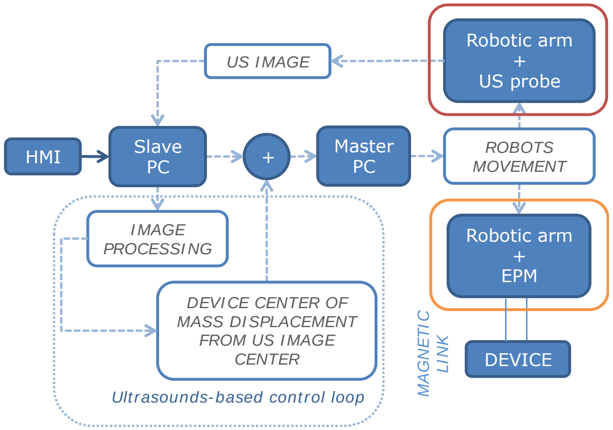

**Therapeutic module: Focused US** thrombolysis enhanced by microbubbles released by means of a magnetic internal mechanism

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

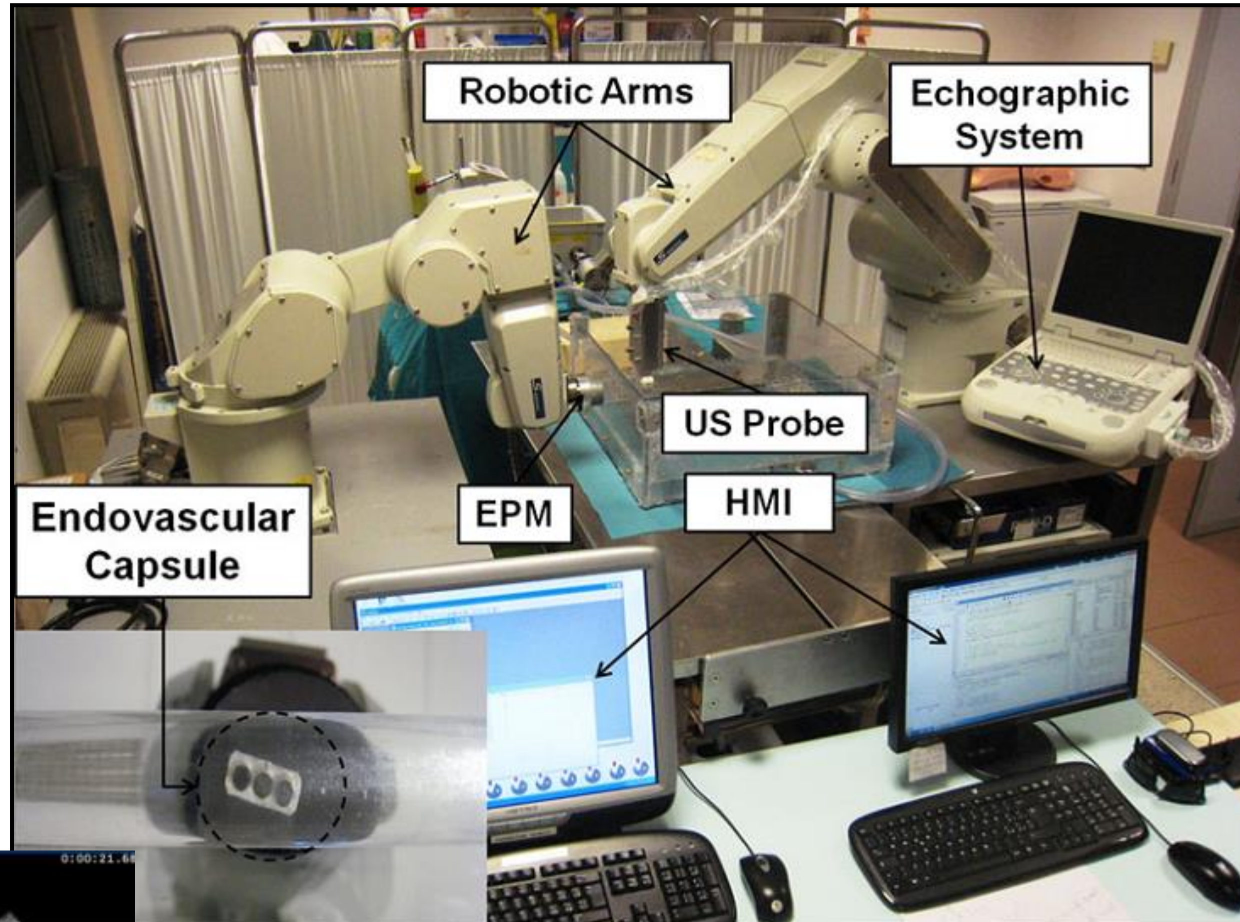
# The MicroVast Robot Carrier

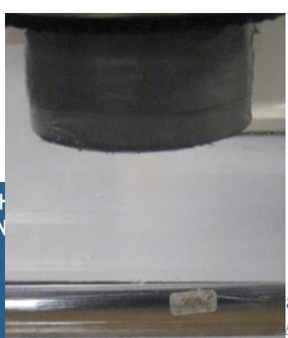


# Navigation Module: System Overview




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

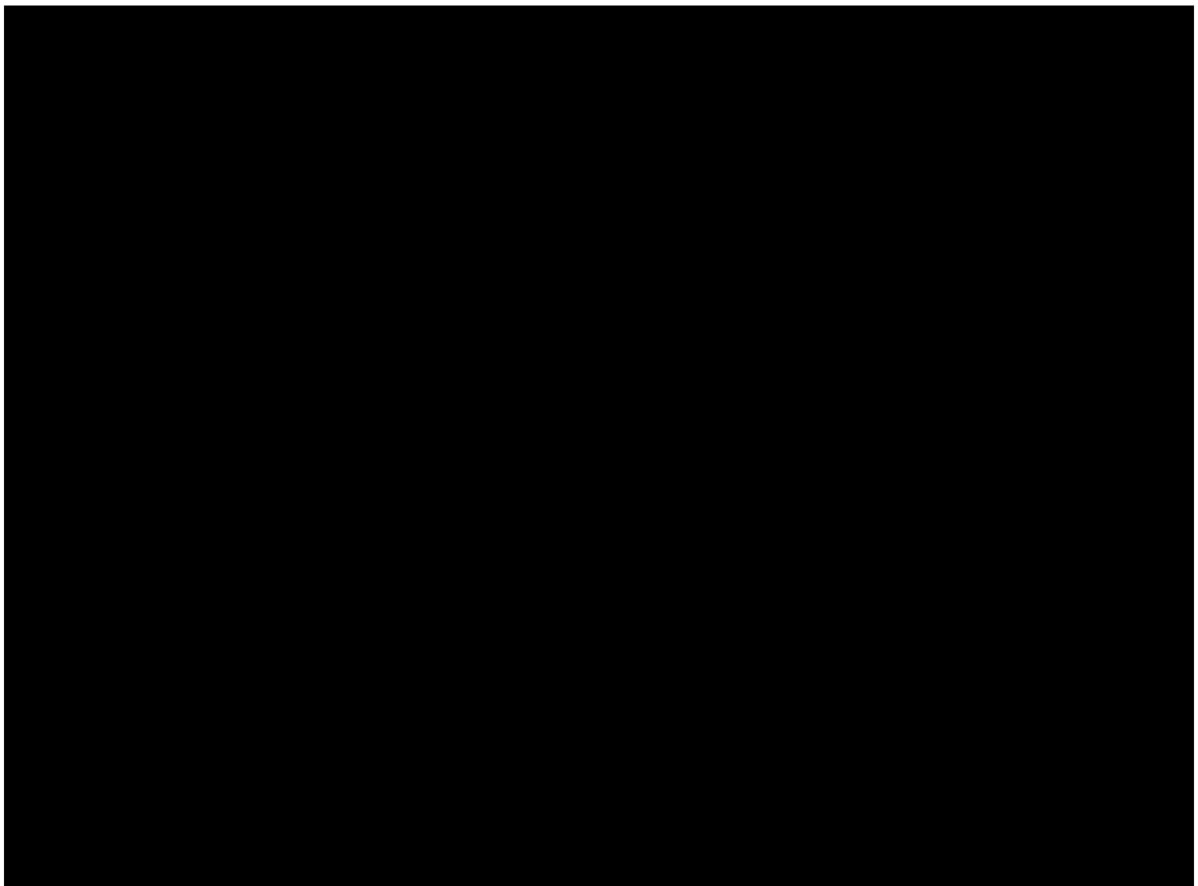


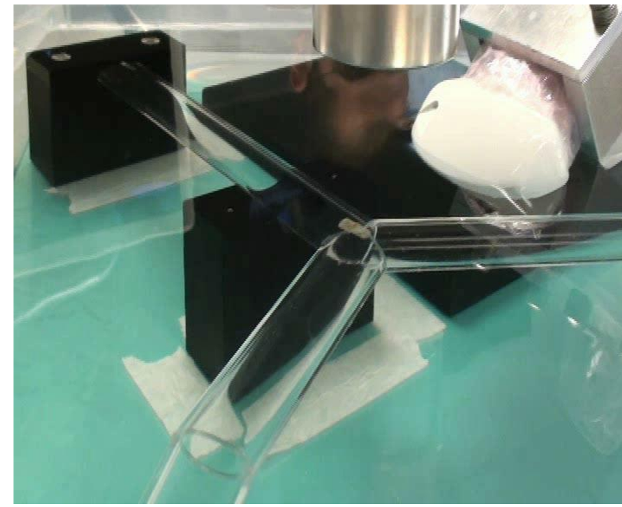
EPM: External Permanent Magnet - HMI: Human Machine Interface

# Navigation Module: in-vitro test

**In-vitro experimental test** of the MicroVast platform on a cardiovascular ecographic compatible phantom with US-based tracking algorithm



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



# Navigation Module: ex-vivo test

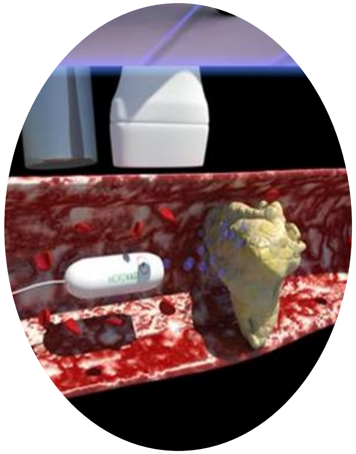
**Ex-vivo MicroVast platform validation on an explanted aortic vessel–** combination of US-based tracking algorithm and pre-operative path registration for autonomous locomotion.

The US-based algorithm control loop is processed with an average time of 13 ms. An average number of 12 features were extracted from each frame of the segmented endoluminal capsule

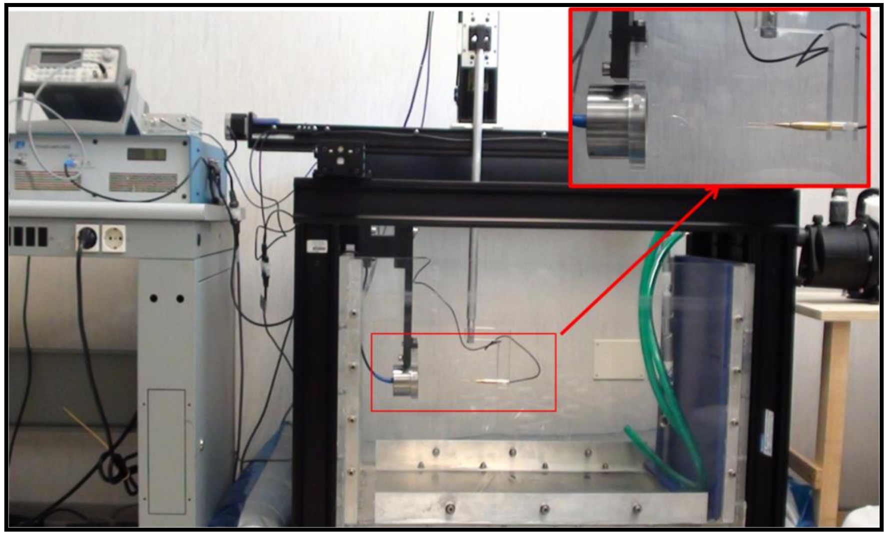
# Therapy Module: Set-up

**High Intensity Focused Ultrasound (HIFU) Thrombolysis (dissolution of a blood clot):**

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



- 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

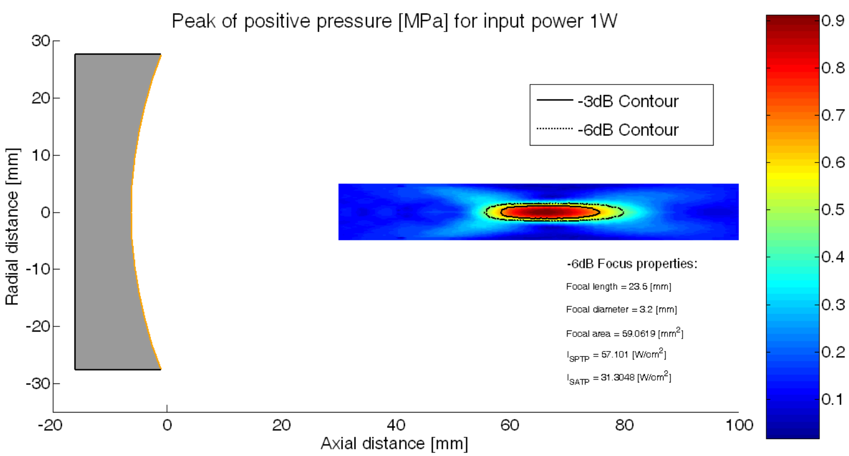


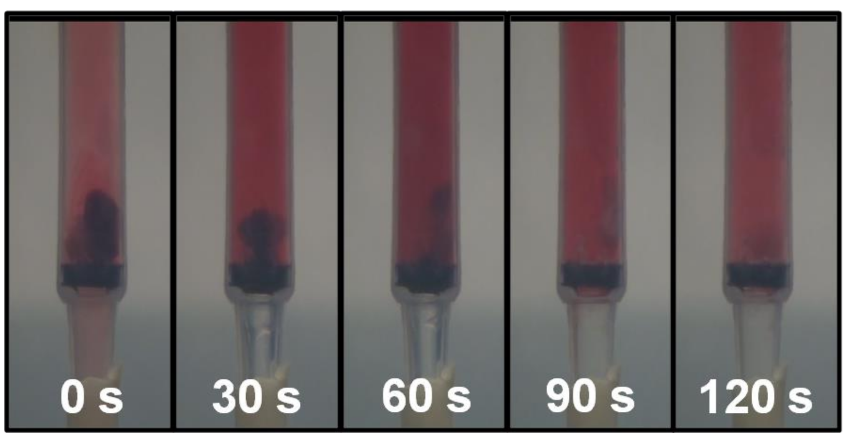
* R. Medel et al., "Sonothrombolysis: an emerging modality for the management of stroke" , Neurosurgery,65(5),2009.

# Therapy module - High Intensity Focused Ultrasound Thrombolysis: Results

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

Velocity 4X



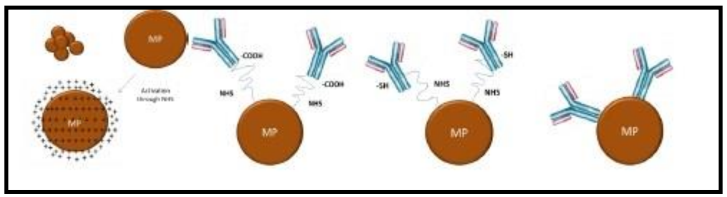


Freq. 1MHz - Power 65W - Pulse Length 450μs - Duty Cycle 1:10 - Flow rate 2ml/min

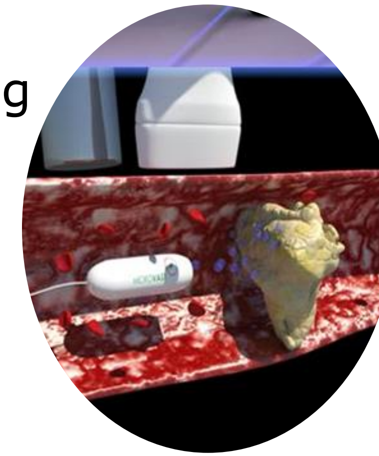
# Debris collection: Set-up & Validation

## ❑ Preparation technique

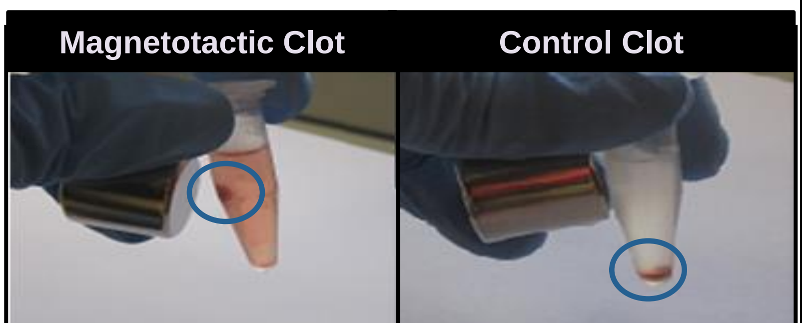
- ✓ Magnetic particles binding to antibody
- ✓ Electrostatic & clot antigen binding to magnetic particles (MPs)

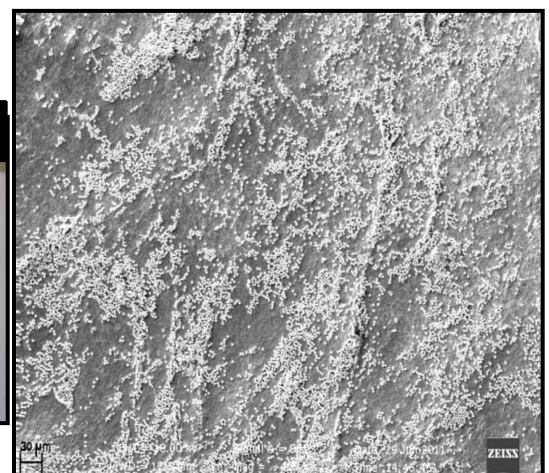


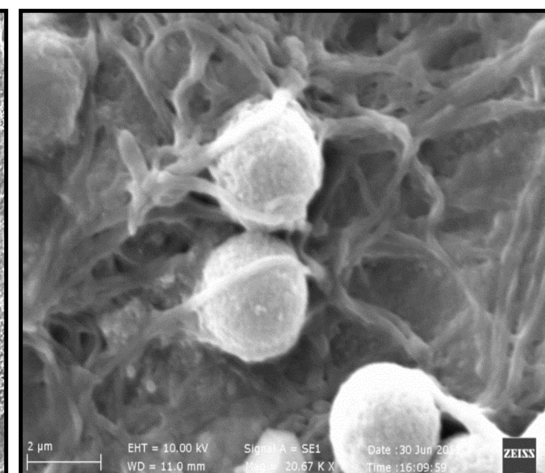

**Debris collection module:** Binding of magnetic particles to thrombus for collection and retrieval of debris.



## ❑ Qualitative assessment of obtained magnetotactic clot

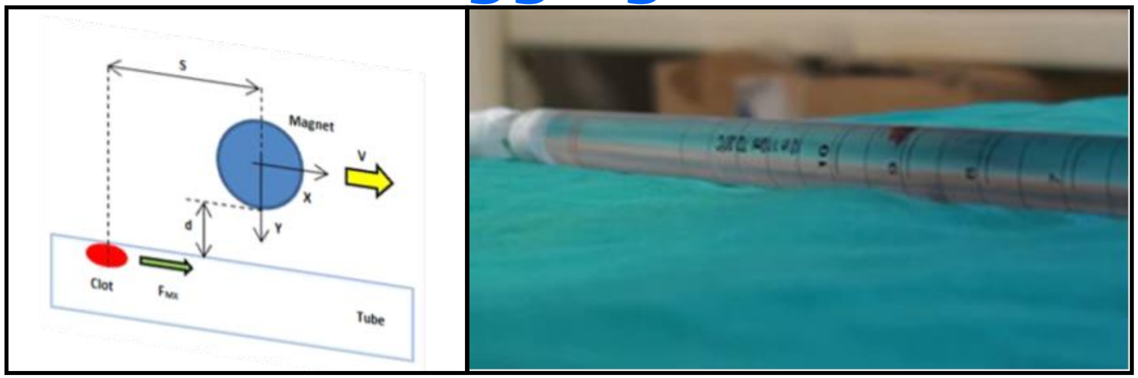


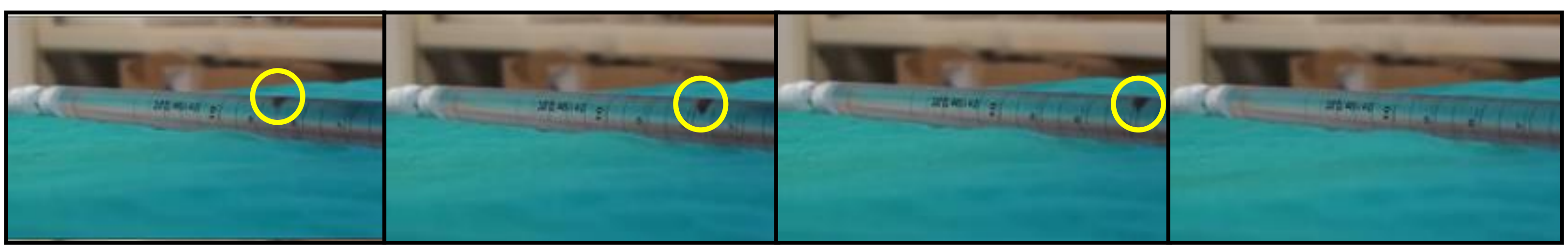
# Debris Collection: Set-up & Results

## ❑ Magnetotactic clot dragging




## ❑ Magnetotactic Clot Dragged in a fluidic channel.

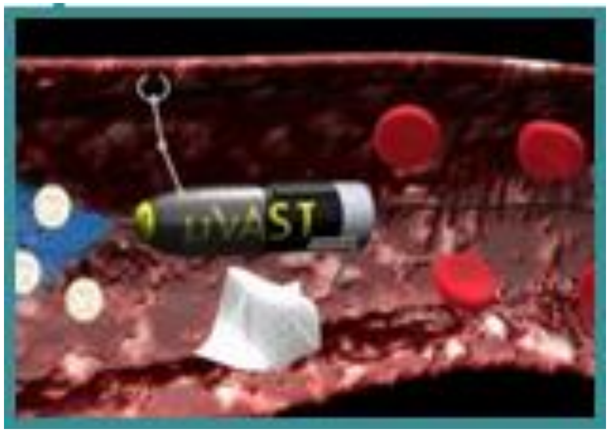
Results: Magnetotactic clot dragged inside a fluidic channel by means of External Permanent Magnet

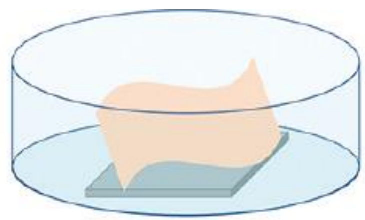


Khorami  Llewellyn et.al "Magnetic Dragging of Vascular Obstructions by Means of Electrostatic and Antibody Binding", ICRA 2012

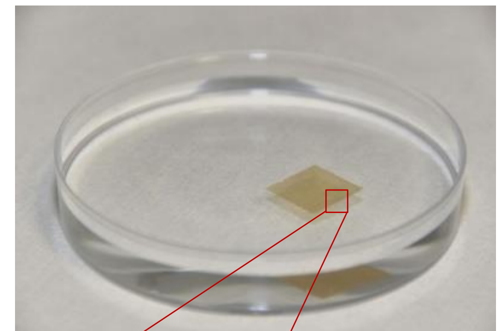
# Polymer nanofilms for intravascular applications

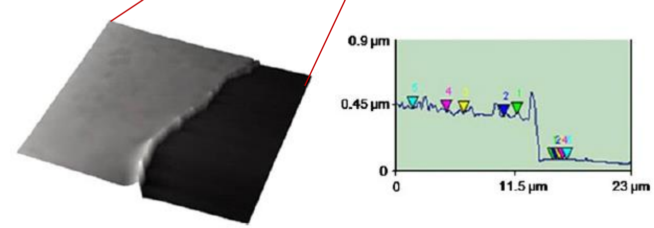
Challenge: development and positioning of functionalized nanostructured polymeric membranes to be used as devices for drug delivery and/or physical stimulation





Release in water



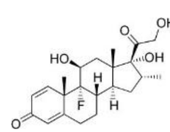



**Thickness: from ~ 50 nm to ~ 500 nm**

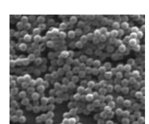
[redacted]

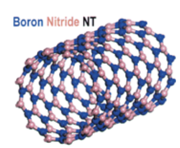
**Inclusion of specific drugs or active nanoparticles in the different layers of the polymeric matrix**

**Anti-restenosis drugs (e.g. Dexamethasone)**




**Magnetic or piezoelectric nanoparticles**






Ricotti *et al. Biomed Microdev.* 12: 809 (2010)
Ricotti *et al. Biomed Mat.* 6: 031001 (2011)
Pensabene *et al. Acta Biomater.* 7: 2883 (2011)
Mattoli *et al. Proc Comp Sci.* 7: 337 (2011)

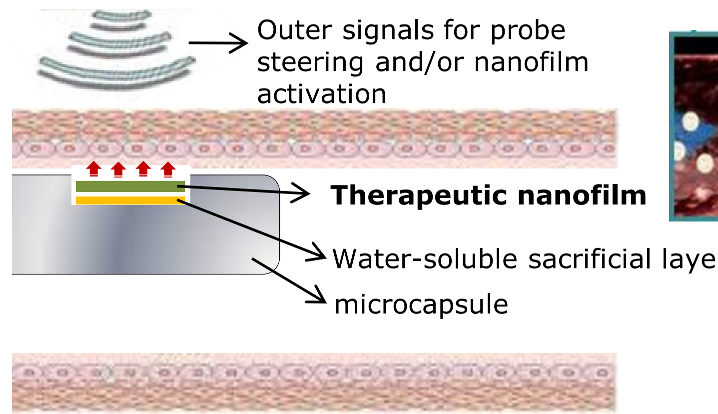
# Polymer nanofilms for intravascular applications

Biodegradable nanofilms able to stably adhere to the artery internal wall and to release there therapeutic agents in a temporized (or triggerable) way would accomplish both the functions of restenosis prevention and wall regeneration.

Critical issues:

• controlled and safe film positioning

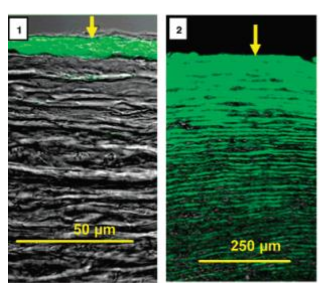
• long-term film stability in dynamic flow conditions




Damaged wall cells: negatively charged

Multilayer nanofilms: positively charged

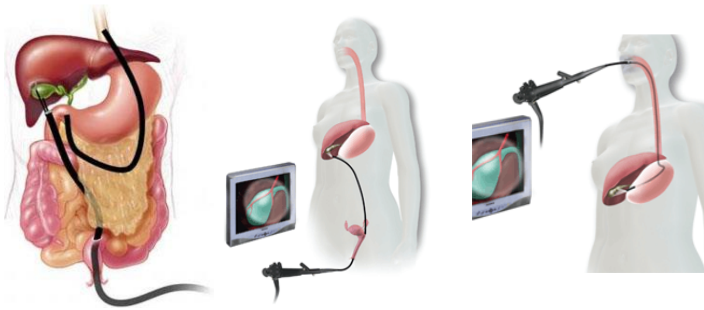
Electrostatic-mediated stability




Lower nanofilm thickness ➡ Higher mechanical stability

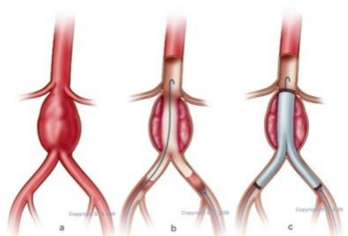
# The Quest for Miniaturization

## ABDOMINAL SURGERY



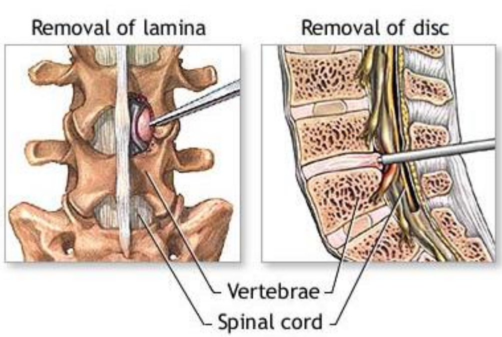
**NOTES (Natural Orifice Transluminal Surgery) SURGERY**
**Reaching** the target (esophagus diameter about 14 mm)
**Bringing** actions to the target

## VASCULAR SURGERY



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

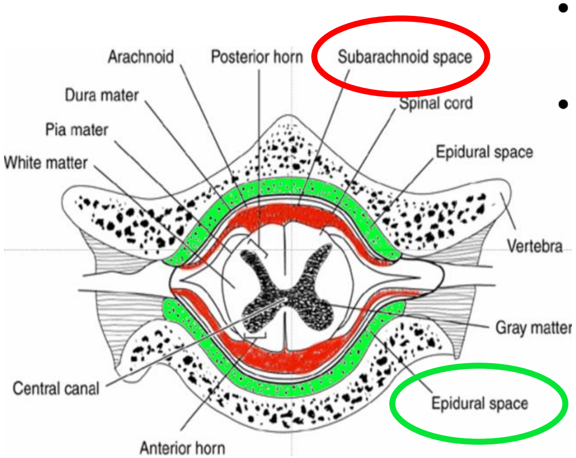
## NEURO ENDOSCOPY



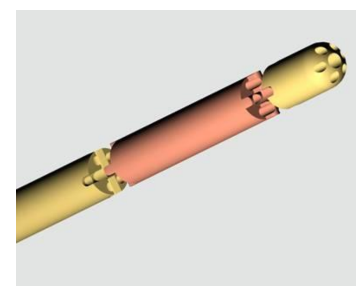

**Challenges in neuro endoscopy:**
**Reaching** the target (spinal cord diameter: **4 to 1.5 mm**)
**Bringing** actions to the target

# Neuroendoscopy of the spinal cord

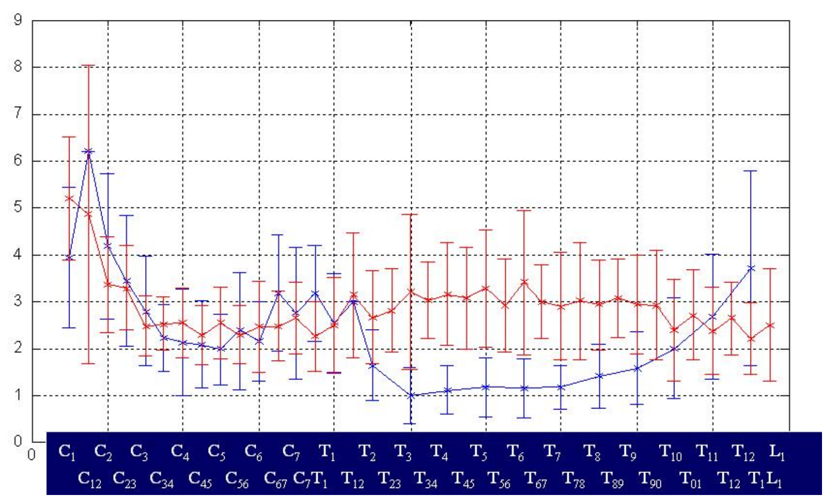
- **Diseases of CNS** can be particularly **devastating** because of limited intrinsic regenerative capacities and **currently** available **therapies** provide **limited functional recovery**;
- Owing to the low penetration rate, it is difficult using **systemic delivery** to achieve the suitable localized drug concentration

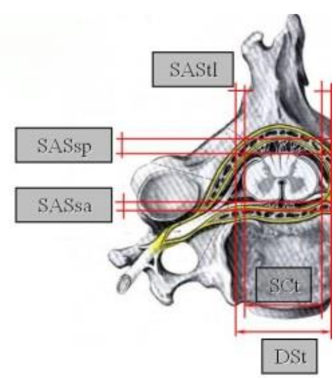


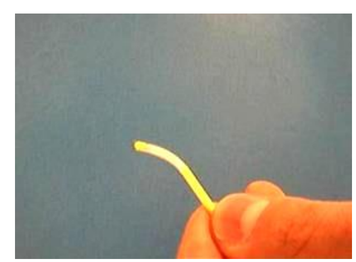

- The medium is suitable for navigation (Cerebro-Spinal Fluid, water-like liquid)
- The **workspace is extremely small (few millimeters)**



*Size of the Sub Arachnoid Space, mm*



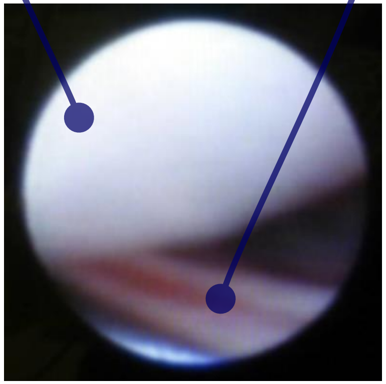
# Neuroendoscopy by an active catheter: in-vivo validation

## In vivo experimentation on Pig in Ozzano (Bologna)

Successful endoscopy (see images below) of the whole spinal cord, from lumbar access up to cervical tract, with **direct nerve stimulation through endoluminal electrode**

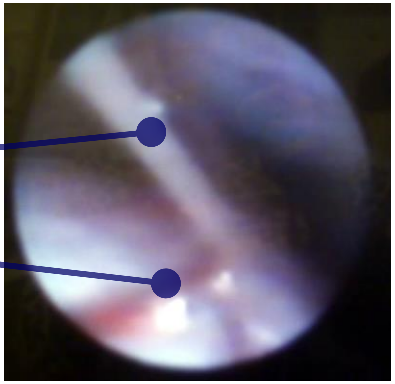
**Pia Mater**

**nerve root with blood vessel**



**Nerve root**

**Pia Mater with blood vessel**



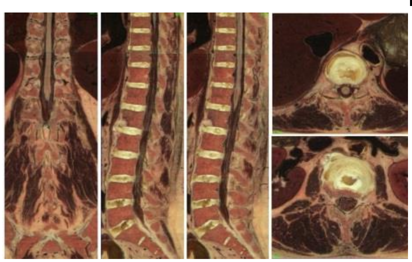
# Magnetic micro/milli-robots inside the Central Nervous System (CNS)

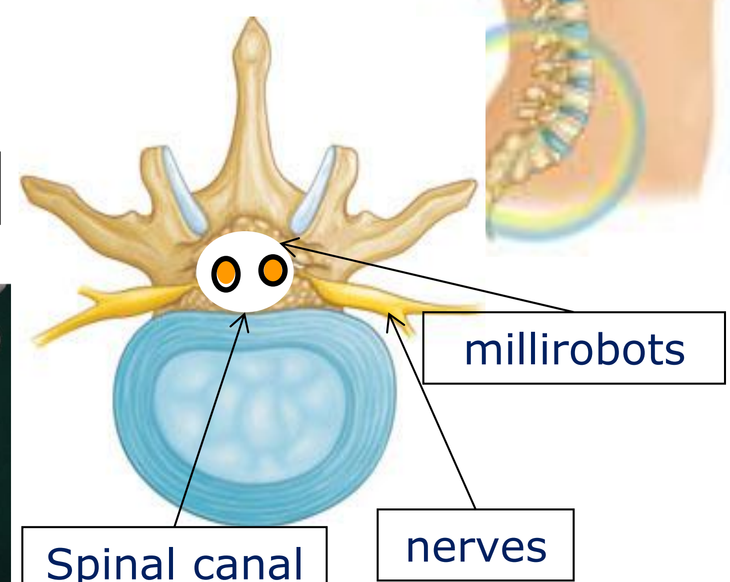
- **Medical diseases of CNS** can be particularly **devastating** because of limited intrinsic regenerative capacities and **currently** available **therapies** provide **limited functional recovery**;
- Owing to the low penetration rate, it is difficult using **systemic delivery** to achieve the suitable localized drug concentration;
- **Medical micro/milli robots** could enable minimally invasive access to reach these locations reducing the morbidity of current procedures while also enabling a broad range of new ones ;
- A feasible approach to the wireless propulsion and control of robots is through externally applied **magnetic fields**.

Permanent magnet

Magnetic Resonance

Electromagnets



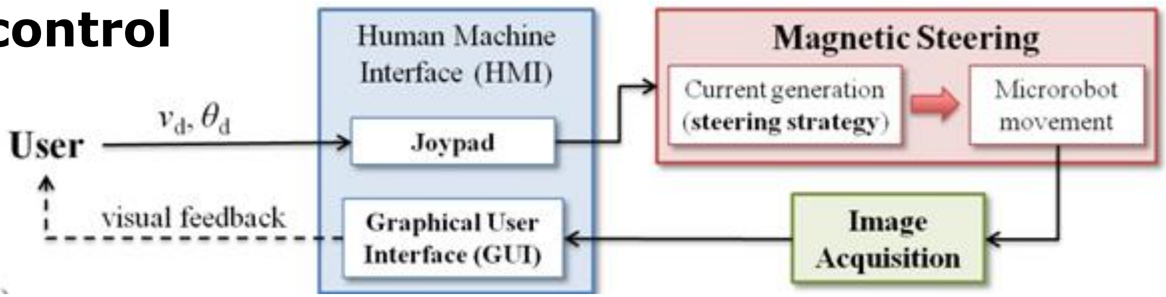


# Control by electromagnets

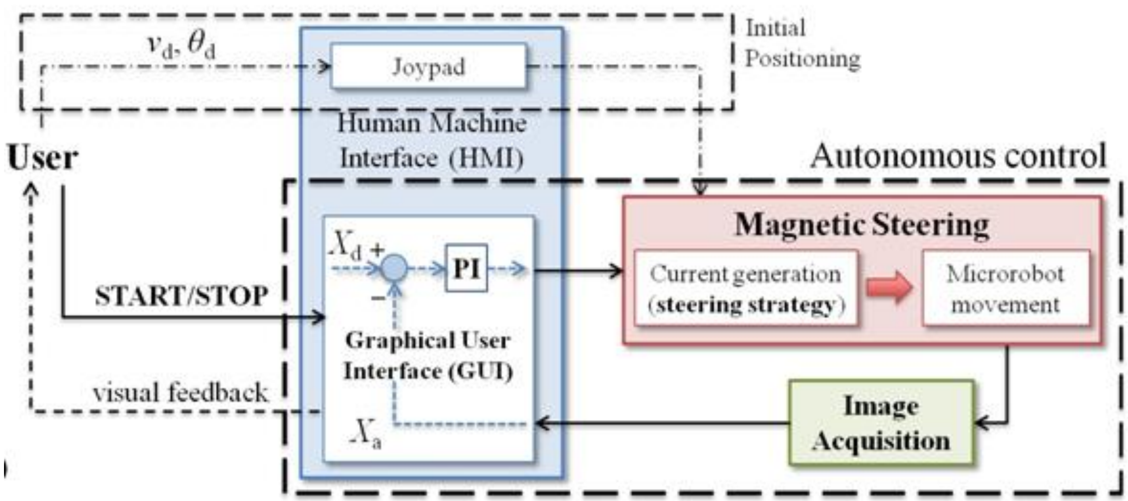
G. Lucarini et al, *Accurate and smooth navigation of magnetic microrobots under different control architectures,* IEEE Transactions on Automation Science and Engineering, under revision.

- Teleoperated and autonomous control were implemented and compared in terms of maneuverability of the microrobot along an eight-shaped path

**Teleoperated control**




**Autonomous control**

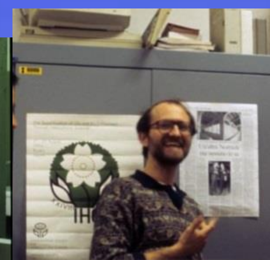



# Next Grand Challenges for Robotics Surgery: transforming (more) dreams into reality

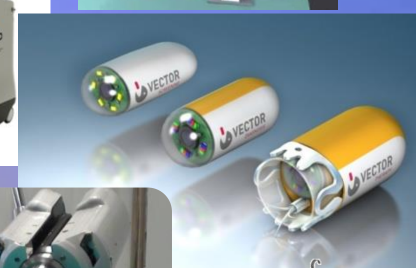
# We had Many Dreams … …Now Some of Them are Reality!

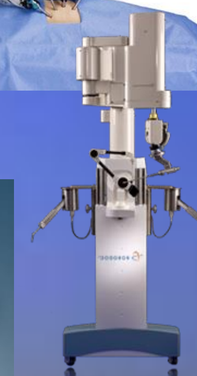
1985

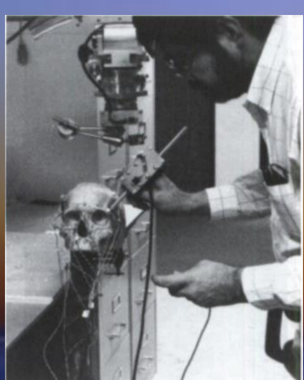
1988



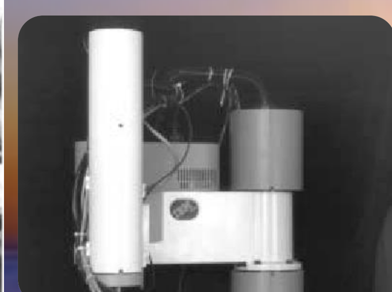
1991

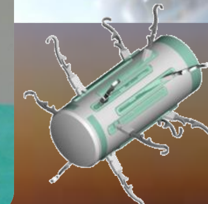






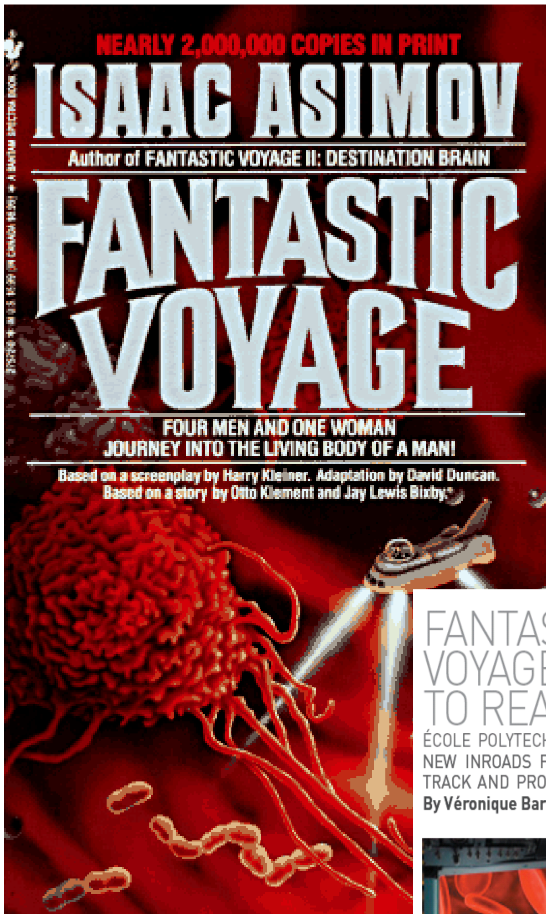
1992





# Science Fiction Becoming Reality

## SCIENCE fiction




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

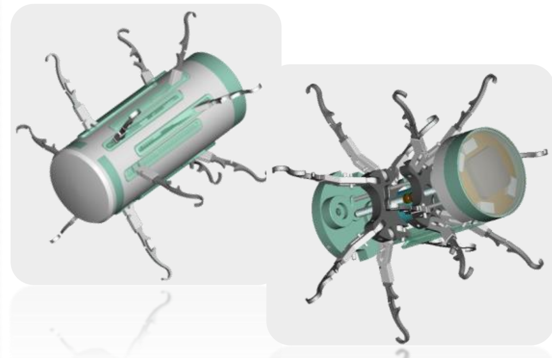
ISSUE #29 // JULY-AUGUST 2007

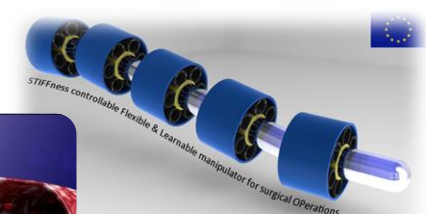
zoom

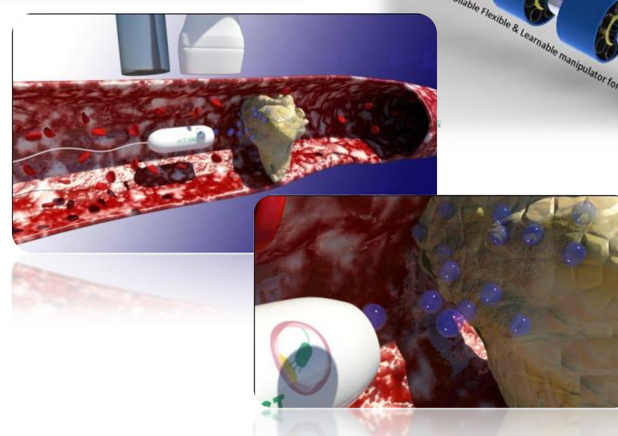
PROJECT

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

## REALITY @ SSSA





# Next Grand Challenges for Robotics Surgery

- Transforming (more) dreams into reality

- Dreaming new dreams

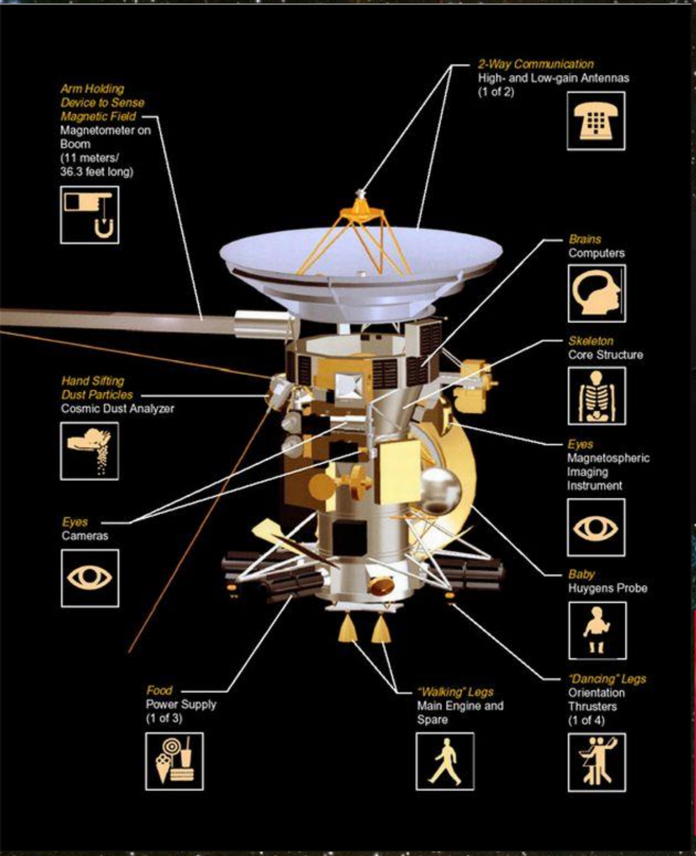
# Next Grand Challenges for Robotics Surgery: *Dreaming New Dreams, Building Bridges and Breaking Barriers*

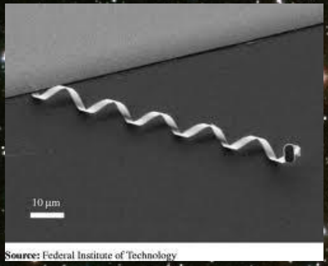
… from wired to wireless

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

…

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

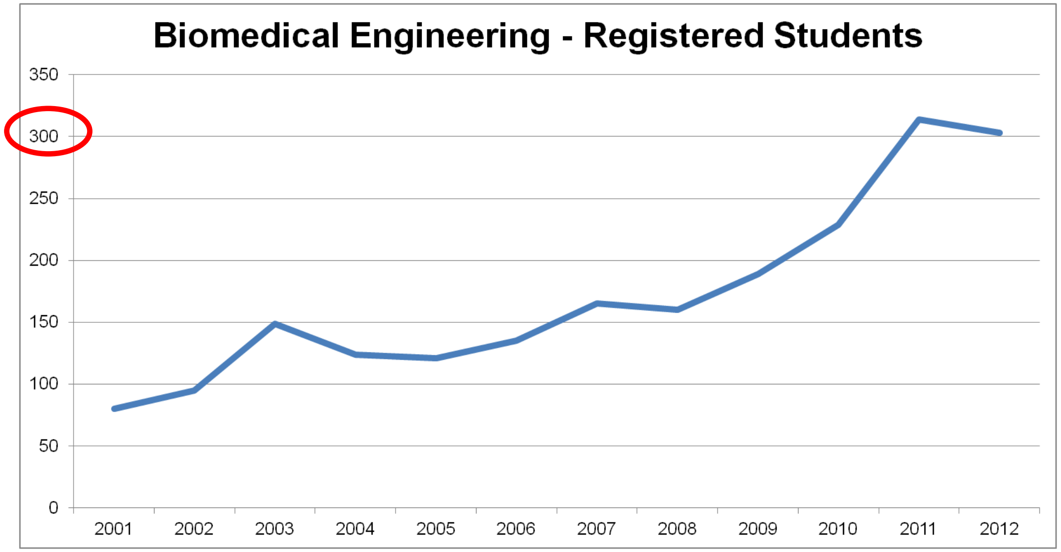


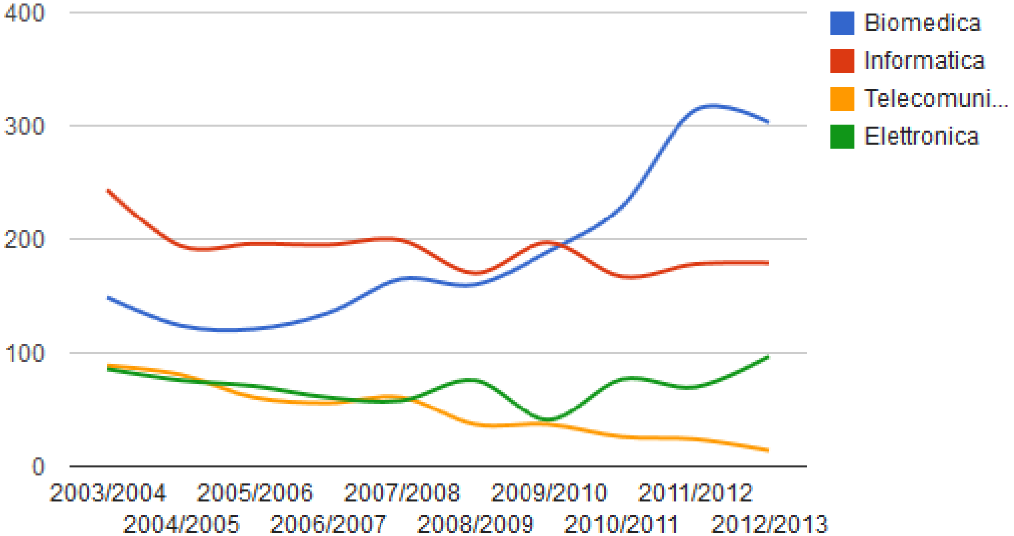
# What's Next in Robotics Surgery in Pisa?

- Education
- Research
- Experimental and Clinical
- Industry

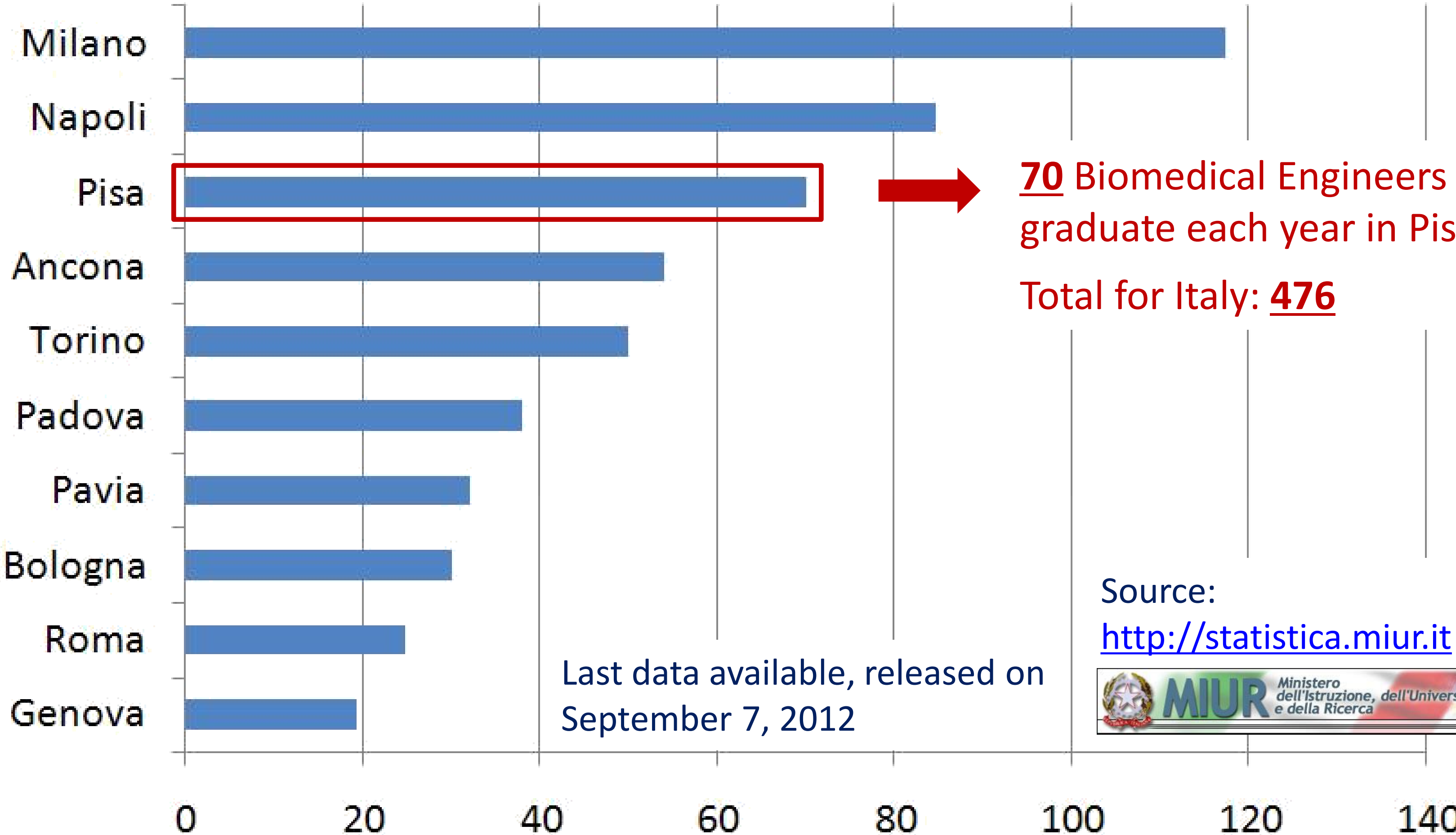
# Students of Biomedical Engineering at the Pisa University: enrollment




The number of registered students is continuously growing, exceeding 300 freshmen in the last two years.



# Pisa is one of the main sources of M.Sc. graduates in Biomedical Engineering in Italy




**70** Biomedical Engineers graduate each year in Pisa

Total for Italy: **476**

Last data available, released on September 7, 2012

Source: http://statistica.miur.it

# The PhD Program in BioRobotics @The BioRobotics Institute of the Scuola Superiore Sant'Anna

- ✓ Team work
- ✓ Interdisciplinarity
- ✓ Internationalization

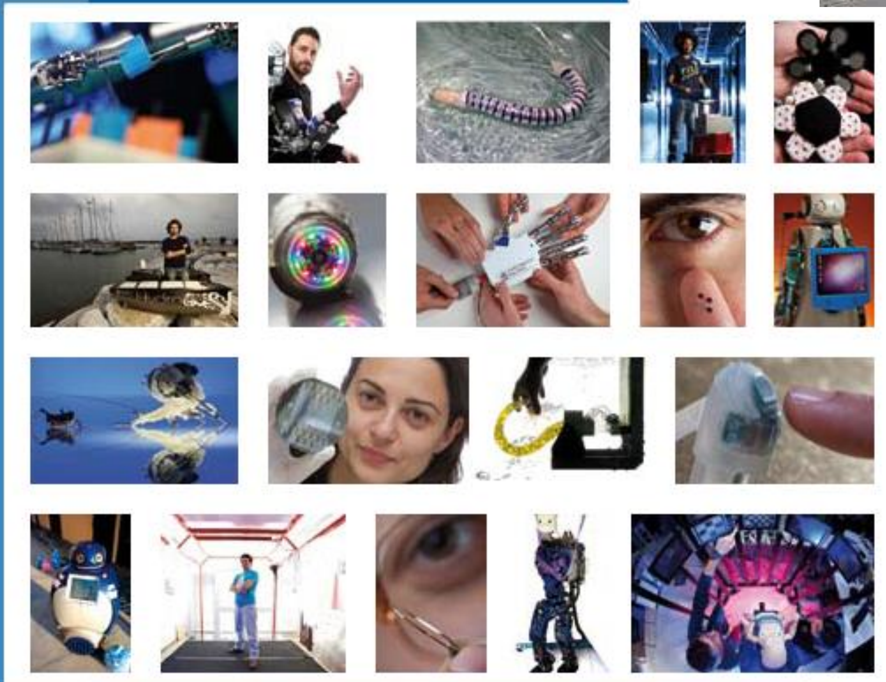
## PhD applications 2013

| PhD candidates | 90 |
|---|---|
| EU candidates | 49 |
| Non-EU candidates | 41 |

## Selected 2013-2016 PhD Students: 31

**6 in Robotics Surgery**

# the BioRobotics Institute



Professor Maria Chiara Carrozza Current Minister of Education, Universities and Research of the Italian Cabinet

Scuola Superiore Sant'Anna

di Studi Universitari e Perfezionamento


www.bioroboticsinstitute.eu

Il Sole 24 Ore
Mercoledì 17 Luglio 2013 - N. 194

# Università
VALUTAZIONE E RISORSE

anvur

## Performance al top

17 Luglio 2013

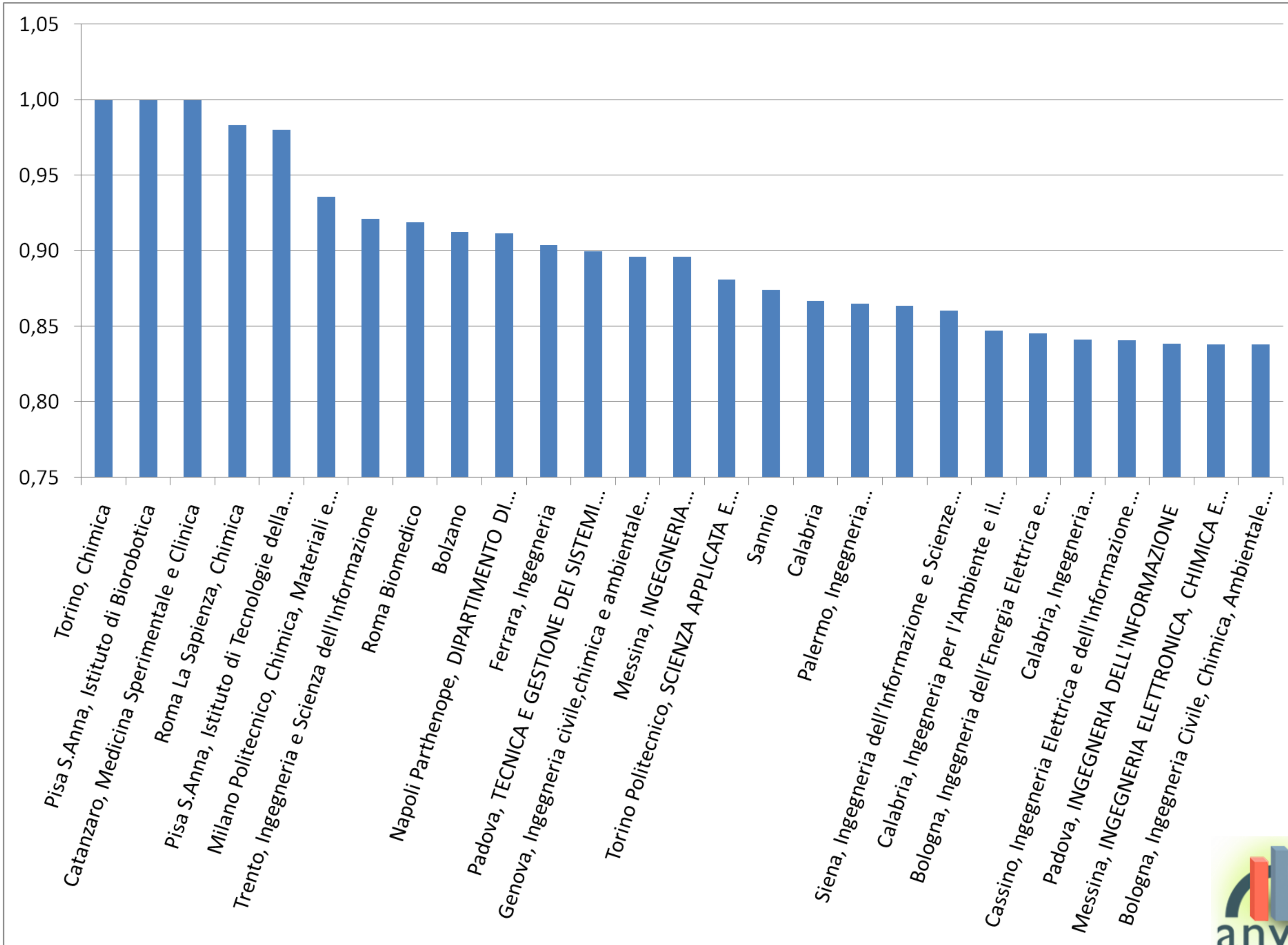
Il Sole 24 ORE
www.ilsole24ore.com
Mercoledì 17 luglio 2013
QUOTIDIANO POLITICO ECONOMICO FINANZIARIO + FONDATO NEL 1865

| GRANDI UNIVERSITÀ | MEDIE UNIVERSITÀ | PICCOLE UNIVERSITÀ |
|---|---|---|
|  |  |  |
| 1 Padova | 1 Trento | 1 Pisa Sant'Anna |
| 2 Milano Bicocca | 2 Bolzano | 2 Pisa Normale |
| 3 Verona | 3 Ferrara | 3 Roma Luiss |
| 4 Bologna | 4 Milano San Raffaele | 4 Trieste Sissa |
| 5 Pavia | 5 Piemonte Orientale, Venezia Cà Foscari | 5 Roma Biomedico |

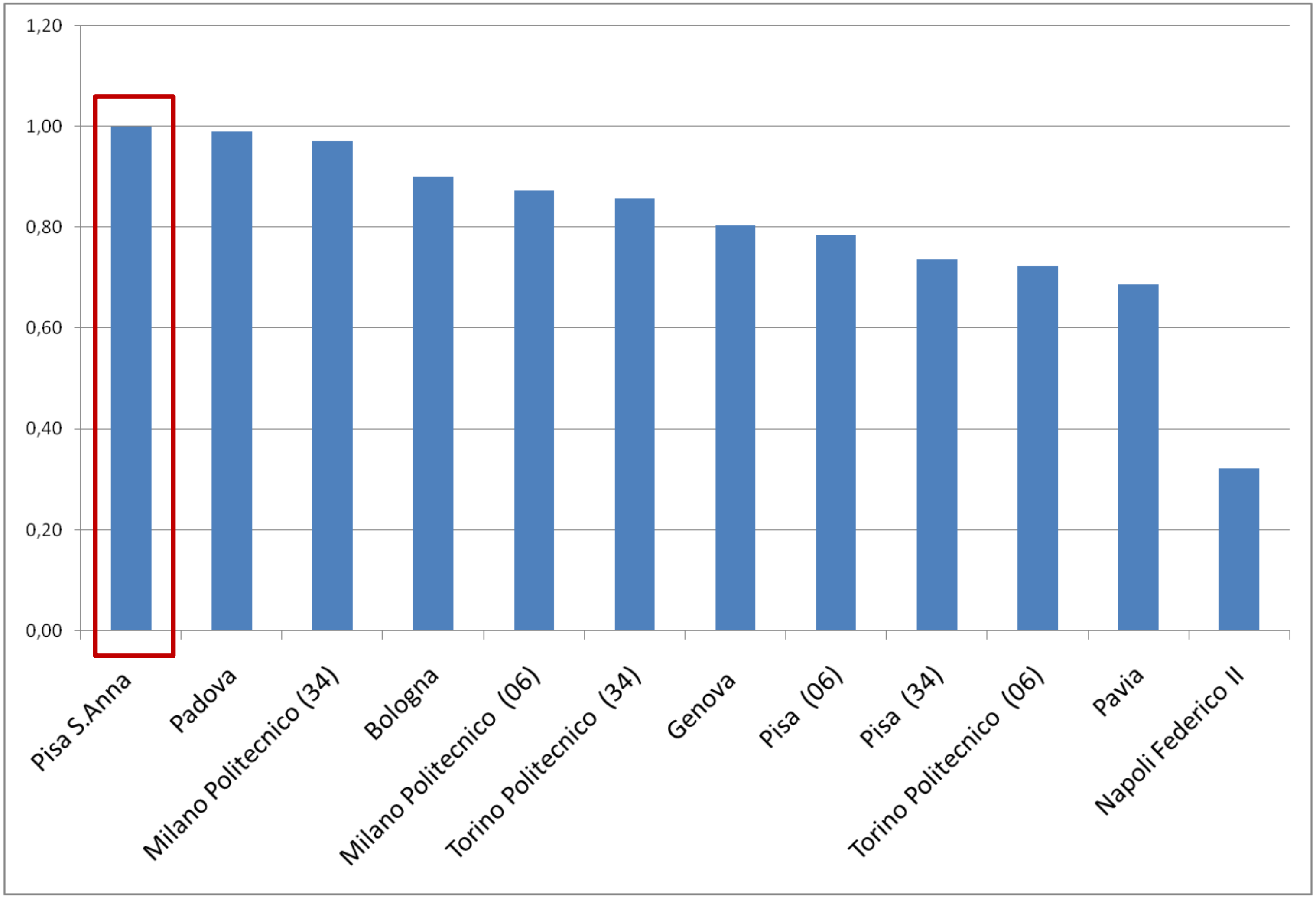
# La ricerca premia gli atenei del Nord

Padova, Trento e Sant'Anna di Pisa le migliori - Il ministro: subito 540 milioni ai virtuosi

# Ranking of Engineering depts. (upper 20%)



# Ranking in Biomedical Engineering



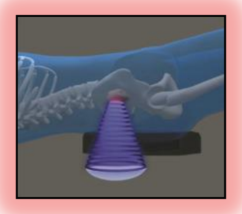
# FUTURA

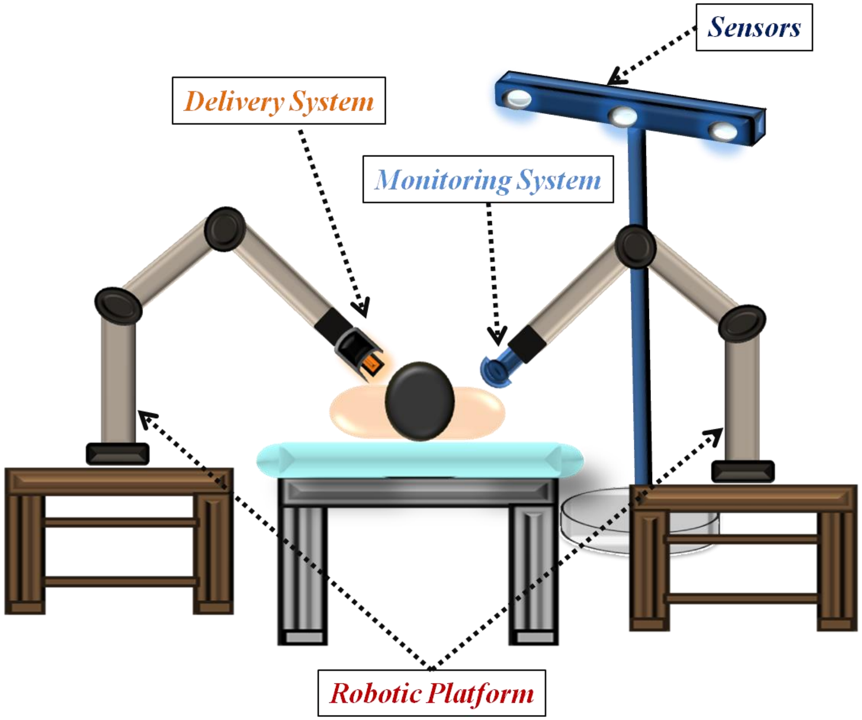
**F**ocused **U**ltrasound **T**herapy **U**sing **R**obotic **A**pproach

SEVENTH FRAMEWORK PROGRAMME

**Merging surgical robotics, non-invasive therapy (e.g. focused ultrasounds) and machine learning for medical imaging**

- ***Robotic platform:*** two serial commercial manipulators
- ***Monitoring system:*** 2D US confocal probe + 3D US probe
- ***Delivery system:*** custom made HIFU transducer
- ***Sensors:*** Smart environmental sensors + Human-Robot Interaction (HRI) monitoring






**UNDER NEGOTIATION WITH EU COMMISSION**

# Surgical Robotics & Allied Technologies Lab

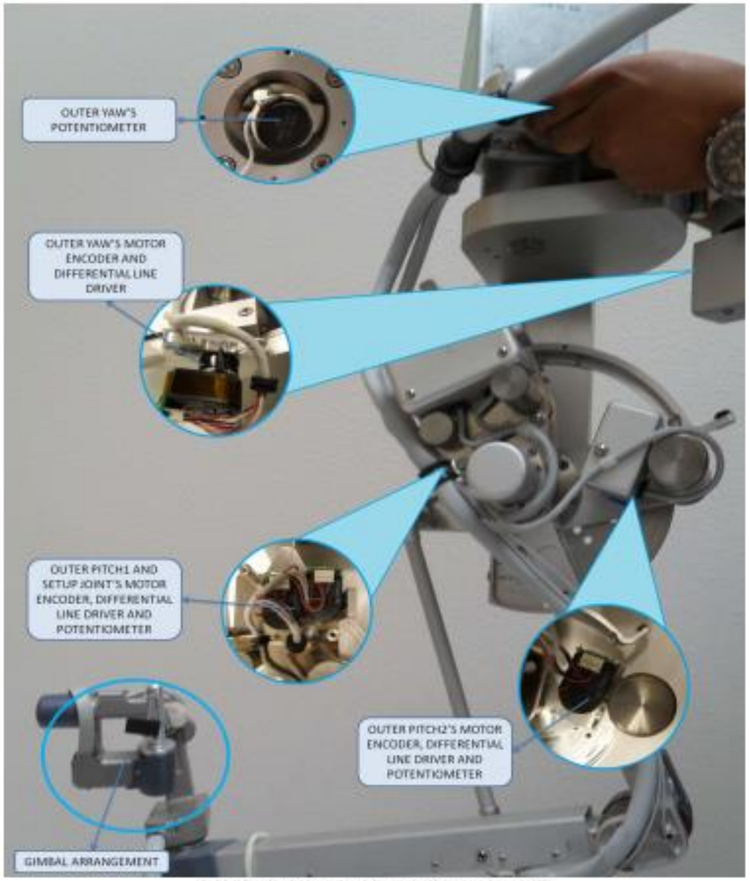
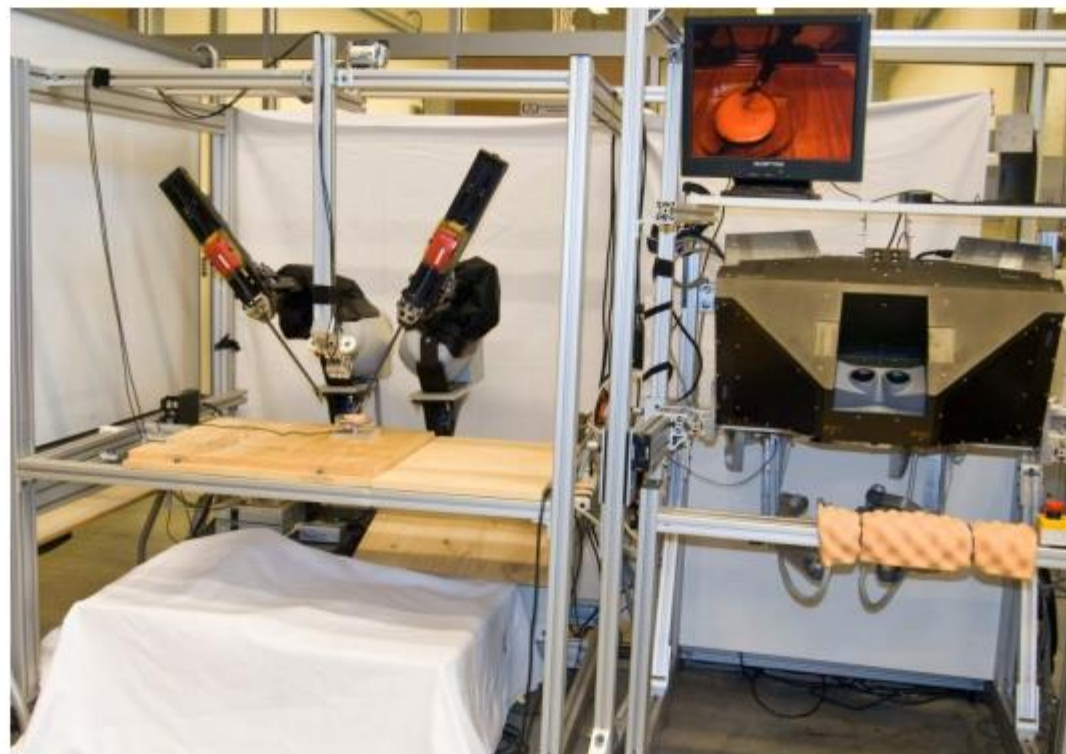


FIGURE 4: MTM WITH COMPONENT PLACEMENT.

Within October, a Da Vinci Research Kit with an open controller will be available at the Institute of BioRobotics (location to be defined 3mx1.5mx2m) .
We **look forward collaboration opportunities between different areas** and we propose the use of the kit for **educational activities.**



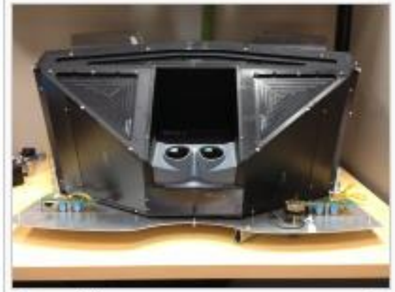
ERC | CISST

https://trac.lcsr.jhu.edu/cisst/wiki/sawIntuitiveResearchKitTutorial#a1Introduction

# User group of Da Vinci Research Kit

MTM

PSM



Stereo Viewer

Foot Pedal Tray

## The User Group

| *University/Group:* | *PI* | *PI Email* | *PI URL* | *Group Wiki Page* |
|---|---|---|---|---|
| The Johns Hopkins University | Professor Russell Taylor | *rht-at-jhu.edu* | [1] [2] [3] | JHU Group Page |
| Worcester Polytechnic Institute | Professor Greg Fischer | *gfischer-at-WPI.EDU* | [4] | WPI Group Page |
| Stanford University | Professor Allison Okamura | *aokamura-at-stanford.edu* | [5] | Stanford Group Page |
| The University of British Columbia | Professor Tim Salcudean | *tims-at-ece.ubc.ca* | [6] | UBC Group Page |
| Vanderbilt University | Professor Nabil Simaan | *nabil.simaan-at-vanderbilt.edu* | [7] | Vanderbilt Group Page |
| University of California, Berkeley | Professor Pieter Abbeel | *pabbeel-at-cs.berkeley.edu* | [8] | Berkeley Group Page |
| Carnegie Mellon University | Professor Howie Choset | | [9] | CMU Group Page |
| Sick Kids Children's Hospital | Professor James Drake | *james.drake-at-sickkids.ca* | [10] | Sick Kids Group Page |
| SUNY, Buffalo | Professor Venkat Krovi | *vkrovi-at-buffalo.edu* | [11] | SUNY Group Page |
| Scuola Superiore Sant'Anna | Professor Arianna Menciassi | *arianna.menciassi-at-sssup.it* | [12] | SSSA Group Page |
| University of Western Ontario & CSTAR | Professor Rajni Patel | *rvpatel-at-uwo.ca* | [13] | CSTAR Group Page |

# El.En. S.p.A. a Global Leader in Medical Laser Technology

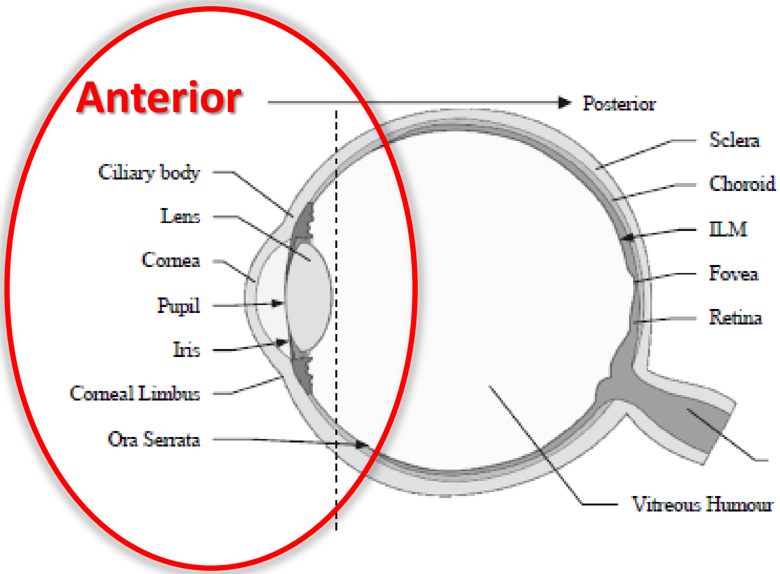
The strategy: integrating medical lasers with image-guided robotic manipulators

# El.En. S.p.A. a Global Leader in Medical Laser Technology

# Minimally Invasive Laser Robotic assisted Diagnosis and Surgery

(MILoRDS, Regione Toscana)

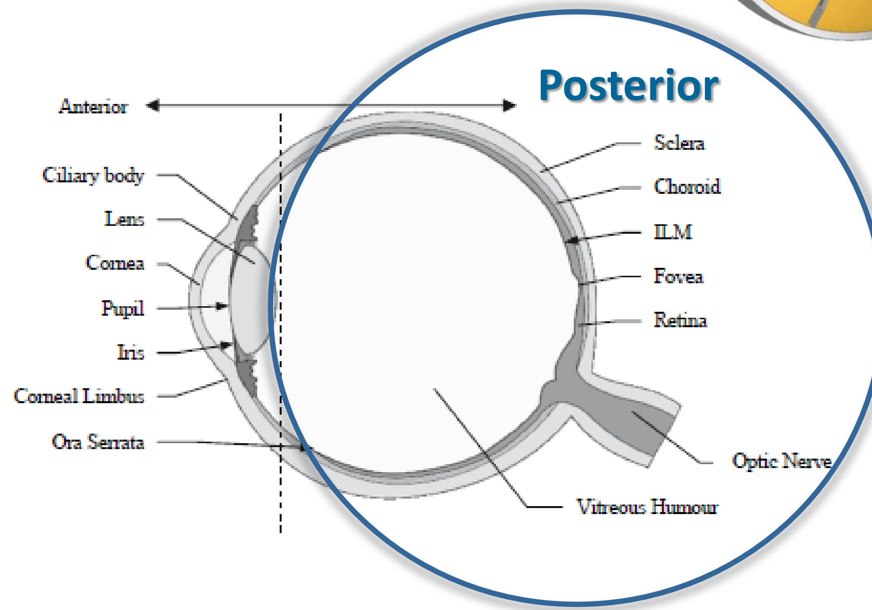
## Objective 1




Laser assisted surgery of the **anterior eye**:

- Corneal transplants
- Glaucoma

## Objective 2

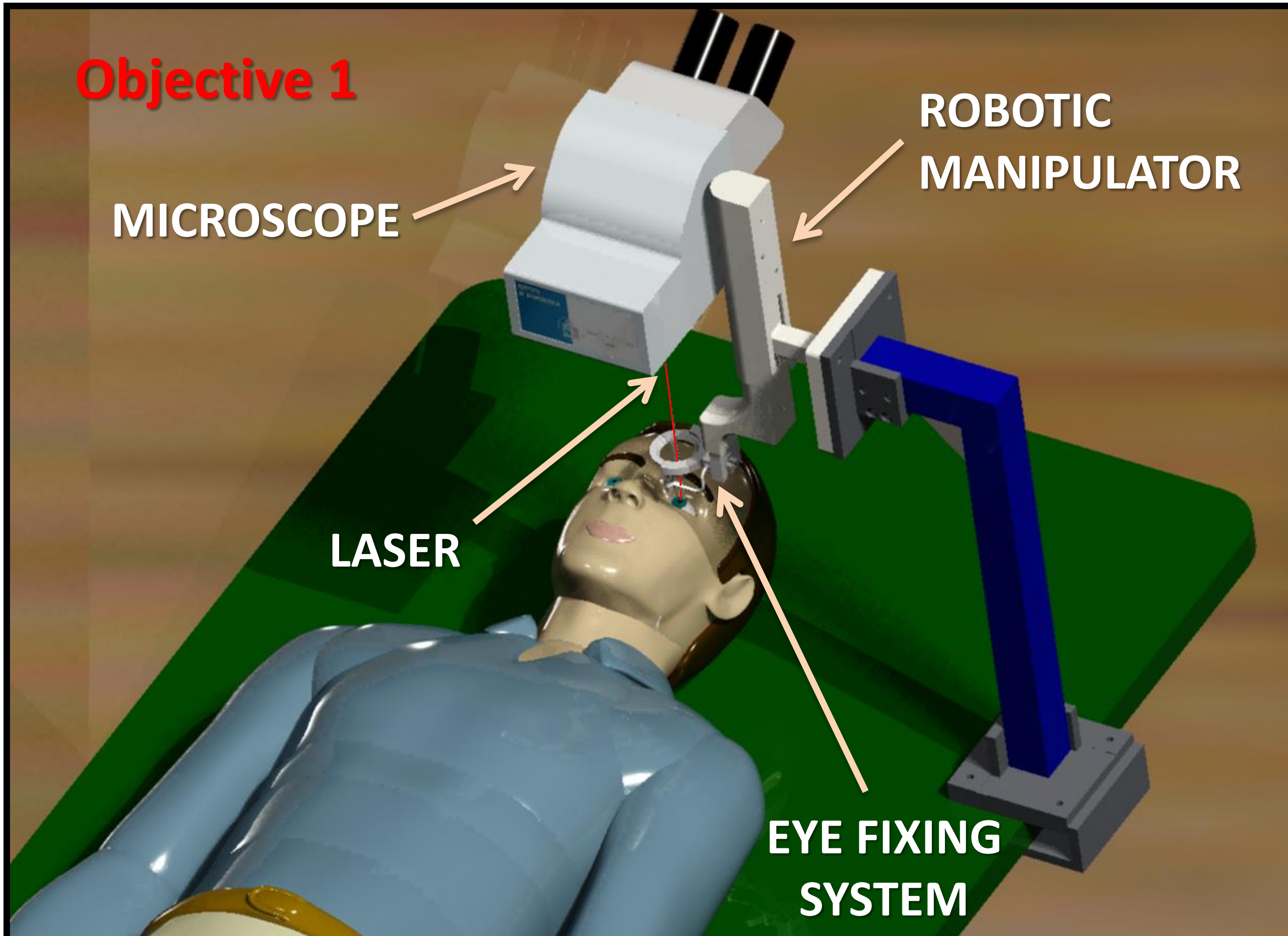



Laser assisted surgery of the **posterior eye**:

- Retinal diseases
- Vitreous humour

# Minimally Invasive Laser Robotic assisted Diagnosis and Surgery

(MILoRDS, Regione Toscana)



# Laser assisted robotic surgery in UROLOGY

ISTITUTO DI BIOROBOTICA
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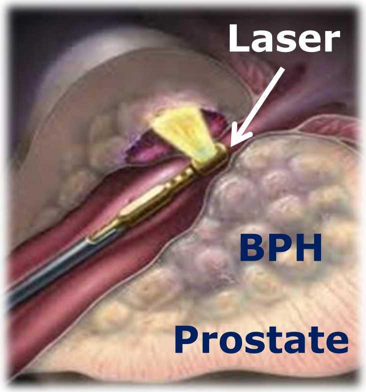
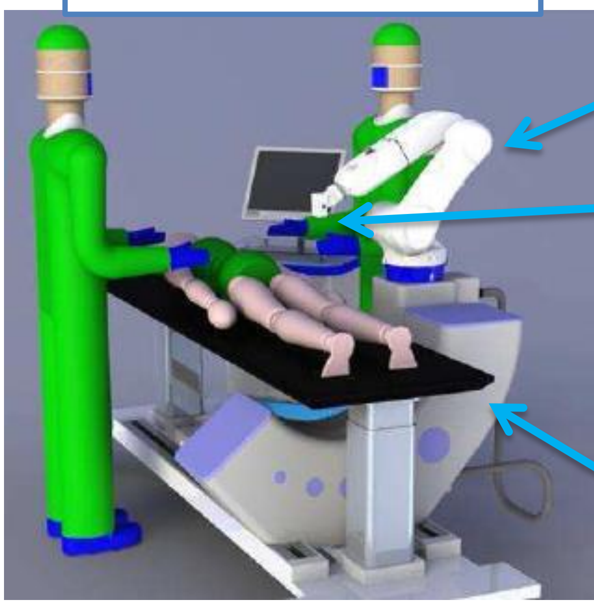



**PROBLEM**:

- To perform the **laser treatment of benign prostatic hypertrophy** (BPH), by reconstructing the channel of the prostatic urethra in a homogeneous way
- To increase the accuracy of the treatment
- To ensure the contact between the laser fiber and the tissue, thus avoiding thermal damage (carbonization) as much as possible

**SOLUTION: a guidance system to provide the surgeon with a 3D visualization and sensor feedback**

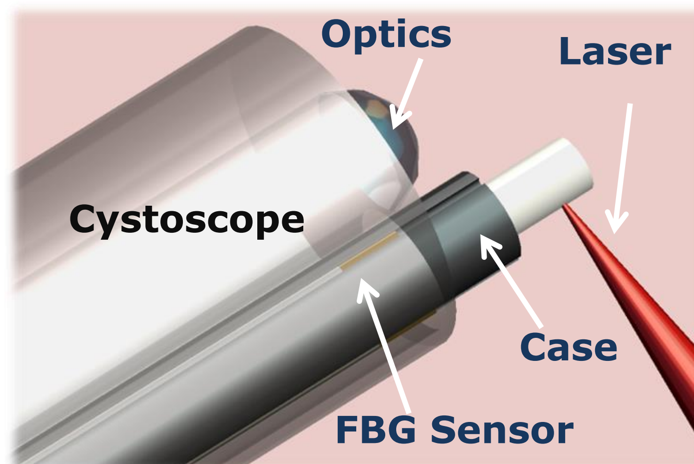
**ROBOTIC PLATFORM**



6 DOF ADEPT Robot

Shared control:
Cystoscope is mounted on the robot's end effector and moved by surgeon

Imaging system (3D RX)




Strain sensor for detecting contact with tissue


POR CReO 2007-13
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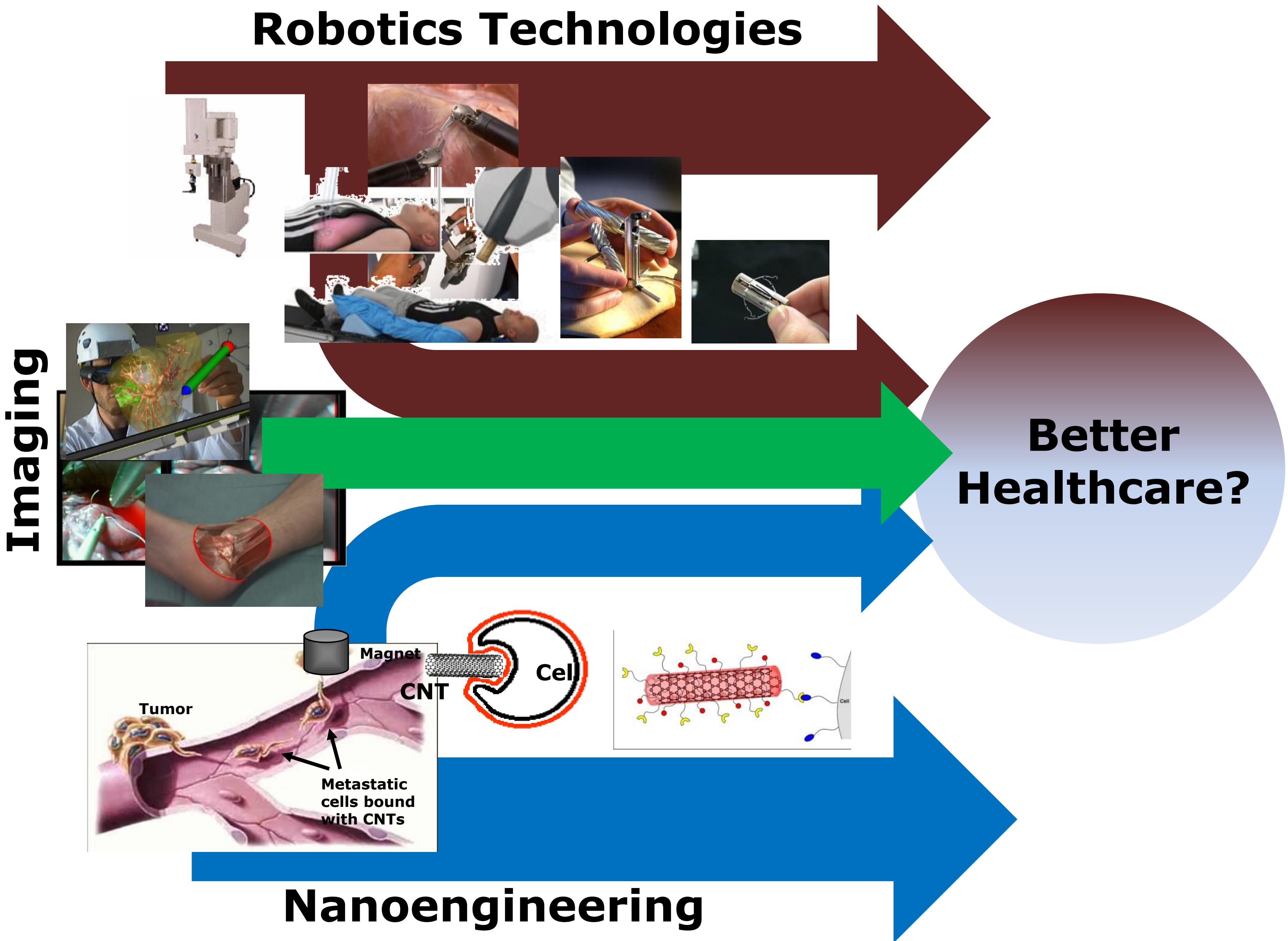
Diritti Valori Innovazione Sostenibilità
FAS

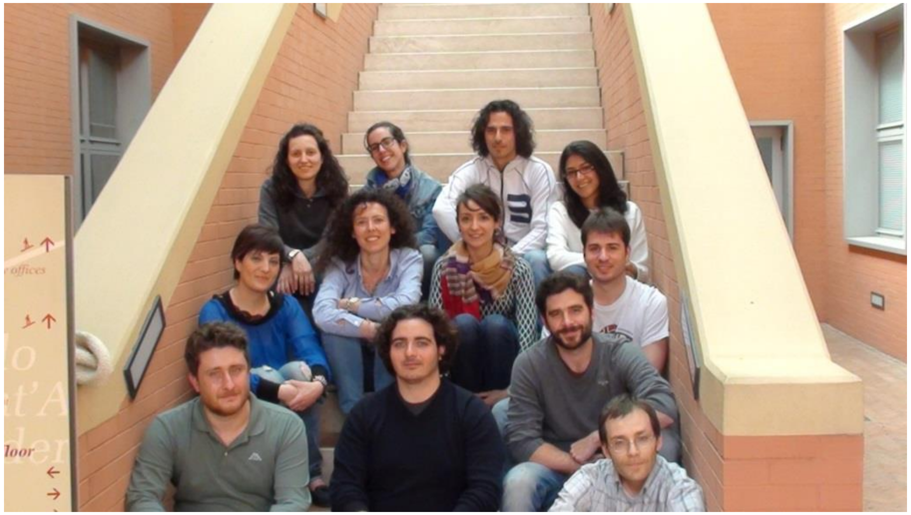


Robotics Technologies
Imaging
Better Healthcare?
Magnet
CNT
Cell
Tumor
Metastatic cells bound with CNTs
Nanoengineering

# Concluding Remarks

- Robotics technologies just begin to show their tremendous **potential** in Surgery
- 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
- Extraordinary **opportunities** for imaginative surgeons and for **collaboration between surgeons, robotics researchers and industry**

# Acknowledgments




**SURGICAL ROBOTICS GROUP**

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